Harish Kumar Sharma
Navneet Kumar *Editors*

Agro-Processing and Food Engineering

Operational and Application Aspects

Springer

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Dedicated
to
the Almighty
and
Mrs. Meenu Sharma and Mrs. Shilpi Goyal

Preface

Agricultural production is on a rising trend across the globe, which is putting pressure on agro-processing industries to timely handle the produce and keep it safe for a longer duration. The agro-processing industries deal with various unit operations from receiving harvested crop to the finished product. The textbook entitled *Agro-Processing and Food Engineering: Operational and Application Aspects* has been conceptualized with a view to cover the most relevant topics in the area for graduating students. In the book, simple illustrations are used in every chapter for easier understanding of the involved fundamentals, concepts, and processes. A number of solved examples are also included in different chapters to provide emphasis on problem solving. Efforts are made to simplify technological aspects, mathematical derivations, etc. to the maximum extent so that young minds could easily understand. Similar approaches are adopted in solved examples, so that concepts can be better understood by students/academicians. Several unsolved questions are also provided at the end of every chapter to review the progress made by students/readers.

The text in the book starts from presenting a comprehensive production status of different popular agricultural commodities. Further, the engineering properties of food materials are presented. The knowledge of the properties remains essential in clearing the understanding with respect to design, operation, and control of various processing equipment and quality of finished products. Material handling systems are used in agro-processing industry to increase the level of mechanization, which improves the consistency and quality of the produce, and therefore the knowledge with respect to designing of efficient material handling system becomes very important to students. The moisture content of the agro-produce, which can be optimally retained through drying/dehydration in cereals, pulses, and oilseeds, assures safer storage for longer duration. The desired size of agro-produce can be achieved by different milling equipment to obtain the material in the form of flour, powder, etc.

The effective mixing is an important unit operation to cater to the need of nutritious substitutes of existing food items and to create uniformity and homogeneity during the operation. The cleaning of grains is performed before other unit operations, and grading of the finished product can be achieved using different graders/separators to control the quality. The storage life of the foods can be enhanced by using various traditional and modern storage structures. The processing can add value; therefore, processing of cereals, fruits and vegetables, oilseeds, and pulses is covered and presented in such a way that the concepts and technological aspects are easier to understand and beneficial to students and the scientific fraternity. The technical manpower involved in various capacities in agro-industries can also get first-hand knowledge through the technological concepts and mechanisms covered in the book.

All the chapters have been written by Teachers/Researchers, working in the field; therefore, the concepts are made simpler and easier to understand. Efforts are made to simplify every aspect; therefore, this handbook is expected to be unique for students. However, feedback in any form from any corner shall be encouraged to further strengthen the quality of the book in the time to come. Since the idea for conceptualization of the book emerged out of the need of students on the various topics covered in this book therefore it is anticipated that this book will cater to the need of students, technicians, academicians, and researchers working in the area of Agro-processing, Food Engineering, Agricultural Process Engineering, Food Technology, and allied fields.

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Harish Kumar Sharma
Navneet Kumar

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Harish Kumar Sharma is a Professor at Sant Longowal Institute of Engineering & Technology (SLIET) (Deemed University) and is currently working as Director of NIT Agartala, and is founder Mentor Director of IIIT Agartala. Dr. Sharma is involved in teaching Postgraduate students and has supervised 16 Ph.D. and 37 M. Tech. students. He has published 193 papers in national/international journals/ proceedings in Food Engineering/Technology, authored/edited 8 books, two proceedings, and two manuals published by reputed national and international publishing houses. He has contributed 23 chapters in books published by national and international publishing houses and visited different countries. Dr. Sharma has successfully handled several projects and successfully transferred a technology on a commercial scale. He has filed two patents and possesses two copyrights and rendered technical assistance to different industries.

Navneet Kumar is an Associate Professor and Head of the Department of Processing and Food Engineering at the College of Agricultural Engineering and Technology, Anand Agricultural University, Godhra, Gujarat, India. He is involved in teaching undergraduate and postgraduate students and has taught more than ten food-process engineering subjects so far. He has guided several master's students as a supervisor and doctoral students as a member of the advisory committees. Dr. Kumar has contributed more than 50 publications as research papers, review papers, books, and book chapters. He has been awarded Fellow of Institution of Engineers (FIE), Distinguished Service Certificate (ISAE), and best research paper award in the field of food engineering (AFSTI). He also has delivered lectures/talks on different aspects of food processing at various institutes across India. He is currently working in drying, dehydration, mathematical modeling, storage stability, traditional foods, and minimal processing.

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1 Agro Processing: Scope and Importance

Harish Kumar Sharma and Navneet Kumar

Abstract

In this chapter, the importance of agro-processing industry is highlighted. The agricultural production of various commodities from the leading countries of the world during the last decade is presented. The chapter includes the status of cereal industry, fruit and vegetable industry, fish industry, livestock industry, poultry industry, sugarcane industry, pulse industry, tea industry, oilseed industry, spice industry and dairy industry across the globe. The overall increase in the production of cereals, fruits, vegetables, fish, livestock, sugarcane, tea, oilseeds, pulses and spices has been observed during the last decade. The growth rate in the production is also expected to increase in number of agricultural sectors in the years to come to meet the increasing global demand. It will expand the agro-processing industry and storage facilities in particular. The untapped contribution of agro-processing industries in the economy of developing countries and employment generation is also highlighted.

Keywords

Agro-processing industries · Cereals · Fruits and vegetables · Fish · Livestock and poultry · Sugarcane · Pulses · Tea · Oilseeds · Spices · Dairy

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1.1 Introduction

The demand for agricultural commodities is mainly driven by the set of parameters, viz. income, price, preference and population. Now, the use of agricultural commodities is not limited to food only, but it has now been expanded to the non-food uses too such as fuels, feed and other industrial applications. Therefore, the expansion is expected towards the different processing units across the world in the future. Processing involves all the activities that led to the transformation of basic food material to be more usable, less prone to deterioration and easily handled so as to make it a more useful product. Processing of produce involves different unit operations to convert it into value-added form starting from harvesting to end use.

The growing urban population, working professionals and fast-pace life style has resuled time constraints for the various household that eventually is popularising numerous processed food products in different developing nations also. Therefore, the agro-processing sector is one of the most important sectors to reach new levels of growth and development. The conversion of basic food stuff to premium food quality product has not only given stability to the processed food industries but also benefited the farmers by increasing their income. However, the growth of the food processing sector depends upon the production of the agricultural produce, demand, export opportunities and policy of the government.

There are countries in which different corporations/agencies ensure procurement of wheat, paddy, pulses, fruits, etc. directly from the farmers to provide higher returns to them. Horticulture Produce Marketing and Processing Corporation (J&K, India) procures apples from local orchards for the production of apple juice concentrate without involving local dealers and suppliers, thus providing high direct return to their yield. Higher returns are also attained as apples used for concentrate production are generally not equally acceptable for direct consumption because of the quality, and therefore it fetches lower price, if sold in the market for direct consumption. Hence, producing juice concentrate adds value to the produce and yields higher returns. Similar approach is needed for the entire cultivated segment to boost up the income level of farmers.

The agriculture sector is considered as the backbone of growth and development of a country. In India, more than 60% of land is occupied by the agro sector and leads in the production of many commodities like tea, sugar, milk, fruits, vegetables, etc. Such huge production is responsible for huge investments and employment generation. However, due to insufficient processing facilities, higher losses are observed. Fruits and vegetables encounter the highest loss percentage of 5.8–18%. With the advances in science and technology, rapid strides are needed in the food processing sector to prevent such losses and convert basic crops into valuable products. This sector requires more attention not only to strengthen the concern of the food security but to promote industrialization, which can enhance rural, social and economic development.

1.2 Agro-Processing Industries

The agro industry is an enterprise that processes biomass. It is also referred to as an establishment, which diversifies the food market by processing raw materials and providing varieties of foods. Agro-processing industries are considered as the most important setup to prevent post-harvest losses of agriculture produce as well as livestock. As per the FAOSTAT database, the processing of barley for the production of beer remains on the top among processed agricultural produce with 186.5 MT in 2018, while the production of sugar remains on the second processed product with a production of 182 MT [1] (Fig. 1.1).

The food processing industries are being promoted by concerned state/ department to:

- Provide hygienic, safe and quality products.
- Provide cost-effective nutritious foods to the people.
- Build a highly productive and competitive industry.
- Promote sensitization of food safety issues.
- Develop knowledge-based industry, which promotes value addition.
- Promote modernization of agriculture and bring the benefits of urbanization to the food processing sector.

The status of different agro-processing industries is described as follows:

1.3 Cereal Industry

Cereal industries have developed very fast in the world as well as in India. Consumers demand more benefits from standard foods. Therefore, cereal based products like extruded snacks, breakfast cereals, biscuits etc. are produced from basic agro products such as wheat, sorghum, oats etc. to provide not only nutritionally rich products but also healthy and palatable to match busy life style. China is the leading producer of cereals followed by the USA and India. Production of various cereals is presented in Table 1.1, and the production is expected to increase further by 1% annually for a time span of nearly 10 years. In the recent years, the supply of the cereals has exceeded the consumption, which has led to the significant buildup of stock and caused the reduction of prices in the international market as compared to the previous decade.

The maximum production of maize remains on the first place with a production of 1148.5 million tonnes, while wheat and paddy remain on the second and third places with a production of 765.8 and 755.5 million tonnes (503.9 million tonnes of milled rice equivalent), respectively [2]. The world cereal production is projected to increase to 3054 million tonnes by the year 2028 [3]. The largest growth is expected in maize production followed by wheat, rice and then coarse grains. The world average yield of the cereals is expected to increase by 1.1% annually, and mostly the increase in the world production of cereals is mainly going to be in Asia, Latin America, Africa and Eastern Europe [3].

Rice is a staple food in most of the states of India especially southern and eastern regions. Tables 1.2 and 1.3 show the production of paddy (rice) and wheat. The global rice production is expected to reach 583 million tonnes by the year 2029 [4]. India accounts production of white and brown rice, which is more than 20% of world production and is considered as one of the largest producers. Indian paddy production reached up to 177.6 million tonnes in 2019. Rice industries are considered as the backbone of our staple food and have a significant contribution to food security. India is one of the world's best *basmati* rice producers and exported nearly 4.45 million tonnes of basmati during 2019–2020 [5]. However, the consumption pattern of rice is going to increase over the next 10 years. The utilization of rice is going to expand nearly by 1.1% annually compared to 1.4% annually in the last decade.

The global rice production is projected to grow over the next 10 years. However, the production in developed countries is going to increase marginally, whereas the growth is going to be robust in the developing nations. Asia is going to contribute to the majority of the production, and the highest growth is expected in India followed by Indonesia, China, Vietnam and Thailand. The production in China is going to see the growth at the slower pace than the previous decade due to decrease in area of plantation. The production of paddy in different countries and the world is shown in Table 1.2. The world rice trade is expected to grow by 2.3% annually, and nearly 75% of total export is traded by India, Thailand, Vietnam, Pakistan and the USA. The largest import is expected in Africa, countries where the demand is going to be higher than the production due to per capita consumption and population growth.

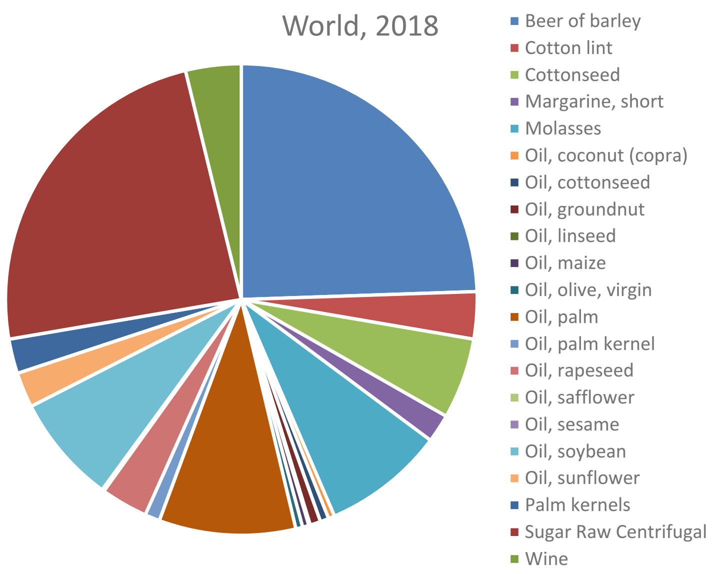

Fig. 1.1 Pattern of processed agricultural production of the world during 2018

Wheat production in India has seen a sharp increase from 6.46 million tonnes (MT) in 1950–1951 from an area of 9.75 MH to more than 93 MT during 2011–2012 from an area of about 30 million hectares (MH). After China, India is the second largest producer of wheat in the world (Table 1.3) with a share of nearly 12% in total production of the world. Global wheat production is going to increase and is expected to reach up to 839 million tonnes by 2029 [4]. The increase in production by the developed nations is projected to add by 41 million tonnes in the year 2028, whereas the production in developing countries is going to add 45 million tonnes. India is further expected to increase its production by 15.5 million tonnes in the year 2028 [3]. The consumption of wheat is also going to increase globally. China, India, Africa and the Middle East are projected to account for nearly two-thirds of the increase in consumption [3]. The production of wheat-based alcohol is also projected to grow in order to boost the production of alcohol.

The export of wheat is also expected to grow over the next 10 years. The Russian Federation is expected to remain as the leading exporter of wheat, which may account for 20% of the world wheat export by 2028 followed by EU and the USA. The import of wheat is widespread across the world, but the top five importing nations are Egypt, Indonesia, Algeria, Brazil and the Philippines [3].

1.4 Fruit and Vegetable Industry

India is the second largest producer of fruits and vegetables after China. Table 1.4 shows the production of fruits and vegetables across the globe. Fruits and vegetables are highly perishable in nature because of high moisture content (70–95%). The different processes such as pickling, dehydration, canning, bottling and other preservation techniques have been introduced to reduce the wastage of fresh fruits and vegetables and to add value. However, the processing varies in different countries depending upon the facilities and domestic patterns and policies. The USA processes around 65% of the total production, whereas the Philippines and China process around 78% and 23%, respectively. The processing in India is lesser than 3% and

Table 1.1 Production of cereals in major producing countries and the world [2]

Year	Production, million tonnes			
	China, mainland	USA	India	World
2010	496.3	401.1	267.8	2460.5
2011	519.4	385.5	287.9	2581.6
2012	539.3	356.2	293.3	2556.1
2013	552.7	434.3	294.9	2759.2
2014	557.4	442.8	296.0	2809.4
2015	618.2	431.9	284.3	2833.6
2016	614.6	503.5	297.9	2917.4
2017	614.0	440.3	310.8	2966.0
2018	608.9	439.7	321.6	2912.3
2019	612.7	421.5	324.3	2979.0

Table 1.2 Production of paddy in major producing countries and the world [2]

Year	Production, million tonnes			
	China, mainland	India	Indonesia	World
2010	195.8	144.0	59.3	694.0
2011	201.0	157.9	58.3	719.1
2012	204.2	157.8	59.7	727.7
2013	203.6	159.2	60.1	731.8
2014	206.5	157.2	59.1	730.8
2015	212.1	156.5	61.0	732.0
2016	211.1	163.7	59.4	739.5
2017	212.7	168.5	59.4	751.7
2018	212.1	174.7	59.2	762.8
2019	209.6	177.6	54.6	755.5

Table 1.3 Production of wheat in major producing countries and the world [2]

Year	Production, million tonnes				
	China, mainland	India	Russian Federation	USA	World
2010	115.2	80.8	41.5	60.1	640.8
2011	117.4	86.9	56.2	54.4	696.9
2012	121.0	94.9	37.7	61.7	673.7
2013	121.9	93.5	52.1	58.1	710.4
2014	126.2	95.9	59.7	55.1	728.8
2015	132.6	86.5	61.8	55.8	742.0
2016	133.3	92.3	73.3	62.8	748.5
2017	134.2	98.5	86.0	47.4	772.3
2018	131.4	99.9	72.1	51.3	733.4
2019	133.6	103.6	74.5	52.3	765.8

does not contribute significantly in the world trade (<1%). But, the processing is expected to grow and is projected to process 16.39 million tonnes by 2024 as compared to 8.31 million tonnes in the year 2019 [6].

The production of fruits and vegetables has been consistently increasing for the last two decades and is projected to have further growth due to the awareness towards health, nutrition, availability and functional aspects. The fruit and vegetable industry in Asia has a tremendous export potential due to a wide range of produce. The short production cycle of vegetables allows farmers to have multiple cropping and produce good volume. Asia produces nearly 74% of the world vegetable production, and China produces more than 50% of the world production of vegetables and produced 588.3 million tonnes of vegetables in the year 2019 (Table 1.4). The domestic consumption in developing countries is still low due to the purchasing capacity and eating habits. Processed vegetables including dried vegetables constitute the large share of export. However, the vegetables in frozen form is going to see the future growth tremendously.

Even fruit and vegetable processing industries in a number of countries do not receive standard quality produce due to inadequate availability of cold stores and cold chain transport, which in turn results in low-grade processed foods. However, significant developments in technology involve efforts to reduce losses by better understanding of harvesting, handling and preservation. Packaging of fruits and vegetables has a significant role in the prevention of losses and increase of shelf life. Much of the produce is produced in rural areas, and due to inadequate facilities and lack of direct approach to the industries, producers receive much lower prices. Keeping in view, the involvement of different government corporations in post-liberalization era has helped the fruit and vegetable industry to improve upon the value chain to a certain extent.

In developing countries, the food industry has been facing problems on different fronts and need to work under the constraints of variation in the quality of raw material and varied prices, inefficient techniques for handling and storage, lack of research facilities, uncertainty in the availability of adequate quantity for processing, high cost of energy, expensive and inadequate cold chain facilities and varied processing conditions from one material to another. Research and Development in future need to focus on these issues and cost effective value-added and diversified products.

1.5 Fish Industry

Fisheries and aquaculture are one of the most important businesses in developing countries because over 500 million people depend on it. The consistent growth of production and utilization across the world can be observed from Table 1.5. The production for produce from inland water increased from 7.5 to 63.4 million tonnes in four decades, which is more than six times the initial inland production. It clearly indicates the interest of the peoples in the inland fisheries and aquaculture, while consistent growth can also be observed in marine production, but the growth rate is comparatively lower; however, it still holds the lion share in the production statistics.

Table 1.4 Production of fruits and vegetables in major producing countries and the world [2]

	Production, million tonnes							
	Fruits				Vegetables			
Year	China	India	Brazil	World	China	India	USA	World
2010	195.1	76.4	41.6	736.9	457.4	99.3	34.7	921.1
2011	204.5	76.1	44.2	761.9	475.4	105.7	34.0	954.3
2012	214.5	78.0	41.6	775.2	483.9	112.9	35.3	977.6
2013	221.5	85.3	41.0	806.4	493.4	119.6	33.6	996.5
2014	227.0	91.0	40.6	822.7	505.8	125.2	35.7	1032.6
2015	229.1	90.8	40.1	835.7	535.0	120.0	34.5	1059.1
2016	232.3	92.0	38.9	839.0	544.7	125.9	34.1	1078.9
2017	236.8	98.0	39.9	844.7	559.2	131.6	32.1	1099.5
2018	239.1	101.9	39.9	871.2	573.8	130.1	31.7	1106.1
2019	246.6	104.2	40.1	883.4	588.3	132.0	30.0	1130.2

The production of fish at the global level is projected to grow (1.1% annually) but comparatively lesser than the previous decade (2.4% annually). The top capture producers are China, Indonesia, Peru, India, the Russian Federation, the USA and Vietnam, and the major aquaculture producers are China, India and Indonesia with a total production of 47.6, 7.1 and 5.4 million tonnes, respectively, in 2018 [7].

In the world trade, the share of top five exporting nations, China, Vietnam, Norway, the European Union and the Russian Federation, is expected to grow by 46% from the current share of nearly 45%. However, the fastest growth is forecasted for Indonesia, and it is expected that it may capture the fourth position in the list of exporting nations and in the world trade by 2028 [3]. In the last four decades, the consumption pattern increased consistently in developing countries, whereas this pattern is nearly invariable in developed countries on an average basis. In the recent years, the growth of capture fisheries is not appreciable, but it is projected to increase mainly due to the higher prices and better management in some parts of the globe. The consumption of fish from aquaculture is expected to increase to 58% in the year 2028 from the current share of nearly 52% [3]. The non-food uses of the fisheries also increased in the developing countries, whereas it decreased in the developed countries. India has nearly 8118 km of marine coastline and 3827 fishing villages along with 1941 traditional fish landing centres and is considered as one of the major suppliers of fish in the world. With a total production of 12.39 million tonnes during the year 2018 makes India as the third biggest producer of the fisheries (Table 1.6). The lack of good management practices and the depletion of the stock of some fisheries are seen as the prime concern at the global level.

The trade of fish meal is also going to increase in the next decade, and Peru is going to be the major exporting nation for the fish meal followed by the European Union and Chile. Likewise, trade in fish oil may also grow. In developing nations, fish processing is mainly carried out for export purposes. The established fish processing industries have their own fishing fleets. Preliminary processing involves handling and storage under optimum conditions. Modern fish industries often have facilities for automatic filleting and freezing of fresh fish. Facilities for processing of fish are relatively small compared to production. Lack of efficient refrigerated transport and unavailability of sufficient cold stores are highly responsible for temperature abuse, which mainly contributes to losses. The efforts are needed to further increase the fish production to meet the global demand. In addition, innovations and commercialization are needed on the organized scale to isolate and fraction out the functional constituents for medicinal uses.

1.6 Livestock Industry and Poultry Industry

The livestock and poultry sectors play an important role in the livelihood of rural people and economy. India has the largest population of livestock in the world, whereas it is the fifth largest producer of broiler. China is the leading producer of eggs in the world followed by the USA and India. India produces almost 6.3 million tonnes of meat and ranks fifth in the world production. However, only 1% is

Table 1.5 Production and utilization of fisheries and aquaculture in the world [7]

Year	Production, million tonnes			Utilization, million tonnes					
				Human consumption			Non-food uses		
	Inland waters	Marine waters	Total	Developed countries	Developing countries	Total	Developed countries	Developing countries	Total
1980	7.5	64.5	72.0	26.4	25.1	51.5	11.7	8.3	20.0
1990	14.1	83.7	97.8	28.5	42.0	70.5	11.9	15.4	27.3
2000	27.3	98.7	126.0	23.8	72.8	96.6	7.7	21.5	29.2
2010	46.8	98.1	144.9	23.0	103.6	126.6	5.2	13.1	18.3
2018	63.4	115.2	178.6	23.8	132.5	156.3	5.4	16.7	22.1

converted into value-added products as per Technology Exports Development Organisations. Table 1.7 shows the production of eggs and meat, and the data indicate that the growth rate of poultry population and average production is comparatively higher as compared to livestock.

The global market for meat products is expanding, and therefore it is an opportunity for the countries to increase their share in the world market. The major increase in meat production was mainly observed in Australia, the European Union, the Russian Federation and the USA, whereas minor increase was also observed in Argentina, Mexico and India. The production of meat is expected to expand over this decade, and major growth is speculated in the developing nations, which may account for nearly 74%. The consumption of meat is also expected to increase, though the growth rate may be a little lower than the previous decade. The consumption of meat is already high in the developed countries and is expected to further increase due to purchasing power and affordability.

The lower prices of pig meat and poultry make them a favourite in developing nations, but the increase in income diversifies the range of products. However, income is not only the parameter for the product consumption, but other factors such as urbanization; environmental, cultural and health concern; and religious beliefs also affect the consumption pattern of meat and meat products. Poultry meat consumption is projected to increase irrespective of income and accounts a major share. In the world trade, Brazil and the USA are the major exporting nations and the export is further expected to increase in this decade, whereas the Asian countries are going to be the major importing nations and the share may be around 56% of the global trade.

Major problem faced by meat industries is mainly due to temperature abuse while transportation and storage. Meat industries in a number of countries have not received much attention from policy makers and scientists. Efforts are needed to further develop infrastructure for export of both fresh and processed meat and poultry. The poultry sector has been growing continuously across the world.

1.7 Sugarcane Industry

In the recent years, the demand of sugar has been slowed down due to the potential concern of health from the excessive consumption of sugars and lesser growth rate of the world population. Brazil produced about 752.9 million tonnes of sugar crops in the year 2019 and tops the world, while India ranks second with a production of 405.4 million tonnes (Table 1.8). The sugar production of the world is projected to increase over the next 10 years. The sugar consumption is going to increase over the next 10 years mainly in developing countries. The main demand is projected in Asia and Africa in the coming years. Sugar-rich processed products, mainly the confectionery and soft drinks, are expected to rise in demand in the urban markets of Asia and Africa.

The largest consumption of sugar, especially in Asia, is expected in India followed by China, Indonesia and then Pakistan, whereas the highest consumption

Table 1.6 Capture production of major producing countries and the world [7]

Year	Capture production, million tonnes					Aquaculture production, million tonnes				
	China	Indonesia	Peru	India	World	China	India	Indonesia	Vietnam	World
2010	14.81	5.39	4.30	4.69	87.12	35.51	3.79	2.30	2.68	57.74
2011	14.99	5.75	8.25	4.31	91.62	36.61	3.67	2.72	2.85	59.79
2012	15.18	5.86	4.85	4.87	88.63	38.14	4.21	3.07	3.08	63.48
2013	15.35	6.12	5.85	4.64	89.73	40.34	4.55	3.97	3.21	66.95
2014	16.12	6.46	3.57	4.98	90.38	42.30	4.89	4.25	3.34	70.51
2015	16.39	6.69	4.82	4.84	91.66	43.75	5.26	4.34	3.46	72.77
2016	15.79	6.54	3.80	5.18	89.64	45.82	5.70	4.90	3.57	76.50
2017	15.37	6.74	4.16	5.53	93.12	46.82	6.18	5.51	3.82	79.54
2018	14.65	7.22	7.17	5.32	96.43	47.56	7.07	5.43	4.13	82.10

in Africa is projected in Egypt and sub-Saharan countries. The consumption of sugar in developed countries is declining due to negative health effect such as diabetes, weight gain, heart diseases, tooth decay, etc. The countries are coming forward to impose taxes on calorific sugar products to reduce the consumption. Mexico is the first to do it. To nullify the effect of this tax, companies are replacing sugar with artificial sweeteners.

The sugarcane industry not only converts sugarcane into premium product sugar but also utilizes many of its by-products including molasses, press cake and green top. These are utilized for the preparation of pulp, paper, particle board, feed, medium, alcohols, acetic acid, sorbitol and many other valuable products. Table 1.8 shows the scenario of the sugar industry over the past two decades and establishes that the world production is almost consistently increasing. In the Russian Federation, the demand of sugar is expected to grow due to higher demand of alcoholic products.

Sugarcane industries need better infrastructure and better transportation facilities to transport sugarcane from the agriculture field to industry. A comprehensive system for the timely payment of raw material to farmers is also needed to be evolved.

1.8 Pulse Industry

India is the leading producer of pulses followed by Canada and Myanmar (Table 1.9). Canada and Myanmar and Australia do not possess adequate processing facilities of the pulses because of the consumption pattern in these countries. These countries do not have consumption of pulses to the larger extent; therefore, attempts have not been made to develop the processing facilities. India requires almost 22.0 million tonnes of pulses to meet the increasing demand. Storage of pulses is always an issue, and these are normally stored in gunny bags or in small tin containers. As per the research findings, pulses need to be stored in air-tight containers at 20–22 °C for long-time storage. Table 1.9 shows the production of pulses in India and across the globe. In the last two decades, the production of pulses increased on an average basis, though it is not the preferred crop for the farmers due to the lesser productivity and lack of assured market. India not only is the largest producer but also consumes diverse range of pulses, which are the main source of proteins in the diet especially for the vegetarian people. The lesser production of pulses as compared to the growth of population changed the ratio of demand and supply in the last two decades and resulted in higher prices and lesser per capita consumption. The improvement in the yield of the pulses and more focus to bring out value-added acceptable and economically viable products for the consumers can further increase the demand and reduce the cost.

Table 1.7 Production of eggs and meat in major producing countries and the world [8]

Year	Production, million tonnes								
	Eggs					Meat			
	China, mainland	USA	India	Indonesia	World	China, mainland	USA	Brazil	World
2010	27.6	5.4	3.4	1.4	69.5	79.2	42.0	23.6	294.4
2011	28.1	5.5	3.5	1.3	70.9	79.4	42.5	24.3	299.0
2012	28.6	5.6	3.7	1.4	72.6	83.3	42.6	24.6	307.1
2013	28.8	5.8	3.8	1.5	74.3	85.1	42.8	25.4	314.0
2014	28.9	6.0	4.1	1.6	75.8	86.4	42.8	26.0	319.7
2015	30.5	5.8	4.3	1.7	78.2	86.0	43.3	26.6	325.3
2016	31.6	6.0	4.6	1.8	80.3	85.2	44.6	27.0	329.1
2017	35.6	6.4	4.8	5.0	89.4	85.8	45.8	27.7	335.7
2018	36.0	6.5	5.2	5.1	85.1	87.1	46.8	28.1	343.6
2019	37.8	6.7	5.8	5.1	88.3	76.3	48.1	28.6	337.2

Table 1.8 Production and processing of sugar crops in major producing countries and the world [1, 2]

Year	Production, million tonnes									
	Sugar crops					Processed raw sugar				
	Brazil	India	China, mainland	Thailand	World	Brazil	India	China, mainland	Thailand	World
2010	717.5	292.3	120.1	68.8	1907.2	39.9	11.4	20.6	6.9	155.2
2011	734.0	342.4	125.2	96.0	2069.6	37.6	12.5	26.6	9.7	169.5
2012	721.1	361.0	134.9	98.4	2097.4	40.2	14.2	28.8	10.2	177.8
2013	768.1	341.2	137.5	100.1	2147.7	39.5	14.5	27.7	10.0	179.0
2014	736.1	352.1	133.6	103.7	2158.0	37.3	14.7	26.6	11.2	179.9
2015	750.3	362.3	112.2	94.1	2117.5	35.2	11.7	30.5	11.0	173.9
2016	768.6	348.4	111.8	94.1	2160.8	40.5	9.6	27.4	9.3	177.5
2017	758.6	306.1	113.8	93.1	2150.4	36.7	10.2	22.2	10.7	177.9
2018	747.1	379.9	119.4	135.1	2205.2	28.0	11.4	34.3	15.4	182.2
2019	752.9	405.4	121.7	131.0	2228.7	–	–	–	–	–

Table 1.9 Production of pulses [2] in major producing countries and the world

Year	Production, million tonnes			
	India	Canada	Myanmar	World
2010	17.2	5.4	5.1	72.0
2011	17.6	4.3	5.0	70.3
2012	16.8	5.3	5.3	74.7
2013	18.9	6.6	5.7	78.9
2014	20.0	6.2	6.1	78.9
2015	17.3	6.1	6.2	79.1
2016	18.1	8.3	6.5	87.8
2017	23.7	7.1	6.6	95.7
2018	25.5	6.3	6.7	92.3
2019	21.5	7.0	6.9	88.4

1.9 Tea Industry

Tea is the most popular beverage in the world after water. China is the largest producer of tea with a production of 2.8 million tonnes in the year 2019 followed by India and Kenya (Table 1.10).

According to FAO, the tea sector is going to observe the compound annual growth rate of nearly 4 to 5.5% in a time span of 2017 to 2024 [9]. The tea industry is considered to provide employment on the large scale, and therefore it is labour-intensive. Material, energy and employee are the major parameters which contribute to the cost among the inputs. To make the industry more competitive, energy and employee cost need to be reduced. The automation and modernization of the industry and application of non-conventional sources of energy can bring down the cost. The tea industry also generates indirect employment in the different sectors such as warehouses, transportation and manufacturing of aluminium foil, tin plates, cardboard paper, tea chest, fertilizers, insecticides, etc. The establishment of tea parks, proper exhibition and connectivity with the tourism industry will help this industry to grow further in rapid pace. In addition, the innovative value-added products such as proven functional tea may again catalyse the growth of tea industry.

1.10 Oilseed Industry

The oilseeds remain as the major source of fat and is one of the essential constituents in the human diet. The body requires about 44-77 g of fat per day based on the 2000 calories a day, which is provided by oilseeds and animals. Indonesia is the leading producer of oilseeds with a production of 264.1 million tonnes in the year 2019 followed by Brazil, the USA, Malaysia, China and India (Table 1.11). India ranks sixth in the world production of oilseeds. Soybean, cottonseed, groundnut, sunflower, safflower, coconut, rapeseed and mustard are the popular oilseeds. Table 1.11 shows the production of oilseed across the world with a total production

Table 1.10 Production of tea [2] in major producing countries and the world

Year	Production, million tonnes			
	China	India	Kenya	World
2010	1.5	1.0	0.4	4.6
2011	1.6	1.1	0.4	4.8
2012	1.8	1.1	0.4	5.0
2013	1.9	1.2	0.4	5.3
2014	2.1	1.2	0.4	5.5
2015	2.3	1.2	0.4	5.8
2016	2.3	1.3	0.5	5.8
2017	2.5	1.3	0.4	6.0
2018	2.6	1.3	0.5	6.3
2019	2.8	1.4	0.5	6.5

Table 1.11 Production of oilseeds in major producing countries and the world [2]

Year	Production, million tonnes						
	Indonesia	Malaysia	USA	Brazil	China, mainland	India	World
2010	165.5	83.8	104.9	76.4	66.8	59.5	833.9
2011	177.1	93.7	97.6	84.7	68.9	60.8	876.6
2012	187.2	95.7	98.8	75.6	69.6	58.3	866.5
2013	200.6	95.7	103.2	89.9	67.6	63.3	940.6
2014	199.3	96.2	121.5	96.0	67.4	58.7	965.5
2015	202.6	99.0	121.4	106.6	63.9	52.0	980.7
2016	209.0	87.0	132.7	104.9	63.6	58.7	990.4
2017	255.6	102.5	138.0	123.3	68.6	59.9	1101.8
2018	259.5	99.1	137.0	128.3	70.2	62.5	1099.2
2019	264.1	99.8	115.1	127.0	75.3	64.8	1101.3

of 1101.3 million tonnes in 2019. The increase in oilseeds is continuous in all the major oilseed-producing countries; however, Brazil observed about 66% growth and stands on the first place in the increase in production during 2010–2019 followed by Indonesia with 60% growth, whereas about 32% production growth was observed in the whole world. Indonesia and Malaysia remain as the main suppliers of palm oil in the world and dominate the vegetable oil market [2].

India is the biggest importer of edible oil in the world and is expected to maintain a high per capita consumption. Therefore, the import is expected to increase substantially along with the major growth of the domestic oilseed production.

Generally, groundnut, rapeseed, mustard, linseed, sesame and castor are grown as the main oil-bearing crops; however, other crops, viz. soybean, sunflower and coconut, also significantly contribute in oil production. Despite the significant contribution in oilseed production, there are countries which cannot fulfil the demand, and hence they import a substantial amount of oil. To meet the demand, the usage of supplementary resources for the production of oil can be an option. Supplementary sources of vegetable oil may include rice bran oil, cottonseed oil, corn oil, etc., and these supplementary sources can be used for consumption to meet the demand.

The protein meal output is also expected to expand globally in this decade but comparatively at a lesser rate than the last decade and is projected to reach 400 Mt. by the year 2028. The protein meal is mainly dominated by the soybean, and it accounts for nearly two-thirds of the protein meal production of the world. Argentina is the largest exporter of the meal, whereas the European Union, China, the USA, Brazil, Argentina and India are going to be the lead players in the production of meal, and these countries are projected to have a share of 75% of the total world production.

1.11 Spice Industry

India is the major producer of spices and mainly produces *cardamom*, *pepper*, *ginger*, *turmeric*, *bean stew*, *cumin*, *celery*, *coriander*, *fennel*, *garlic*, *dill seed*, *chilli*, *tamarind*, *clove*, *fenugreek*, *ajwain* and nutmeg among several others. Spices are the essential components of diet for numerous people in the world. India is the largest producer and consumer of spices in the world. The country produces nearly 75 of the 109 varieties listed by ISO (International Organization for Standardization). In addition, it is the major exporter of spices across the globe and accounts half of the world trade. To develop this industry, functional spice parks are now established to enable processers and exporters to forge a closer and lasting relationship with spice growers. Table 1.12 shows the production of spices in major countries and the world.

In the year 2019, a total of 110 million tonnes of spices and spice products were exported to the USA, China, Hong Kong, Vietnam, Bangladesh and several other countries. India contributes around 35% ginger production, 30% pepper production and 90% turmeric production of the world.

Spices can be used in different applications such as sauces, dressings, bakery products, beverages, frozen foods and several other packaged foods and food products. Besides, spices are also used in the cosmetic industry. *Sage* and *rosemary* herbs are generally used for essential oils, which find applications in perfumes. Perfume industry incorporates spices such as cinnamon, vanilla, clove, etc. for the different fragrances. The food sector is the promising potential buyer of the spices, and the spice market is expected to grow nearly at the rate of 5% per annum till the year 2025. Seed spices are used in *Unani* and *Ayurvedic* medicines since long, but their potential effects and mechanism need to be explored and developed to cure different diseases and infections. As the demand is increasing, the production of spices and related industries is now being set up in different other countries also. The functional and medicinal uses of spices are proven based on the scientific aspects; therefore, their application can be propagated in the world over in all the culinary foods.

1.12 Dairy Industry

India is the world's largest milk producer, whereas the USA and China contribute to the milk production as the second and third largest countries across the globe. The world milk production, mainly of 81% cow's milk, 15% buffalo milk and the rest 4% percent from other milch animals such as sheep, goat, camel, etc., grew nearly by 1.6% to 880 million tonnes in 2018.

The world production of milk is expected to grow at the rate of nearly 1.7% annually. India and Pakistan are the important milk producers and are expected to contribute a major share in the world market in the coming 10 years. Currently, in India, the production is consistently increasing, but it does not have a large impact on the world trade due to the high domestic demand. Major countries, such as the European Union, New Zealand and the USA, are the major dairy product exporters, and their production increased by 0.8%, 3.2% and 1.1%, respectively, in the year 2018. In addition, Australia and Argentina are also exporting milk products internationally and expected to grow over the next 10 years.

The European Union, the second largest producer, is expected to have grown slowly as compared to the world average. This industry is well versed and has diversified its market offering products like cheese, yogurt, ghee, butter, concentrated milk, dry powders and several other processed products. Less than 30% of the milk is processed into the different commercial products. Butter and cheese have the better demand considerably. Cheese consumption especially in North America and Europe has got a major market share. WMP and SMP, which are mainly used in a number of applications such as bakery product, different liquid milks, infant formula, confectionery, etc., are largely traded and mainly used for the trades.

North Africa, the Middle East, South East Asia, developed countries and China are the major importers of dairy products. China is one of the major importers of dairy products. The developed nations import good amount of cheese and butter. The relatively higher prices of milk fat may lead to the substitution by the vegetable fat, which may bring variation in the production of milk fat and demand in the international market. Likewise, the role of plant-based dairy substitute such as soy, rice, almond-based drinks, etc. has increased in the recent years in different regions. But, there are different views regarding their wider acceptability and health aspects, which may create uncertainty on the long-term impact of these substitutes in the milk and milk product demands.

India is self-reliant in terms of the production and consumption of milk, but there are regions such as South East Asian countries, the Middle East and Africa where the demand for the milk and milk products is expected to grow faster than the production, which will lead to the increase in import of dairy products. Transport of liquid milk is expensive; therefore, the demand is expected to be meted out with the milk powders. The milk powders are largely produced across the globe due to the application in various food products.

Indian dairy industry has successfully developed a direct link between producers and ultimate users by procuring milk from the producer in rural areas and then

Table 1.12 Production of spices and condiments in major producing countries and the world [2]

Year	Production, million tonnes									
	Pepper					Vanilla				
Year	Ethiopia	Vietnam	Brazil	Indonesia	World	China, mainland	Indonesia	Madagascar	Mexico	World
2010	265	105	52	84	682	1300	2600	2742	395	8257
2011	307	112	45	87	723	799	3500	2791	362	8602
2012	407	120	43	88	817	432	3100	2929	390	8052
2013	289	125	42	91	720	335	2600	3021	463	7600
2014	204	152	42	87	662	286	2000	3139	420	7081
2015	323	177	52	82	829	566	2000	2922	482	7218
2016	425	216	54	86	971	812	2326	2888	513	7780
2017	347	253	79	88	983	554	2481	3191	515	7995
2018	329	263	102	89	1039	458	2356	3169	495	7738
2019	374	265	109	89	1103	379	2329	3217	522	7715
	Cinnamon					Cloves				
Year	China, mainland	Indonesia	Sri Lanka	Vietnam	World	Indonesia	Madagascar	Sri Lanka	Tanzania	World
2010	63	88	16	21	191	98	10	4	9	128
2011	66	90	16	24	199	72	12	4	9	103
2012	69	90	16	27	204	100	15	4	7	131
2013	70	92	16	29	209	110	17	4	7	143
2014	71	91	17	30	213	122	21	6	9	166
2015	75	92	20	33	223	140	22	6	9	184
2016	76	92	25	35	231	140	23	8	9	190
2017	78	92	25	37	236	113	25	7	9	164
2018	81	90	24	39	238	131	24	6	9	180
2019	83	90	25	41	243	135	23	4	9	182

(continued)

Table 1.12 (continued)

Year	Nutmeg, mace and cardamoms					Anise, badian, fennel and coriander				
	Guatemala	India	Indonesia	Nepal	World	India	Iran	Mexico	Syria	World
2010	23	16	16	5	67	420	66	46	41	827
2011	26	16	20	6	75	537	62	53	48	954
2012	35	18	25	6	93	537	53	54	52	924
2013	38	17	28	7	98	546	40	65	48	908
2014	38	21	33	5	107	584	66	54	28	1004
2015	35	22	34	5	107	546	63	69	28	1082
2016	35	38	33	6	125	632	63	80	28	1166
2017	36	43	33	7	132	1529	64	133	116	2153
2018	38	43	44	7	146	1503	66	127	142	2073
2019	38	38	44	8	142	1448	68	101	83	1971

Year	Ginger					Spices nes (bay leaves, dill seed, fenugreek seed, saffron, thyme, turmeric)				
	China, mainland	India	Nepal	Nigeria	World	India	Ethiopia	Turkey	Indonesia	World
2010	365	385	211	162	1719	1.5	0.2	0.1	0.1	2.3
2011	420	702	216	460	2366	1.7	0.2	0.2	0.1	2.6
2012	460	756	255	380	2464	1.5	0.2	0.2	0.1	2.4
2013	390	683	235	497	2445	1.5	0.3	0.2	0.1	2.6
2014	470	655	276	168	2302	1.5	0.3	0.2	0.1	2.6
2015	496	760	243	413	2753	1.3	0.2	0.2	0.1	2.3
2016	550	1109	272	775	3624	1.5	0.3	0.2	0.1	2.7
2017	546	1070	280	835	3519	1.6	0.3	0.2	0.1	2.7
2018	570	1762	284	700	4081	1.4	0.3	0.2	0.2	2.6
2019	581	1788	298	691	4081	1.4	0.3	0.3	0.3	2.8

Table 1.13 Production of milk in major producing countries and the world [8]

Year	Production, million tonnes				
	China, mainland	India	Pakistan	USA	World
2010	41	122	35	88	724
2011	41	128	37	89	742
2012	42	133	38	91	759
2013	40	138	39	91	768
2014	42	147	40	93	794
2015	36	156	42	95	803
2016	35	165	43	96	814
2017	35	176	52	98	855
2018	35	188	54	99	880
2019	36	188	56	99	883

transporting it to district units and finally processing. Table 1.13 shows the production of milk. Though the production of milk is steady, still the processing of milk at the organized scale in developing countries is a challenge. In addition, the value addition is needed, and more focus on the value-added products will further expand this industry in the future.

In general, the overall increase in the production of cereals, fruits, vegetables, fish, livestock, sugarcane, tea, oilseeds, pulses and spices was observed during the last decade. The growth rate in the production is also expected through increase in the area under cultivation and productivity level [10, 11] in the years to come to meet the increasing global demand. This will expand the agro-processing sector and storage facilities in particular. The agro-processing industries also contribute in the economy, employment generation to the rural youths, as a source of foreign exchange through export, human resource development through training and creation of stable markets for raw, intermediate and finished products [12]. Bakeries, breweries, soybean processing, rice processing, wheat milling units, pulse milling, poultry processing, tea/coffee processing, sauces, pickles, traditional sweets and snacks are the major processing units. The agro-processing industry is the untapped sector in a number of developing countries and the countries which are the leading producers of the different agricultural produces.

1.13 Exercise

1. Discuss the importance of the agro-processing sector in the development of a nation with a view to mitigate the challenge of population growth.
2. What is the status of cereal production in the major producing countries in the world? Explain the various types of major cereal processing units.
3. What is the importance of pulses in agricultural production? Despite the substantial production of pulses in Canada, Myanmar and Australia, why has the processing industry not taken shape in these countries?

4. Discuss the significance of spices in agro-processing sectors. What are the production patterns of spices in the world? Discuss in brief.
5. Which are the leading producers of milk? How dairy processing units performed during the last decade? Which are the major exporting nations of milk and milk products? Why is the export share of the largest milk-producing country comparatively much lesser?
6. What is the status of the fruit and vegetable industry across the world? Why is the processing of fruits and vegetables at all needed? What are the problems faced by the fruit and vegetable industry?
7. Illustrate briefly the status of the following:
   (a) Tea industry.
   (b) Fish industry.
   (c) Sugarcane industry.
   (d) Livestock and poultry industry.
   (e) Oilseed industry.

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2 Engineering Properties of Foods

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Abstract

In this chapter, the concept related to various engineering properties like geometrical, frictional, rheological, textural, optical, and thermal and their application during different stages of food processing have been discussed. Methods and instruments involved for the measurement of all these properties and their importance in relation to food quality and safety are also explained. Geometrical and frictional properties of foods have great importance in food characterization, handling, processing, and monitoring of quality food products. These properties affect the chemical and physical characteristics of foods at micro and macro levels during processing and storage. Water activity and its measurement methods are also discussed in brief. Rheological properties are related with the flow and deformation of food systems. The chapter also explains the rheology of solid and liquid foods along with rheological models. Texture profile analysis of food is also briefly explained for easier understanding. Optical parameters are one of the important quality indicators of foods. The spectral sensitivity, tristimulus value, and chromaticity coordinates are discussed. Various color measurement systems like Munsell, Hunter, CIELAB, etc. are also explained. For accurate calculation of energy balance during heating and cooling process, it is important to know the

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behavior of thermal data of foods in terms of specific heat, thermal conductivity, and thermal diffusivity. The determinations of different thermal properties are illustrated with diagrams and solved examples.

Keywords

Size · Shape · Volume · Density · Porosity · Frictional properties · Water activity · Rheological properties · Textural parameters · Colour · Thermal properties

Engineering properties of foods are useful in the design and development of various agricultural machineries for different unit operations such as cleaning, grading, drying, dehydration, milling, handling, transportation, and storage. The properties are also used to monitor the safety and quality of different foods. The broad categories of engineering properties useful for handling of grains and other agricultural commodities during different unit operations are physical properties, rheological properties, thermal properties, optical properties, surface properties, etc. Basic information on these properties is of great importance and helps the engineers, food scientists, and processors toward efficient processing and equipment development. Some of the physical properties usually encountered in handling of different foods are described.

The major physical properties of foods consist of shape, size, density, volume, porosity, and surface area which are important for the measurement of bulk or individual units of the material. Size and shape are the important parameters to control the quality of different agro-based commodities and play a significant role in different unit operations such as dehydration/drying, screening, separation, etc. The measurement of surface area is important in fruits and vegetables to estimate the respiration rate, spray coverage, color evaluation, and heat and mass transfer in various heating and cooling processes. Surface area measurement can be done with planimeter, coating method, and peeling method and by image analysis.

2.1 Size

Size is an important property of foods. For the powders, particle size is critical as it affects the viscosity and solubility during reconstitution. Agro-produce size determination is important for sorting of fresh produce into different size groups which has different market prices. The different sizes of produces require different packages for their better protection during transportation. For the production of uniform quality of the processed foods, grading of agro-produce is necessary in the food processing industry.

2.1.1 Methods of Size Measurement

2.1.1.1 Projected Area Method

The projection of food material is captured along three mutually perpendicular axes using image capturing devices. The following dimensions are defined in this method (Fig. 2.1):

1. The maximum diameter/longest dimension of the maximum projected area is referred to as the major diameter or length.
2. The maximum diameter/longest dimension of the minimum projected area or minimum diameter/smallest dimension of the maximum projected area is referred to as the intermediate diameter or width.
3. The minimum diameter/smallest dimension of the minimum projected area is the minor diameter or thickness.

2.1.1.2 Micrometer Measurement

The characteristic dimensions can be determined by micrometer or caliper. The diameters (inside and outside), depth of the holes, and distance between the parallel surfaces can be measured. Micrometer is often used as an inspection instrument to measure distances between surfaces (Fig. 2.2a). Vernier caliper is a measuring tool and is used for measuring linear dimensions (Fig. 2.2b). Both micrometer and vernier caliper are available in digital form to get more accurate and precise measurement.

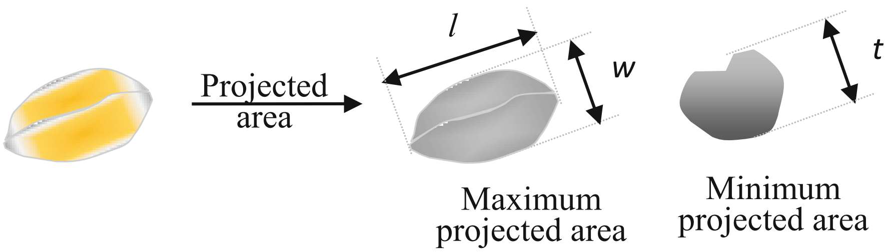


Fig. 2.1 Dimensions of food material

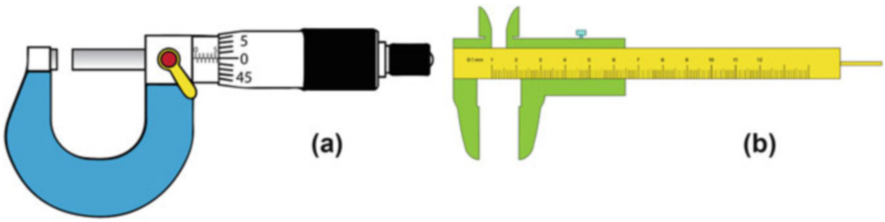


Fig. 2.2 (**a**) Micrometer. (**b**) Caliper

2.1.1.3 Measurement of Particle Size of Particulate Foods

Particle size of particulate foods is important for separation and grading processes and can be evaluated by using sieve systems, settling rate methods, and an electrically charged orifice. Particle size analyzer is commonly used for powders to determine its particle size and the distribution pattern in a lot.

2.2 Shape

Shape is an important parameter especially in grading of foods and in controlling the quality of different foods. The shape is generally expressed in terms of aspect ratio and sphericity.

2.2.1 Sphericity

Sphericity is defined as the ratio of irregular solid volume to the sphere volume that has a diameter equal to the major diameter of the solid so that it can circumscribe [1] (Fig. 2.3). The degree to which a particle approaches the shape of sphere is referred to as sphericity. The volume of the smallest circumscribed sphere of a given radius can be easily calculated by the mathematical equation/formula, and the liquid displacement method can be used to determine the volume of irregular solid, described in the volume section of this chapter.

$$\text{Sphericity } (\Phi) = \left(\frac{\text{Volume of irregular solid}}{\text{Volume of smallest circumscribed sphere}}\right)^{\frac{1}{3}}$$

In case food material resembles with triaxial ellipsoid with three intercepts a, b, and c, wherein a is the largest intercept (Fig. 2.4), the volume of triaxial ellipsoid is given by:

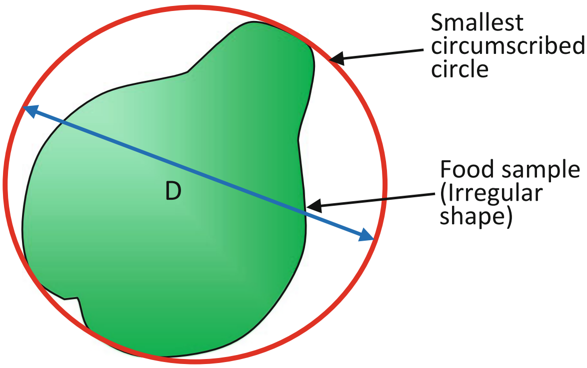


Fig. 2.3 Sphericity based on volume

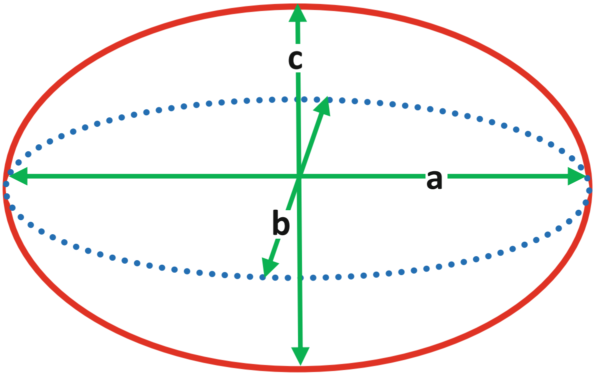


Fig. 2.4 Intercepts of triaxial ellipsoid

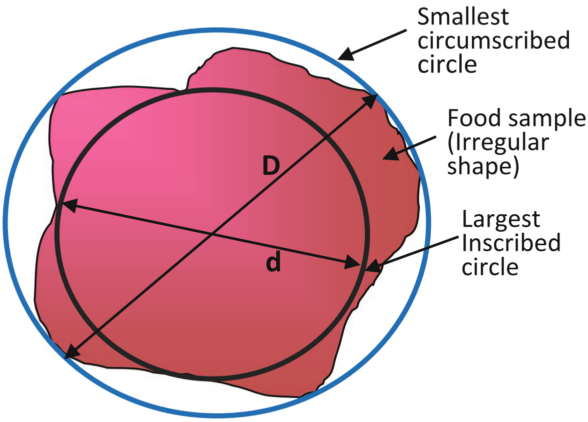


Fig. 2.5 Sphericity based on diameter of an irregularly shaped food

$$\text{Volume of triaxial ellipsoid} = \frac{\pi}{6} \times a \times b \times c$$

The volume of the smallest circumscribed sphere can also be calculated using a as the diameter of the circumscribed sphere as:

$$\text{Volume of the smallest circumscribed sphere} = \frac{\pi}{6} \times a^3$$

The sphericity of food material with triaxial ellipsoid shape can be represented as:

$$\text{Sphericity } (\Phi) = \left(\frac{\frac{\pi}{6} \times a \times b \times c}{\frac{\pi}{6} \times a^3} \right)^{\frac{1}{3}} = \frac{(abc)^{1/3}}{a}$$

Sphericity can also be defined as the ratio of the largest inscribed circle diameter (d) to the smallest circumscribed circle diameter (D) (Fig. 2.5) [2]:

$$\text{Sphericity } (\Phi) = \frac{d}{D}$$

Q1. The average values of three mutually perpendicular intercepts of sapota are 4.0, 7.0, and 3.8 cm. Estimate the sphericity of the fruits.

Solution:

$a = 7.0$ cm, $b = 4.0$ cm, and $c = 3.8$ cm

$$\text{Sphericity } (\Phi) = \frac{(abc)^{1/3}}{a} == \frac{(7.0 \times 4.0 \times 3.8)^{1/3}}{7.0} = \frac{4.74}{7.0} = 0.68$$

2.2.2 Aspect Ratio

The aspect ratio (Ra), which expresses the shape of a material, is the ratio of length (a) to width (b) of the material/sample [2]:

$$\text{Aspect ratio} = \frac{a}{b}$$

Q2. The average values of three mutually perpendicular intercepts of grain seeds are 11.0, 4.0, and 3.5 mm. Estimate the sphericity and aspect ratio of the grains.

Solution:

$a = 11.0$ mm, $b = 4.0$ mm, and $c = 3.5$ mm

$$\text{Sphericity } (\Phi) = \frac{(abc)^{1/3}}{a} == \frac{(11.0 \times 4.0 \times 3.5)^{1/3}}{11.0} = \frac{5.36}{11.0} = 0.49$$

$$\text{Aspect ratio} = \frac{a}{b} = \frac{11.0}{4.0} = 2.75$$

2.2.3 Radius of Curvature

The radius of curvature (ROC) is very useful for the conveyors design. ROC is generally used to determine how easily the object will roll.

In a device to measure ROC, there is a metal base that has indicator and holes; pins are placed into the holes (Fig. 2.6). The sample is placed between the two pins, and when both the pins come in contact with the surface, the needle of the indicator is pushed, and the sagittal height (S) is recorded. ROC can be calculated as:

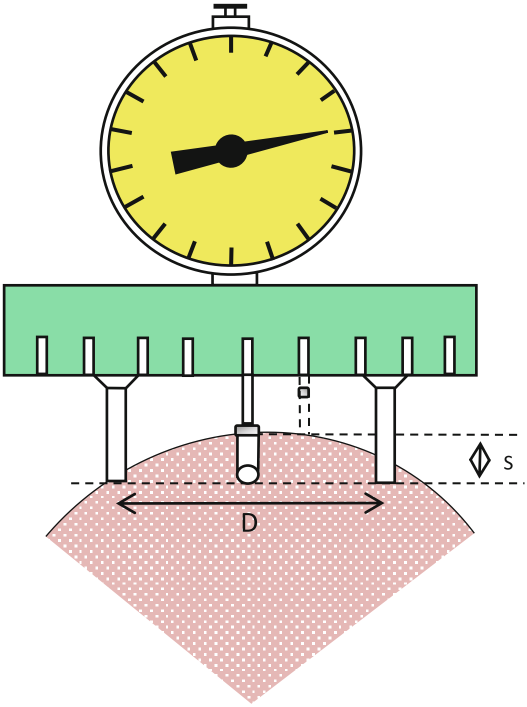


Fig. 2.6 Radius of curvature measurement device

$$\text{Radius of curvature} = \frac{(D/2)^2 + S^2}{2S}$$

where D and S are the spacing between the pins (m) and sagittal height (m), respectively.

The minimum and the maximum ROC for smaller objects of relatively uniform shape can be calculated using intermediate diameter (H) and major diameter (L) by the following formula:

$$\text{ROC}_{\text{min}} = \frac{H}{2}$$

$$\text{ROC}_{\text{max}} = \frac{H^2 + \frac{L^2}{4}}{2H}$$

2.2.4 Roundness

Roundness refers to the edges of a solid and sharpness of the corners and can be defined as the ratio of the average ROC of the corners to the largest inscribed circle radius (Fig. 2.7a).

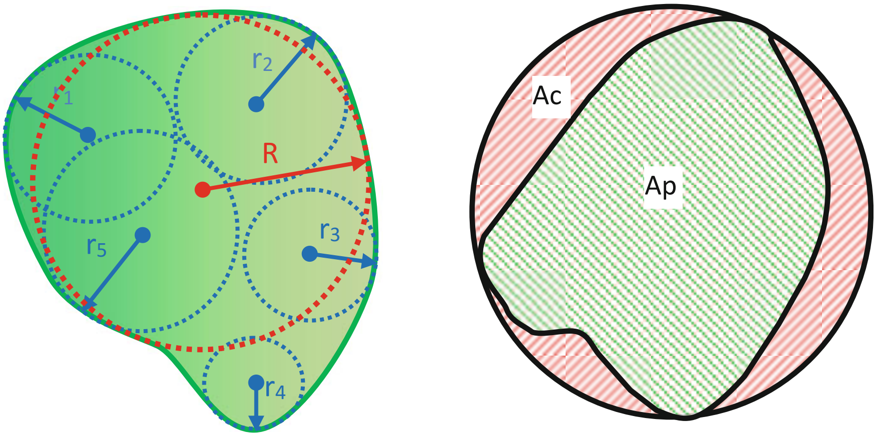


Fig. 2.7 Roundness based on (**a**) ROC of corners. (**b**) Projected area

$$\text{Roundness} = \frac{\sum_{i=1}^{N} \text{ROC}/N}{R}$$

where ROC is the radius of curvature (m), R is the radius of the largest inscribed circle (m), and N is the total number of corners.

Roundness can also be defined as [1] (Fig. 2.7b):

$$\text{Roundness} = \frac{A_p}{A_c}$$

where A_p is the largest projected area of the object at rest position (m^2) and A_c area of the smallest circumscribing circle.

2.3 Volume

The three-dimensional space occupied by an object is referred to as volume. The SI unit of the volume is the cubic meter. The volume of liquid is also measured in terms of liters and gallons. Volume is an important property to determine space or containers needed for transportation, packaging, and storage.

2.3.1 Types of Volume

2.3.1.1 Solid Volume

The volume of solid material, which excludes all interior pores that are filled with air (closed pores) (Fig. 2.8a), is referred to as solid volume, which can be measured by gas displacement method.

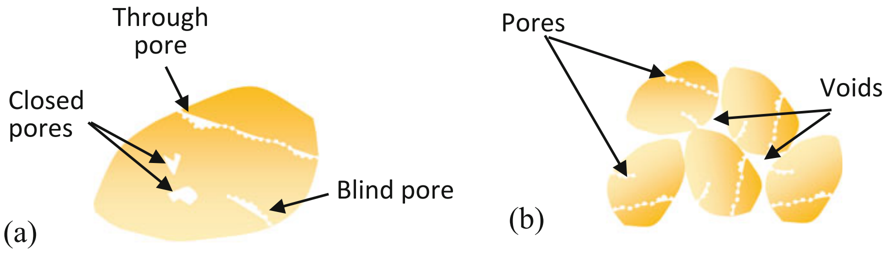


Fig. 2.8 Food materials with (**a**) pores and (**b**) void spaces

Table 2.1 Volume of various regularly shaped samples

Shape	Volume
Cube	$V = a^3$, where a is the side of cube
Cuboid	$V = l \times w \times h$, where l, w, and h are the length, width, and height, respectively
Sphere	$V = (4/3)\ \pi r^3$, where r is the radius of sphere
Cylinder	$V = \pi r^2 h$, where r is the radius and h height of cylinder
Cone	$V = (1/3)\ \pi r^2 h$, where r is the radius and h height of cone
Prism	$V = A \times h$, where A and h are the area of the base and height, respectively

2.3.1.2 Apparent Volume

It refers to the volume, which includes all interior pores (Fig. 2.8a). Apparent volume of regularly shaped samples is determined from the characteristic dimensions, whereas solid or liquid displacement method can be the choice for irregularly shaped sample.

2.3.1.3 Bulk Volume

It is the volume of the substance, when stacked in bulk. The substance may include all pores and void volume outside the boundary (Fig. 2.8b). Bulk volume can be measured by determining the volume of the bulk sample by keeping the material in a container.

2.3.2 Measurement of Volume

2.3.2.1 Estimation of Volume of Regularly Shaped Samples

The volume of regularly shaped samples can be determined from its characteristic's dimensions (Table 2.1). The volume of irregularly shaped samples can be experimentally measured by solid, liquid, or gas displacement methods. Recently, the technique has been developed to determine the volume of some food products such as melon, lemon, and peaches by MATLAB using image processing tools.

2.3.2.2 Determination of Volume by Solid Displacement Method

It is the best method to determine the volume of baked goods. In this method, rapeseeds are filled in a known volume of glass container (V_1) through tapping, and then the surface is smoothened through the ruler (Fig. 2.9). The container is emptied, and food samples are kept in the empty container. The rapeseeds are poured into the container, which occupy and fill the remaining space of the container (V_2). The difference in the volume of rapeseeds indicates the volume of the sample ($V_1 - V_2$).

2.3.2.3 Liquid Displacement Method

It is generally used to determine the volume of solid samples which does not absorb liquid (generally water). In this method, a known volume of water (V_1) is poured in a graduated cylinder or beaker (Fig. 2.10). The food sample is then placed in water and immersed completely, which results in the rise of water volume (V_2). Food sample volume is determined by calculating the difference of volumes ($V_2 - V_1$).

2.3.2.4 Gas Displacement Method

This method is useful for the accurate estimation of volume of porous solids. The method consists of pycnometer system having two airtight chambers, having equal volumes, V_1 and V_2. These chambers are connected with small diameter tube (Fig. 2.11). The sample to be measured is placed in the second chamber. All valves are closed except the valve 1 to supply gas in the first chamber. When the desired pressure is reached, valve 1 is closed, and the equilibrium is attained. After recording the equilibrium pressure, valve 2 is opened to fill gas in the empty spaces of the second chamber. The mass of gas (m_t) is divided into one, which fills the first chamber (m_1), and the other that fills the empty space of the second chamber (m_2). If the system is isothermal, then:

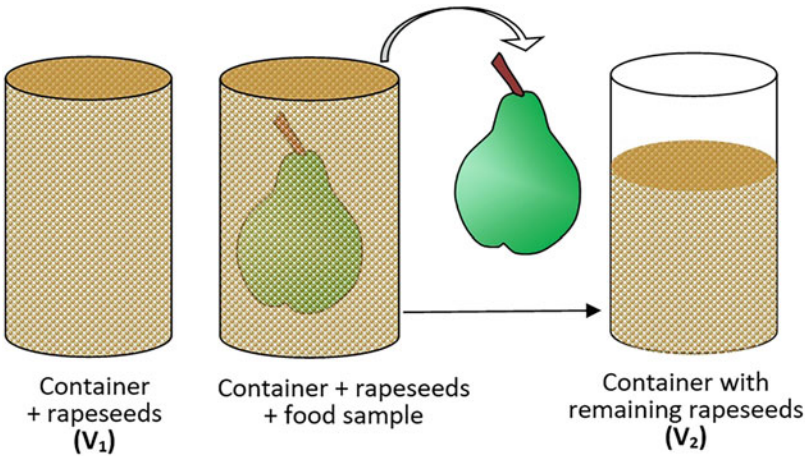


Fig. 2.9 Volume of food sample by solid replacement method

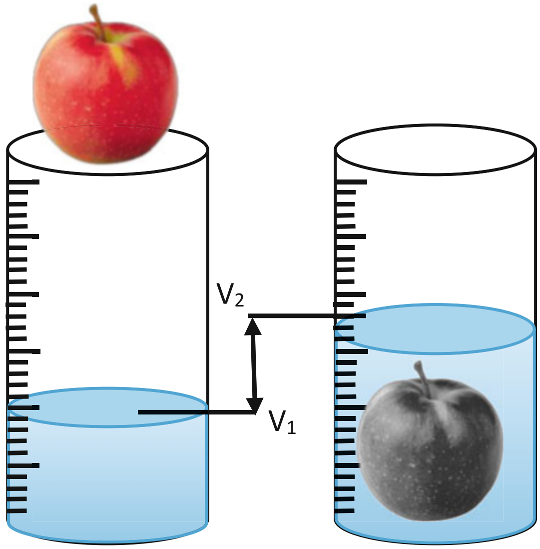


Fig. 2.10 Liquid displacement method of volume measurement

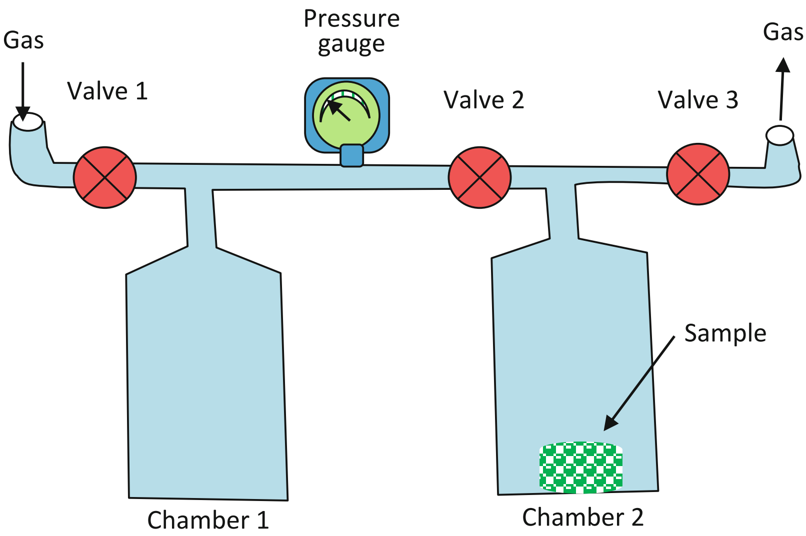


Fig. 2.11 Gas displacement method of volume measurement

$$P_1V_1 = P_2V_1 + P_2V_E$$

where V_E is the empty space volume in the second chamber.

$$V_E = V_2 - V_S = V_1\left(\frac{P_1 - P_2}{P_2}\right)$$

where V_s is the solid volume, which can be calculated as:

$$V_S = V_2 - V_1\left(\frac{P_1 - P_2}{P_2}\right)$$

2.4 Density

The density of a substance is represented as mass per unit volume and plays an important role in the characterization and quality assessment of foods. Density data is used for various food processing operations such as centrifugation, sedimentation, pneumatic transport of powders, and pumping of liquids. The moderate changes in temperature and pressure hardly affect the density of solids and liquids, whereas the density of gases is influenced by the change in pressure and temperature. The density of gases increases with the increase in pressure, whereas it decreases with the increase in temperature.

2.4.1 Solid Density

Solid density is determined from the measured weight and volume. The volume of samples (irregularly shaped) can be measured by displacement methods. The meals, grains, and powders are bulk solids and made up of small particles. But, the individual small particles may vary in size and weight over a large range. Therefore, density is expressed in different forms.

2.4.1.1 True Density

In the case of composite material or a pure substance, true density is referred. For the known composition, true density can be calculated as:

$$\rho_T = \frac{1}{\sum_{i=1}^{n} \frac{m_i}{\rho_i}}$$

where m_i and ρ_i are the mass fraction and density of ith constituent, respectively.

The true density of fresh fruits and vegetables varies in the range of 865–1067 kg/m^3 and 801–1095 kg/m^3, respectively, whereas the density of frozen fruits and vegetables is less than the fresh and reported as 625–801 kg/m^3 and 561–977 kg/m^3, respectively [3].

2.4.1.2 Particle Density (PD)

It refers to the particle density, which includes the volume of solids and closed pores. It excludes externally connected pores (Fig. 2.8a). It is very useful for the characterization of individual grains or seeds. PD can be obtained by dividing the weight of the sample from the volume. Considering the negligible diffusion of liquid in the seeds during measurement, liquid displacement technique can also be the choice.

In most of the cereals, pulses, fruits, and vegetables, the presence of closed pores is limited or negligible; therefore, particle density is invariably used as true density [4].

2.4.1.3 Apparent Density

It refers to the density, which includes all internal pores. This type of density is very useful for characterizing the intact material like grain bulk, bread loaf, baked cake, etc. Apparent density is generally estimated by dividing the sample weight by apparent or external sample volume.

2.4.1.4 Bulk Density (BD)

It refers to the density of a material, when stacked or packed in bulk. It includes both internal and external pores of the material. BD depends upon a number of factors such as size, geometry, solid density, surface properties, and the measurement technique. The ratio of weight and bulk volume is used to calculate the bulk density.

The apparent density depends on the composition and structure of food material. The bulk density depends on the method of packing of food material, and it changes with the number of tapping, pressure, and vibration.

2.4.2 Liquid Density

The maximum density of water is 1000 kg/m^3 at 4 °C. The density decreases as the temperature of water rises above 4 °C. The density also increases with the addition of solid matter in the water except fat. Therefore, density data can be used for the determination of purity of substances.

The specific gravity at standard temperature of liquid is often more convenient to measure, which can be determined as:

$$\text{Specfic gravity(Temp)} = \frac{\text{mass of liquid}}{\text{mass of equal volume of water}} = \frac{\text{density of liquid}}{\text{density of water}}$$

The specific gravity can be measured using pycnometers and hydrometers. The pycnometer (density bottle) is available in different standard volumes. For the measurement of specific gravity, the clean, dried, and empty bottle is taken and filled to the top with liquid, and the cap is put back. Let the excess liquid flow out, and then clean and weigh the bottle accurately. The specific gravity (SG) at standard temperature can be calculated as:

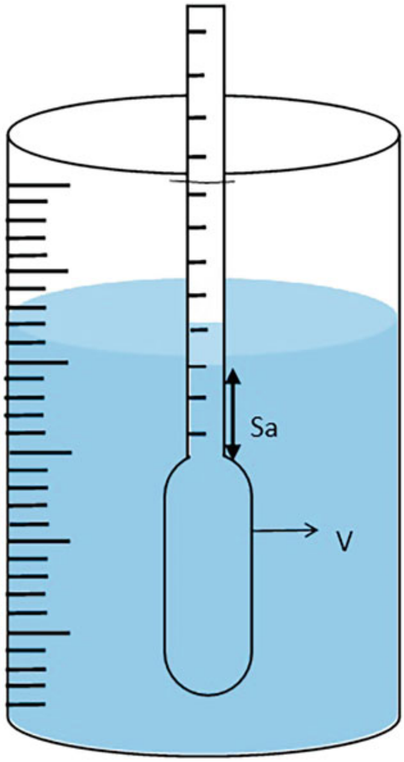


Fig. 2.12 Hydrometer measurement of liquid density

$$\mathrm{SG(Temp)} = \frac{w_3 - w_1}{w_2 - w_1}$$

where w_1 is the weight of empty bottle and w_2 and w_3 are the weights of bottle filled with water and liquid sample, respectively.

The hydrometer can also be used for measuring liquid density, and it works on the principle that it displaces its own weight of liquid upon dipping. It has a graduated stem that is extended from a tubular-shaped bulb. Hydrometer is placed in the beaker containing the liquid sample (Fig. 2.12).

The length to which the hydrometer sinks depends upon the liquid density. The hydrometer sinks more in the liquid of lower density. The ratio of hydrometer weight to displaced liquid volume can provide the liquid density at standard temperature:

$$\text{Density of liquid} = \frac{W}{Ax + V}$$

where W is the hydrometer weight (kg), A is the stem cross-sectional area (m^2), x is the length of the stem immersed (m), and V is the volume of the bulb (m^3).

Hydrometers of different density ranges are available for various applications. In density hydrometer, lactometer is commonly used for determining the density of the milk. The scale of lactometer varied in the range of 25–35 as the bovine milk density falls in the range of 1025–1035 kg/m^3 [5]. Oleometer is used for measuring specific gravity of oils. The nomenclature of some other hydrometers are based on their specific application other than density such as alcoholmeter for measuring percent alcohol by volume, Brix saccharometer for measuring percent sucrose by weight in a solution, and salometer for measuring percent salt by weight in a solution.

2.5 Porosity

Porosity of foods may characterize the microstructure of dried and intermediate moisture foods. Porosity refers to the volume of the void space by air in the solid foods. It is an important physical parameter in different processes such as baking, frying, drying, extrusion, etc. Porosity data may be useful in mass and heat transfer calculations of various drying and dehydration processes.

It can be expressed as:

$$\text{Porosity}\ (\varepsilon) = \frac{\text{Volume of void space}}{\text{Total volume}}$$

2.5.1 Measurement of Porosity

2.5.1.1 Direct Method

Porosity is calculated from the difference of bulk volume of the sample and volume of the sample without voids. This method is applicable only for the soft material in which force does not exist in any form on the surface of solid particles.

2.5.1.2 Optical Microscopic Method

The microscopic view of the random section of the sample can be used to determine the porosity. This method is useful for the samples that have uniform porosity throughout the sample. Pore size distribution and area fraction of pores can be determined by using image analysis technique.

2.5.1.3 Density Method

The measured densities can be used to calculate porosity.

Apparent Porosity

Apparent porosity (ε_{app}) or internal porosity is the ratio of volume of internal pores to the total volume of the sample [6] and can be expressed as:

$$\varepsilon_{\text{app}} = \frac{\text{Volume of all internal pores}}{\text{Total volume of sample}}$$

$$\varepsilon_{\text{app}} = 1 - \frac{\text{Apparent density } (\rho_{\text{app}})}{\text{True density } (\rho_T)}$$

Internal porosity includes three kinds of pores, namely, blind pores that are closed from one end (ε_{BP}); closed pores, which are closed from all sides (ε_{CP}); and open pores that are open from both ends (ε_{CP}) (Fig. 2.8a).

$$\varepsilon_{\text{app}} = \varepsilon_{\text{CP}} + \varepsilon_{\text{BP}} + \varepsilon_{\text{OP}}$$

Bulk Porosity

Bulk porosity ($\varepsilon_{\text{bulk}}$) or external porosity is the ratio of the volume of external pores to the total bulk volume when packed and can be expressed as:

$$\varepsilon_{\text{bulk}} = \frac{\text{Volume of all external pores}}{\text{Total bulk volume of stacked sample}}$$

$$\varepsilon_{\text{bulk}} = 1 - \frac{\text{Bulk density } (\rho_{\text{bulk}})}{\text{True density } (\rho_T)}$$

Then, total porosity (ε_{TOT}) is the sum of the internal and external pore volume fraction when the material is packed bulk and represented as:

$$\varepsilon_{\text{TOT}} = \varepsilon_{\text{app}} + \varepsilon_{\text{bulk}}$$

Therefore, the total porosity can be expressed as:

$$\varepsilon_{\text{TOT}} = \varepsilon_{\text{CP}} + \varepsilon_{\text{BP}} + \varepsilon_{\text{OP}} + \varepsilon_{\text{bulk}}$$

2.6 Frictional Properties

Frictional properties include coefficient of frictions and angle of repose, which are important in the designing of bulk handling systems and storage structures. In addition, frictional properties also play an important role in the designing of hoppers, conveyors, trough, chutes, and bins. The important properties are discussed as follows.

2.6.1 Angle of Repose

Angle of repose is used to characterize the bulk solid foods like grains, seeds, powders, etc. When granular solids are piled on the plane surface, the sides make an angle with the horizontal, which is referred as the angle of repose. Major factors, such as grain size and shape, moisture, density, friction between the particles, surface roughness, etc., can affect the angle of repose.

Smooth surface and round-shaped grains have low angle of repose, whereas very fine and sticky materials have high value of angle of repose. This property is determined by placing a square-shaped box having top and bottom sides open, on a flat surface. The box is filled with the sample, and gradual lifting of the box allows accumulation of the sample and formation of conical heap on the surface (Fig. 2.13). Freely flowable materials have angle of repose lesser than 30°, whereas extremely non-flowable/cohesive/sticky materials have angle of repose >55° [7].

2.6.2 Coefficient of Frictions

This physical property is very useful to check the pressure of cereal grain against silos and bin walls.

2.6.2.1 Coefficient of External Friction

The coefficient external of friction is characterized by the friction between the grains and surface of machine or storage structure. The apparatus for the determination of coefficient of external friction has a box/frame for keeping the material (Fig. 2.14). The box remains open from the bottom so that grains can remain in contact with the surface of the test material. Initially, weights are kept on the pan to initiate the movement of the empty box. The test is again performed after filling the material in the box, and the following expression is used to estimate the coefficient of external friction:

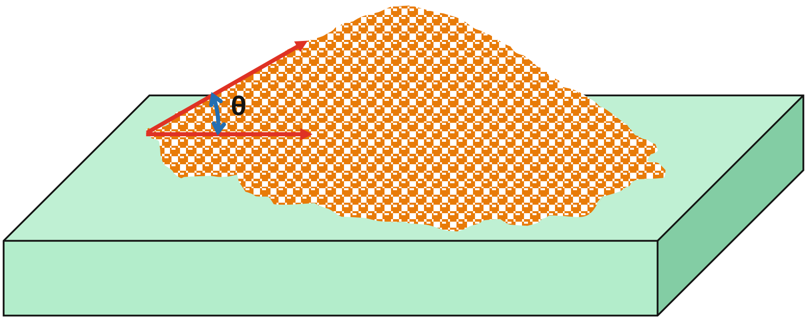


Fig. 2.13 Explanation of angle of repose

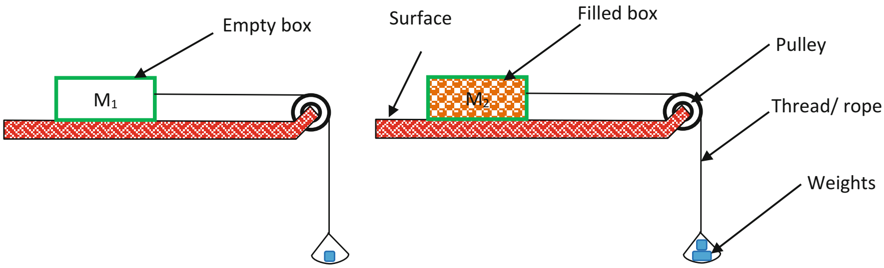


Fig. 2.14 Apparatus for the estimation of coefficient of external friction

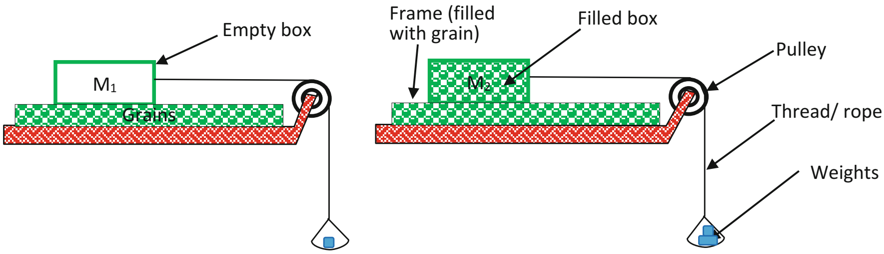


Fig. 2.15 Apparatus for the estimation of coefficient of internal friction

$$\text{Coefficient of external friction}, \mu' = \frac{M_2 - M_1}{M}$$

where M is the mass of the sample in the box (g), M_1 mass kept on the weighing pan to cause the sliding of the empty box (g), and M_2 mass kept on the weighing pan to cause the sliding of the filled box (g).

2.6.2.2 Coefficient of Internal Friction

The coefficient of internal friction is characterized by the friction among the grains. The apparatus for the determination of coefficient of external friction is modified by fixing a frame on the sliding surface for keeping the grains and making an even surface (Fig. 2.15). The box remains open from the bottom as mentioned in the external friction so that grains can remain in contact with the surface of evenly spread grains in the frame. Initially, weights were kept on the pan to initiate the movement of the empty box. The test is again performed after filling the material in the box, and the following expression is used to estimate the coefficient of internal friction:

$$\text{Coefficient of internal friction}, \mu = \frac{M_2 - M_1}{M}$$

where M is the mass of the sample in the box (g), M_1 mass kept on the weighing pan to cause the sliding of the empty box (g), and M_2 mass kept on the weighing pan to cause the sliding of the filled box (g).

2.7 Water Activity

Water is one of the major constituents of foods responsible for its quality and safety. It is considered as the root cause for the growth of microorganisms and initiation of many chemical and biochemical reactions responsible for the perishability of foods. However, the different foods having the same water content may differ in perishability, which may be due to the varied proportion of free and bound water in the foods. Many techniques like drying, dehydration, and addition of water binding compounds like salt, sugar, gums, etc. are used to decrease the amount of free water and simultaneously increase the amount of solute matter to decrease the perishability. Therefore, the presence of free water is the major cause of the deterioration of foods.

Water activity (a_w) of foods refers to the amount of free water available for the growth of microorganisms and other chemical, biochemical, and enzymatic reactions responsible for the deterioration of foods. It is a more reliable indicator as compared to water content to judge the perishability of foods. The term a_w is defined as the ratio of partial pressure of the water of the sample (p) to that of vapor pressure of pure water (p_0) at constant temperature.

$$\text{Water activity } (a_w) = \frac{p}{p_0}$$

In other words, water activity can also be defined as the percent equilibrium relative humidity (ERH) surrounding the product at a specific temperature. Besides water activity, other factors like oxygen concentration, solute concentration, type of solute, pH, etc. also influence the rate of many degradative reactions. It also indicates the energy status of the water in a food system. Dissolved solutes like salt and sugar bind water through ionic interaction, dipole-dipole interaction, and hydrogen bonds. The chemical groups of undissolved components of foods like proteins and starches bind with water through ionic bonds, dipole-dipole forces, van der Waals forces, and hydrogen bonds. These factors bind the water and reduce its energy level to make it unable to escape out in vapor form and as a result exert no partial pressure and show zero water activity.

As per the definition of water activity, it is determined at a particular temperature as it is a temperature-dependent parameter. The change in temperature affects the binding of water, dissociation of water, solubility of salts in water, and their physical state. Water activity is affected by all these factors, but their effect is product specific.

2.7.1 Water Activity Measurement Methods

Water activity is generally expressed in between 0 in dry bones and 1.0 in pure water, but most of the foods are ranged in between 0.2 (dried foods) and 0.99 (moist fresh foods). In practice, a_w is typically quantified as the equilibrium relative humidity (ERH). Commercial instruments are divided into two categories. One is based on chilled mirror dew point technology, whereas the other is based on relative humidity (RH) using sensor that alters its electrical resistance. The approaches differ in terms of ease of use, accuracy, repeatability, measurement speed, calibration stability, and linearity. Water activity measurement can be done in the lab using a variety of procedures and devices based on colligative properties, isopiestic transfer, hygrometers, etc.

2.7.1.1 Dew Point Method

In this method, a sample is equilibrated with the headspace in a closed chamber having a mirror and a condensation detecting device at dew point. The RH of the air in the chamber is equal to a_w of the sample at equilibrium. Precisely, mirror temperature is controlled by thermocouples, and the point at which condensation first emerges is detected to observe the change in reflectance by photoelectric cell. In addition, both sample and mirror temperatures are measured at the same time. The use of both temperatures eliminates the necessity of equilibrium conditions and minimizes the computation time to less than 5 min. The mirror style of instruments has the disadvantage of the mirror becoming coated with dust. Another problem of this method is that confectionary products containing propylene glycol cannot be evaluated for water activity since the propylene glycol will condense on the mirror. Highly dry substances ($a_w < 0.03$) equilibrate at such a slow rate that measurements can take much longer than the standard 5 min.

2.7.1.2 Capacitive Sensor Method

Some water activity measuring instruments are based on capacitance sensors. These instruments use a hygroscopic polymer sensor and related circuitry to generate a signal that is proportional to the ERH and thus the water activity (as ERH/100). The ERH of the ambient air is measured by the sensor, and it is equivalent to sample water activity only if both the sample and sensor are at constant same temperature. Capacitive devices are capable to measure a_w in the range of 0 to 1.00 with a resolution of 0.005 and an accuracy of 0.015. Capacitance sensors are less costly, but they aren't always as precise or quick as the chilled mirror dew point method. These sensors require more time of about 30–90 min to attain constant relative humidity level.

2.7.1.3 Vapor Pressure Method

In this technique, vapor pressure is measured, and a_w is calculated as the ratio of vapor pressure of sample to the vapor pressure of pure water at constant temperature. The schematic diagram of this method is shown in Fig. 2.16. A sample of 10–50 g is placed in the sample flask and connects to the tube. About 10–15 g of silica gel or

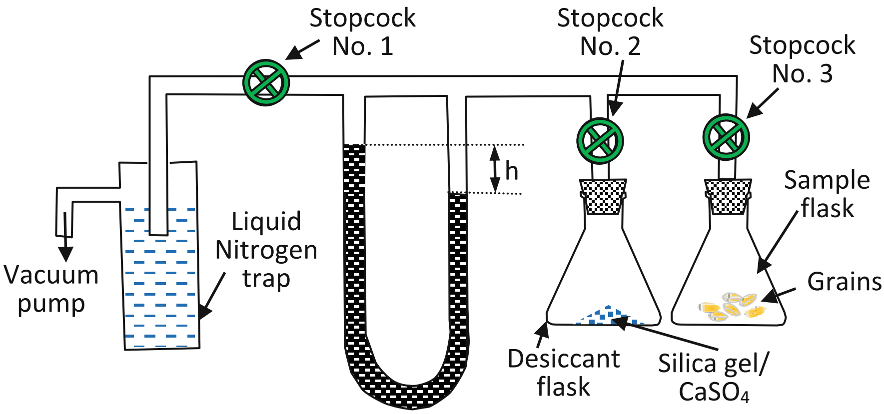


Fig. 2.16 Schematic diagram of the vapor pressure method

$CaSO_4$ is placed in the desiccant flask. The sample flask is isolated by closing the stopcock no. 3, and the system is completely evacuated to a pressure of less than 200 mmHg (0.263 atm.) by opening all stopcocks/valves [8]. The sample flask is also allowed for the evacuation of air for 1–2 min. Thereafter, stopcock nos. 2 and 3 are closed. The equilibrium time of about 40 min is given, and then pressure exerted by the sample is noted as h_1 in the manometer. The sample flask stopcock no. 1 is closed, and the desiccant flask valve 2 is opened to absorb water vapor. After reaching equilibrium, the pressure exerted by volatiles and gases is noted as h_2 in the manometer. Then, water activity is calculated by the following expression:

$$a_w = \frac{(h_1 - h_2)}{p_0} \rho g$$

where h_1 and h_2 are the difference in manometer heights for the pressure exerted by the sample and desiccant and p_o, ρ, and g are the vapor pressure of pure water, density of oil filled in the manometer, and gravitational acceleration, respectively.

Sample size, equilibration time, temperature, and volume can all have an impact on this technique. This technique is incompatible with biological materials that have active respiration or materials that have a high concentration of volatiles.

2.7.1.4 Freezing Point Depression Method

This method is the most appropriate for liquid foods having water activity above 0.85. It is a more suitable method for the samples having large amount of volatile constituents that mainly cause error in the vapor pressure method [9]. In the two-phase mixture of ice and solution, the vapor pressure of ice and concentrated solution is the same at equilibrium, and the water activity is solely dependent on temperature. Therefore, the water activity of the solution at below freezing temperature is calculated as:

$$a_w = \frac{\text{Vapor pressure of ice}}{\text{Vapor pressure of water}}$$

2.7.1.5 Thermocouple Psychrometer Method

Here, wet bulb temperature depression is used to evaluate the water activity of the sample. In the chamber where the sample is equilibrated, a thermocouple is inserted. The thermocouple is then sprayed with water before this water can evaporate, causing the temperature to drop. The temperature decrease is proportional to the rate of water evaporation from the thermocouple's surface that is a function of RH in equilibrium with the sample.

2.7.1.6 Isopiestic Method

The sample in this method is equilibrated with the dried reference sample such as microcrystalline cellulose in the evacuated desiccators at 25 °C, and change in weight in the reference sample is recorded. Following that, the water content of the reference material is determined, and the water activity is calculated using the standard sorption isotherm of the reference sample. This method is economical and easy to perform but not suitable for highly perishable foods as the equilibrium adjustment time is very long.

In the recent times, water activity analyzers are very popular and precise and render ease in operation. The determination of water activity of foods is mainly carried out by using these digital meters in the laboratories and industries.

2.7.2 Water Activity Analyzer

The different instruments, based on different techniques, are available today in the market that may have different ranges of water activity. An instrument, having a range of water activity, 0.030–1.000 with a resolution of 0.0001 [10], based on the dew point or capacitance principles is illustrated as follows:

The instrument has two parts, i.e., sample block and top block, which are joined by hinging arrangement. The diagram of one such dew point-based water activity analyzer is presented in Fig. 2.17. Both the blocks have provision for controlling the temperature of the sample. A mirror is provided in the top block to precisely control the temperature using a thermoelectric cooler. The sample is placed in the cup for the measurement of water activity. The exact point of condensation is appeared on the mirror, which is sensed by a photo detector cell. The thermocouple attached to the mirror provides the value of condensation temperature. The signal is then sent to the processor, and the water activity is displayed on the panel. A fan in the sample chamber reduces the time to reach equilibrium.

In the case of capacitance-based instrument, a capacitance humidity sensor is suspended in the headspace, which has polymer material-based electrodes to sense the humidity changes. The sensor is provided to measure the specific capacitance, which is sent to the processor to determine the water activity. The a_w of the sample

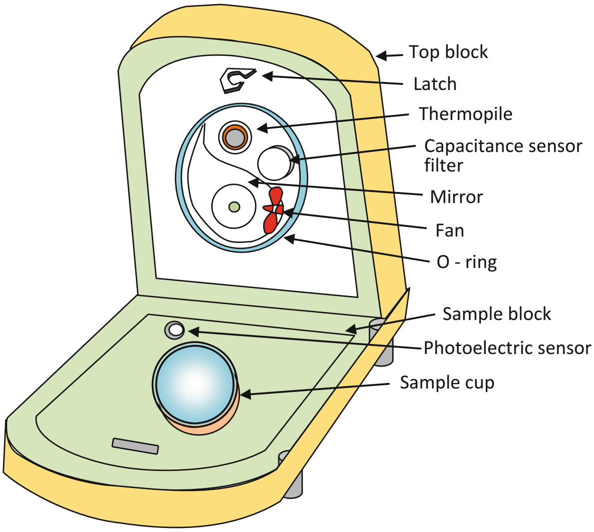


Fig. 2.17 Water activity analyzer

maintains the equilibrium with the RH of the air enclosed in the chamber. The accuracy of dew point-based apparatus is better. It may also be equipped with moisture content determination feature.

2.8 Rheological Properties of Foods

Rheology is the science that deals with the deformation or flow behavior of material. The knowledge of rheological properties is useful in the designing of mechanical handling systems of agricultural product. In liquid foods, the knowledge of flow behavior is essential to calculate the size of pipe and power requirement of the pump for transporting it from one point to another point. Rheological properties play an important role in the quality control and development of different foods. Rheology can be classified on the basis of physical state of the material as shown in Fig. 2.18.

2.8.1 Rheology of Solids

Rheology of solid foods can be better understood by thorough study of stress-strain relationship. The applied stress depends on the area of specimen and is categorized as normal stress and shear stress. The force applied perpendicular to the plane per unit area is called normal stress. It may be tensile or compressive stress depending upon the stretch ability or compressibility of the materials [6] (Fig. 2.19). The resultant strain is called normal strain and defined as the change in length per unit length in the same direction of applied stress. The shear stress or tangential stress is the tangential force acting on the surface, and the resultant shear strain is the change in the angle formed between two planes.

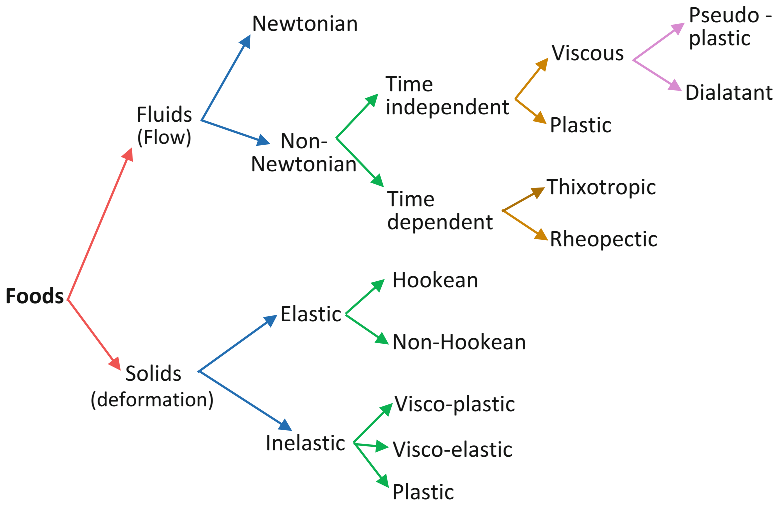


Fig. 2.18 Rheological classification of foods

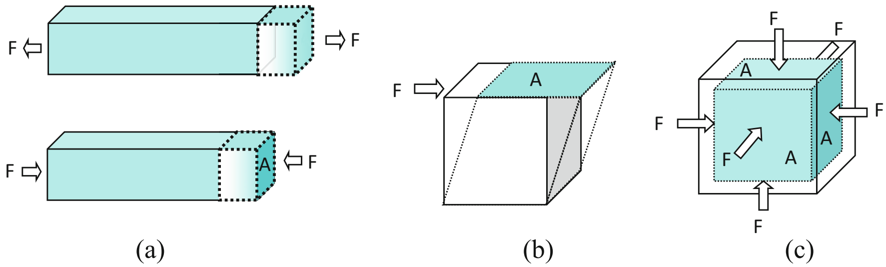


Fig. 2.19 Types of stresses. (**a**) Normal stress (tensile and compression). (**b**) Shear stress (dragging). (**c**) Bulk stress (compression)

When a stress is applied, immediately produced strain is proportional to the applied stress. In the compression of a food sample, the behavior of stress-strain curve is shown in Fig. 2.20. During the unloading of stress, the amount of strain that is recovered due to the elastic component of food sample is known as elastic strain, while the unrecovered strain due to the plastic nature of food sample is known as plastic strain. The fraction of elastic and plastic strain is known as degree of elasticity and degree of plasticity, respectively. The solid materials that recover completely after the removal of stress is known as purely elastic solid or Hookean solid. The magnitude of stress-to-strain ratio is called modulus. For Hookean solids, depending upon the method of applying stress, three types of moduli can be defined (Table 2.2).

Poisson's ratio (μ) can be calculated by the ratio of the strains, in perpendicular and in the direction of the applied force [6].

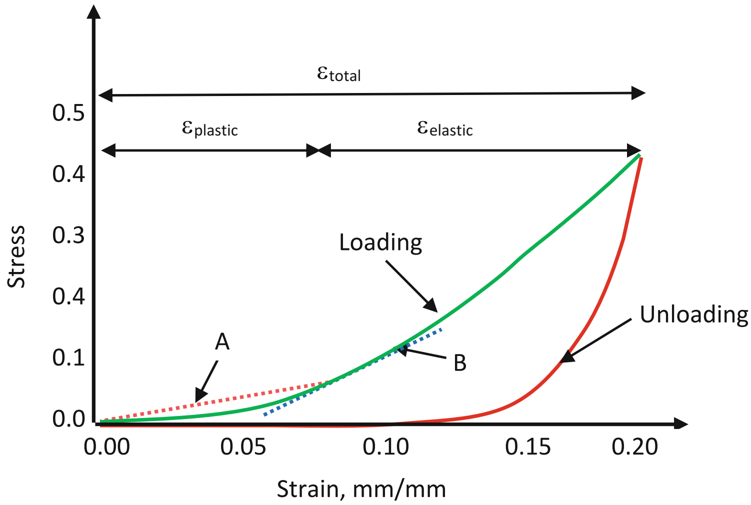


Fig. 2.20 Stress-strain curve for the compression of food

Table 2.2 Modulus of Hookean solids

Modulus		Stress type	Strain type	Expression
Modulus of elasticity: It is referred to as Young's modulus and can be defined as the ratio of normal stress to normal strain	(E)	Normal (σ)	Normal (ε)	$E = \sigma/\varepsilon$
Modulus of rigidity: It is referred to as shear modulus and can be defined as the ratio of shear stress to shear strain	(G)	Shear (τ)	Shear (γ)	$G = \tau/\gamma$
Bulk modulus: It can be defined as the ratio of pressure applied from all the directions to volumetric strain	(K)	Pressure (ΔP)	Volume (ΔV)	$K = \Delta P/\Delta V$

$$\mu = \frac{\text{Change in width per unit width}}{\text{Change in length per unit length}} = \frac{\Delta D/D}{\Delta L/L}$$

If the volume change does not occur in the material, when it is stretched or compressed, Poisson's ratio of such material is 0.5. The material, that can be compressed without any change in diameter due to the presence of large amount of air in the structure, Poisson's ratio is zero [5].

2.8.2 Viscoelastic Behavior

Some foods that exhibit properties of both, fluids and solids, i.e., viscous properties and elastic properties, are known as viscoelastic foods. Many food materials like

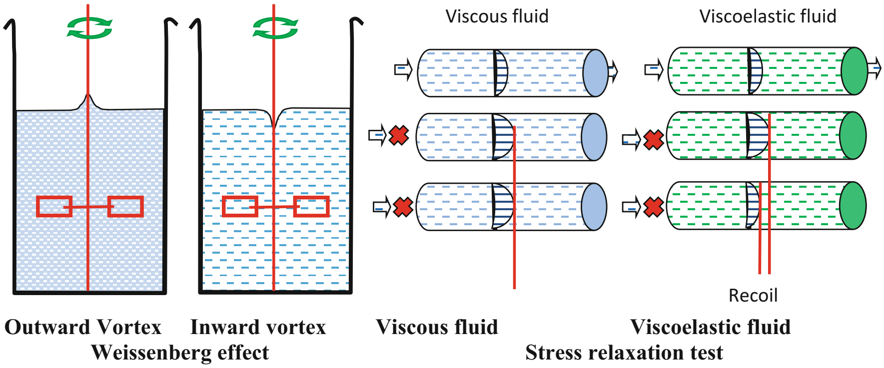


Fig. 2.21 (**a**) The Weissenberg effect and (**b**) recoil phenomenon of viscous and viscoelastic foods

dough, cheese, cream, and gel products are the common examples of viscoelastic foods. When stress is applied to such foods, these may start deforming continuously, and when stress is removed, the strain is not immediately reduced to zero as happens in the elastic materials.

The two most common phenomena observed in viscoelastic foods are the Weissenberg effect and recoil phenomenon (Fig. 2.21). The Weissenberg effect can be easily observed during the mixing of cake batter. When the batter is agitated, the batter climbs on the rotating rod, and vortex is formed outward to the batter (Fig. 2.21a). However, the same type of vortex is formed inward to the batter in the case of viscous fluids. The recoil phenomenon of viscoelastic food can be observed by sudden stop of flow. Fluid particles move back due to tensile force, but viscous fluid particles resist their flow to move back and try to remain in position when the motion is stopped [11]. Due to the opposite action of tensile force and viscous force, a gap or coiling occurs between the particles (Fig. 2.21b).

The tests (1) stress relaxation test, (2) creep test, and (3) oscillatory test can be performed to study the viscoelastic behavior of food.

2.8.2.1 Stress Relaxation Test

In this test, the materials are deformed to a fixed strain. The stress needed to keep this strain decreases with respect to time. The behavior of different types of material is represented in Fig. 2.22. The figure showed that ideal viscous materials relax instantaneously, and stress becomes zero, but ideal elastic materials required the same amount of stress to maintain constant strain. Viscoelastic materials relax gradually but not to zero; a minimum equilibrium stress (σ_c) is required depending on the amount of elastic component present in the solid material. But the minimum equilibrium stress is zero in the viscoelastic liquid materials. Higher mobility of liquid molecules causes quick recovery than the solid molecules.

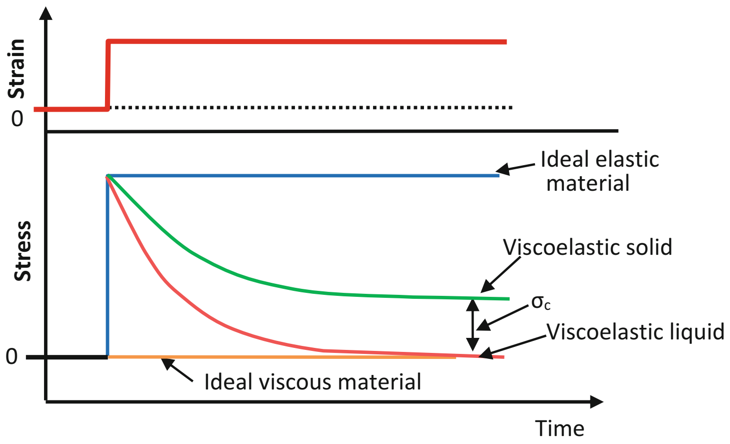


Fig. 2.22 Stress relaxation curve for elastic, viscous, and viscoelastic foods

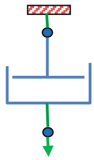
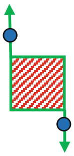
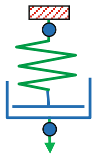
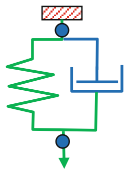
2.8.3 Rheological Models

The three most common basic mechanical models, viz., Hookean, dashpot, and friction, generally show ideal elastic, ideal viscous, and ideal plastic behavior of the materials (Table 2.3). In these models, ideal elastic material is represented by spring element, and the deformation produced in the elastic materials is proportional to the applied force. When applied force is removed, the spring extension recovers completely. Ideal viscous material or Newtonian liquid is represented by dashpot, and the rate of deformation is proportional to the applied force. Another characteristic of material is the ideal plastic behavior, which is represented by friction element. The rheological behavior of viscoelastic material is complex and can be better understood by combinations of basic mechanical models and properties of both elastic and viscous components. The three most common combined models of viscoelastic materials are the Maxwell, Kelvin-Voigt, and Burger model. In these models, the behavior of viscoelastic materials is represented by springs and dashpots in different ways. In the Maxwell model, both elements are connected in series, whereas in the Kelvin model, these are connected in parallel. The Burger model is the series combination of the Kelvin-Voigt and Maxwell models [1].

The Maxwell model is used to study stress relaxation with time in a sample, subjected to a constant applied strain. The Kelvin-Voigt model is used to study strain increasing behavior with time in a sample, subjected to a constant applied stress. In the Maxwell model, the deformation consists of two parts; one is purely viscous, whereas the other is purely elastic.

Although both the Kelvin-Voigt and Maxwell models represent the viscoelastic foods, both models react differently in creep and relaxation (Fig. 2.23). In creep test, when a constant load is applied, a final steady-state deformation is obtained in the Kelvin-Voigt model, whereas the Maxwell model results in a continuing flow because the viscous element is not limited by the spring element. The Kelvin-

Table 2.3 Rheological models and their symbols

Rheological model	Material type	Stress	Symbol
Hookean	Ideal elastic	$\tau = G\gamma$	
Dashpot	Ideal viscous	$\tau = \mu\gamma$	
Friction	Ideal plastic	$\tau = \tau_0 + k\gamma$	
Maxwell	Viscoelastic	$\tau = \tau_0 \exp(-t/\lambda_{\text{rel}})$	
Kelvin-Voigt	Viscoelastic	$\tau = G\gamma + \mu\gamma$	

Voigt model recovers completely but not instantly, when the load is removed; however, the Maxwell model does not show recovery completely but instantly. No stress relaxation is shown in the Kelvin-Voigt model, whereas the Maxwell model shows [1].

2.8.4 Texture

The measurement of texture is mainly based on the stress-strain relationship and is an important parameter to measure and understand the quality of solid foods. During mastication, food breaks into smaller parts and makes it more digestible. Various sensory receptors in the mouth transmit the perceived information to the brain. This information is integrated with the stored information in the memory and gives the

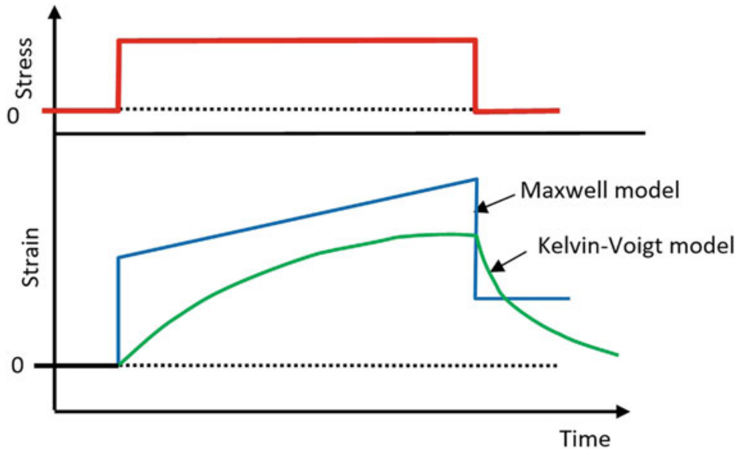


Fig. 2.23 Behavior of creep test curve for the Maxwell and Kelvin-Voigt models

overall impression of the texture of the food. Texture is a quality parameter, which is closely associated with the mechanical and structural properties of foods. Dr. Szczesniak [12] introduced five independent mechanical parameters and three dependent parameters. Hardness, cohesiveness, adhesiveness, springiness, and viscosity are the five independent parameters, and fracturability/brittleness, gumminess, and chewiness are the three dependent parameters. Texture can be affected by the different compositional, processing, and storage parameters besides geometrical parameters.

Texture analysis plays an important role in controlling the quality along with process and product development and correlates the sensory characteristics of foods. The most common methods for analyzing the textural properties of foods are based on the sensory and instrumental method-based parameters. The instrumental measurement method can further be divided into three groups [13]:

- Fundamental: It measures the basic rheological parameters like viscosity, elasticity, etc. of the food item.
- Empirical: It measures the parameters that are not defined appropriately, but have a crucial role in the food texture like the hardness and consistency.
- Imitative: It measures all important parameters related to texture of food just like human action of chewing in mouth or squeezing by hands.

2.8.4.1 TPA and Texture Analyzer

Texture profile analysis (TPA) is the measurement and description of the textural attributes/characteristics that are perceived/measured in foods. Various instruments are used like tenderometer to measure tenderness or maturity, penetrometer to measure hardness or consistency, and texture analyzer to determine different mechanical parameters. TPA is commonly referred to as the double compression

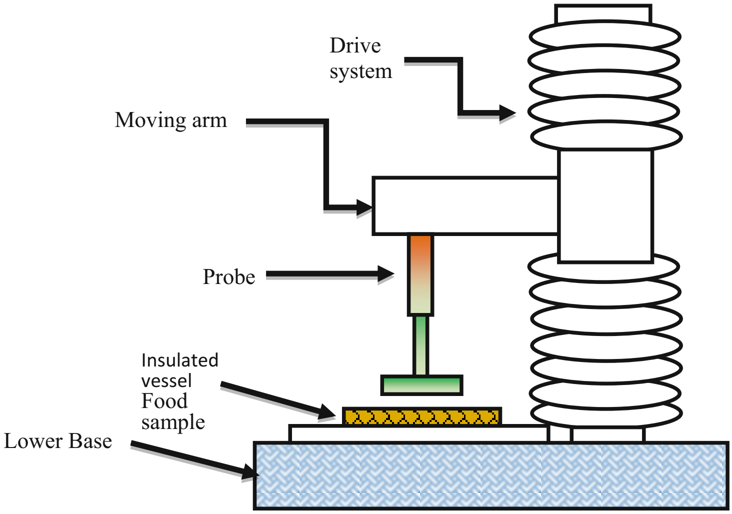


Fig. 2.24 Texture analyzer

test or the two-bite test. Now, the texture analyzer has become very common and replaced the sensory attributes with the mechanical parameters (Fig. 2.24). It can quantify various parameters in only one experiment. Now, hardness, cohesiveness, springiness, and resilience are the primary recommended TPA characteristics. TPA determination may not be appropriate in a number of products, such as hard candy, almonds, caramel, etc., because all the primary attributes are not needed in these products.

The texture analyzer has a number of operational parameters, which must be selected appropriately to conduct the correct test. The pre-speed test is the speed, which represents the movement of probe and arm downward till it touches the upper surface of the sample. As soon as it touches the surface, the data recording is triggered, and plotting of stress with time can be observed. The probe moves at the test speed to the specified distance or strain. After reaching at the specified distance, the probe/arm moves up at the test speed till the original condition. It holds for waiting time and presses the sample again at test speed for the second compression. The probe/arm moves to the original position at post-test speed, once the second compression is over. The following operational settings may be selected [14]:

1. Selection of probe: In the case of flat probe used for compression, the diameter of probe should be more than the sample size. However, smaller diameter probe may be selected for penetration to study the sample behavior. The puncture, knife, and Kramer shear probes should not be used for TPA as it does not imitate the mastication process.

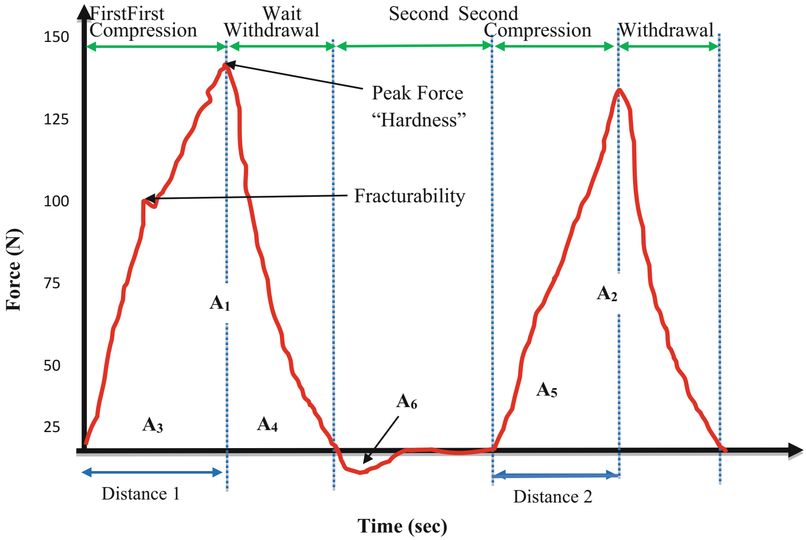


Fig. 2.25 A representative graph of texture profile analysis (TPA)

2. Speed of compression and withdrawal: Generally, the compression and withdrawal test speed should remain the same for maintaining the uniformity during texture profile analysis test.
3. Strain or travel distance: The strain may be selected from 25 to 90%. The strain should be kept according to the mastication process of food item selected for the study.
4. Wait timing: The wait time implies the time duration needed after the completion of the first compression and withdrawal to regain its original height before the second compression. It should be selected according to the nature of the product.
5. Sample preparation: The sample for the texture profile analysis should be prepared according to the requirement of texture analyzer. The sample size, shape, and temperature affect the TPA test; therefore, these should be adequately maintained while testing.

A representative texture profile analysis graph of a food is presented in Fig. 2.25. The texture profile analysis provides the following parameters to characterize the food material:

1. Hardness: It is represented by the peak force obtained during the first compression. Usually, the peak is obtained at the maximum strain or deepest compression level. The unit of hardness is Newton (N).
2. Fracturability: It is the amount of force required to make the first fracture in the food material during the first compression. The fracturability is represented in Newton (N).

3. Cohesiveness: The cohesiveness of the material is expressed as the area under the second compression and withdrawal (A_2) divided by the area under the first compression and withdrawal (A_1) on force and time diagram. It represents the resistance offered in the second compression with respect to the first compression.

$$\text{Cohessiveness} = \frac{A_2}{A_1}$$

4. Springiness: It represents the property of the material to spring back after the first compression is over. It is measured as the ratio of the distance measured during the second compression for reaching at the maximum stress to the distance measured to reach at the maximum stress during the first compression on the time axis of TPA graph.

$$\text{Springiness} = \frac{\text{Distance 2}}{\text{Distance 1}}$$

5. Gumminess: This provides information regarding the characteristics of semi-solid foods. It is estimated by multiplying hardness and cohesiveness. The gumminess is represented in Newton (N).

$$\text{Gumminess } (N) = \text{Hardness} \times \text{Cohessiveness}$$

6. Chewiness: This characteristic is used for solid products and can be estimated by multiplying hardness, cohesiveness, and springiness. The chewiness is represented in Newton (N).

$$\text{Chewiness } (N) = \text{Hardness} \times \text{Cohessiveness} \times \text{Springiness}$$

7. Resilience: It is the property of the product, which indicates the material's ability to regain its original height. It can be measured in single compression test by dividing the area under the first withdrawal (A_4) by the area under the first compression (A_3). The speed of the compression and withdrawal must remain the same for the estimation of resilience.

$$\text{Resilience} = \frac{A_4}{A_3}$$

8. Adhesiveness: After the completion of the first compression and withdrawal, the negative force, generated during wait period, is referred to as adhesiveness. It is represented by the area under the negative force (A_6). The adhesiveness is represented in Newton-seconds (N s).

2.8.5 Rheology of Liquid Foods

Liquid foods flow under gravity and hold the shape of its container. Flow properties are important to understand the structure, quality control, and sensory evaluation of foods. A flow characteristic is related with the viscous behavior of liquids, and the same is illustrated in Fig. 2.26. Consider a liquid film of thickness y between the two flat plates of area A. At time $t = 0$, the force F is applied in the lower plate and set it in motion with the velocity V. With the passage of time ($t = t$), the linear distribution of velocity profile is obtained between the plates (Fig. 2.26). The force per unit area,

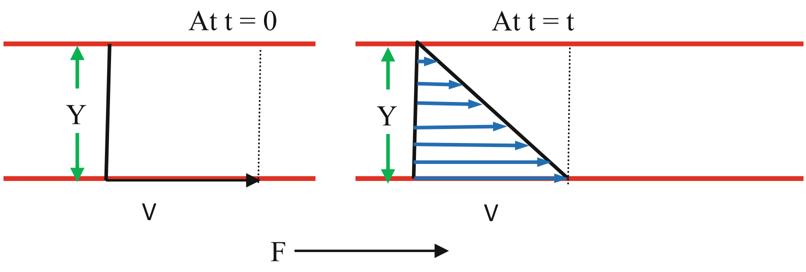


Fig. 2.26 Viscosity profile of Newtonian fluid between two parallel plates

needed to keep the motion of the lower plate, is directly proportional to the velocity gradient.

$$\tau = -\mu \frac{dv}{dy} \quad \text{(Newton's law of viscosity)}$$

where τ is the shear stress (N/m^2) and μ is the viscosity (Pa s). The negative sign indicates that velocity decreases with the direction of momentum.

Viscosity is referred to as the internal resistance to flow under the applied shear force. It is the fluid property which depends on temperature. Most of the fluid viscosity decreases with temperature due to the decrease of cohesive force between the liquid molecules. Based on the rheological behaviors of liquid foods, classification is made into three groups, viscous, plastic, and time-dependent fluid.

2.8.5.1 Viscous Fluid

Viscous fluids are continuously deformed with applied stress and can be categorized into Newtonian and non-Newtonian fluids. Newtonian fluids follow Newton's law of viscosity, and viscosity of the fluids remains constant and is independent of the shear rate. Therefore, the relation between shear stress and shear rate is a straight line passing from the center. Non-Newtonian fluids follow the power law, and relationship between shear stress and shear rate is not a constant [15]. The viscosity of these fluids is not constant and depends on the applied shear force and time, and therefore the term apparent viscosity is used.

$$\tau = k\left(\frac{dv}{dy}\right)^n$$

where k is the apparent viscosity or consistency and n is the flow behavior index. The value of n is less than 1 for shear-thinning fluids, and n is greater than 1 for shear-thickening fluids.

2.8.5.2 Shear-Thinning (Pseudoplastic) Fluids

In shear-thinning fluids, the apparent viscosity decreases with the increase in shear rate (Fig. 2.27). The breakdown of the structure of food during shearing action is the main cause of this flow behavior [16]. The shear-thinning fluids showed the convex downward curve on a shear stress-shear rate diagram (Fig. 2.27). Fruit and vegetable

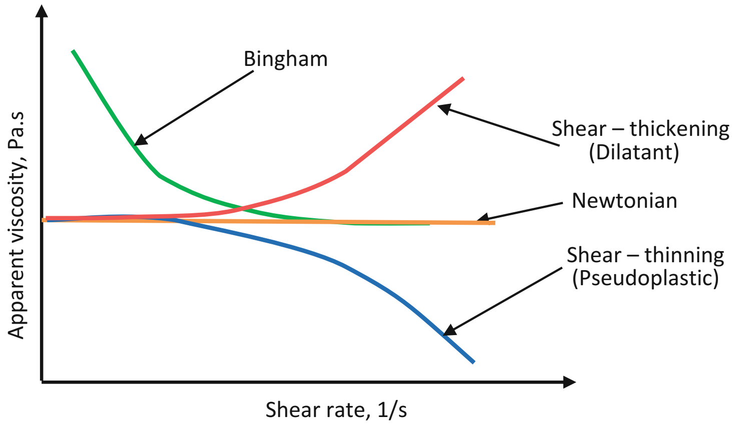


Fig. 2.27 Apparent viscosity of time-independent fluids [18]

products such as concentrated fruit juices, paste, and puree are the major examples of shear-thinning foods. The shear-thinning behavior of cake batter is observed with the increase of fat and emulsifier [17].

2.8.5.3 Shear-Thickening (Dilatant) Fluids

In shear-thickening fluids, the apparent viscosity increases with the increase in shear rate (Fig. 2.27). This behavior might be due to the building of structural molecules of fluid with the shear [16]. The shear-thickening fluids represent the concave curve on a shear stress-shear rate diagram (Fig. 2.27). The most common example of shear-thickening fluids is the cornstarch suspension. Shear-thickening behavior is observed to a greater extent in the waxy starches like barley, maize, rice, and potato than the normal rice, wheat, and maize starches [19]. The greater extent of shear-thickening behavior of waxy starches might be due to the higher fraction of amylopectin contents. The shear-thickening fluids that exhibit increase in apparent viscosity along with volume expansion are called dilatant fluids.

2.8.5.4 Plastic Fluids

These fluids are categorized as Bingham plastic and non-Bingham plastic. No flow occurs until a minimum yield stress is applied in the Bingham plastic fluids (Fig. 2.28). Once the yield stress is exceeded, flow occurs like a Newtonian fluid. Tomato paste, tomato ketchup, and mayonnaise are the good examples of this kind of fluids. Non-Bingham plastic fluids also require minimum yield stress to start their flow but behave like non-Newtonian fluids beyond the yield stress. Rice flour-based batter is the best example of non-Bingham plastic fluids.

2.8.5.5 Time-Dependent Fluid

The apparent viscosity of some fluids changes with time under constant shear rate. These fluids are classified into two categories, thixotropic and rheopectic [6]. A thixotropic fluid undergoes a decrease in apparent viscosity with time (shear thinning

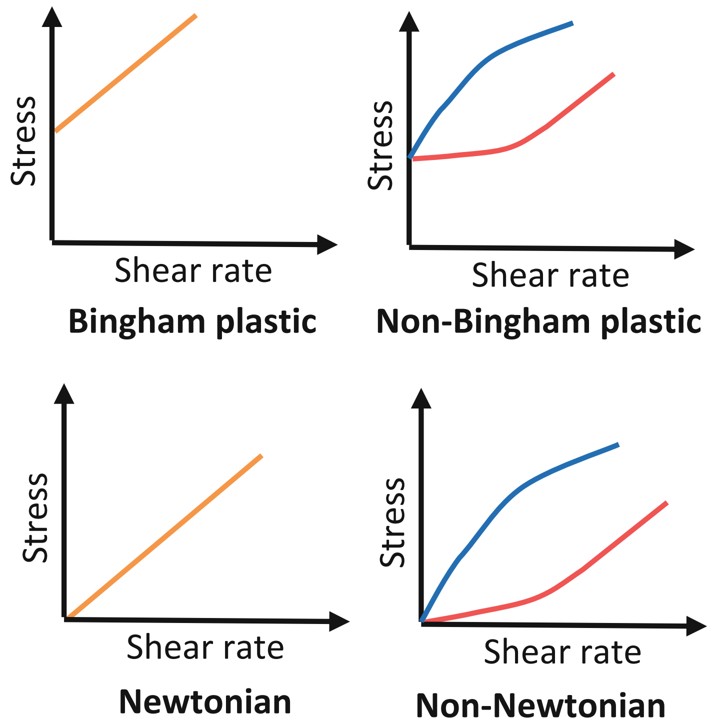
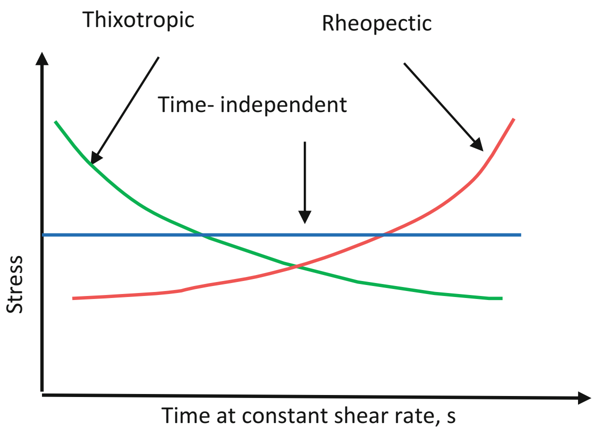


Fig. 2.28 Shear stress versus shear rate curve of different fluids

Fig. 2.29 Time-dependent behavior of fluids



with time) at a constant shearing action (Fig. 2.29). Thixotropic behavior is commonly observed in gelatin, salad dressings, *bael* (*Aegle marmelos*) sherbet, curd, egg white, and shortening. After the removal of applied shear, this behavior may be irreversible, reversible, or partially reversible.

A rheopectic fluid showed the opposite behavior as the thixotropic fluids, in that the fluid's apparent viscosity increases with time (shear thickening with time) as the constant shear rate is applied (Fig. 2.29). Starch-milk-sugar pastes exhibit time-dependent flow behavior but showed thixotropic behavior at pasting temperature range of 85–95 °C, while at low pasting temperature of 75 °C, it exhibits rheopectic behavior [20].

2.9 Colors

Color is one of the important food properties, which plays a vital role in creating stimulation among the consumers to buy or consume. The natural colors are the best choice; however, permitted synthetic colors are added to make the food attractive. The red, blue, and violet colors can be derived from anthocyanins present in raspberries, beetroot, and red cabbages, while the green color is from chlorophylls present in leaves or stems. Carrots, apricots, and tomatoes are also good sources of yellow, orange, and red colors.

2.9.1 Color Models and Space

A color model is defined as a mathematical model for describing the color of material with a combination of three or more values of specific color, viz., red, green, and blue. The color models are used to prepare a set of colors based on the individual color values and specific conditions. The developed set of resulting colors is known as color space. A number of color systems are used for the identification of color in food processing industries. The popular color spaces used to describe the color of food materials are CIE (International Commission on Illumination), Hunter, and Munsell color systems.

2.9.1.1 Spectral Sensitivity

A human eye has blue, green, and red receptor/cones to identify any color; therefore, all the colors can be represented in terms of blue, green, and red. These colors are needed to formulate any specific color. The variation spectral sensitivity of these color components is represented by x_λ, y_λ, and z_λ color-matching functions for blue, green, and red color receptors, respectively (Fig. 2.30). The higher sensitivity x_λ, y_λ, and z_λ functions are observed in short wavelength (420–440 nm), middle wavelength (530–540 nm), and long wavelength (560–580 nm) regions. The long, medium, and short (LMS) color space uses sensitivity of peaks from all three types of cones of the human eye.

2.9.1.2 Standard Observer

The observed view is an important criterion due to the distribution of receptors in the eye, which affects the tristimulus value. The standard observer/standard colorimetric observer considers 2° angle for an average chromatic response received by the

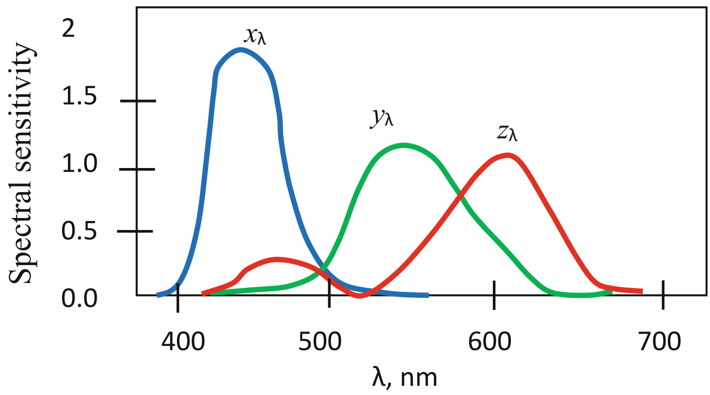


Fig. 2.30 Spectral sensitivity curves corresponding to the human eye

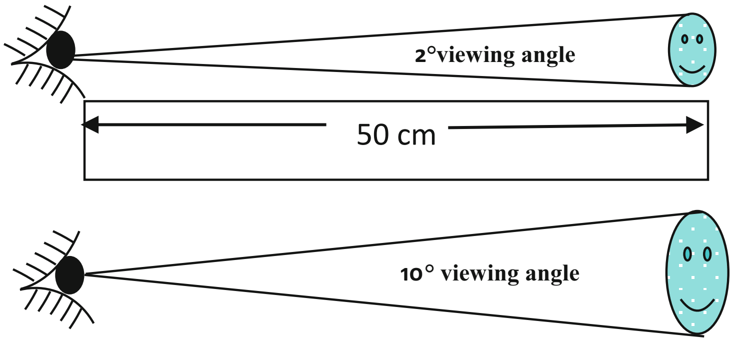


Fig. 2.31 Standard 2° and supplementary standard 10° views

human eye. These color values were captured as standard user using 2° field of view from a distance of 50 cm from the source (Fig. 2.31). The additional supplementary standard is also used at 10° field of view [21].

2.9.1.3 Tristimulus Values

The tristimulus values are used as the amounts of three primary colors in an additive color model in the three color spaces. These are represented as *X*, *Y*, and *Z*, and the values observed by 2° standard are known as tristimulus values (CIE) (2° XYZ tristimulus values), which can be estimated from x_λ, y_λ, and z_λ using the following expression.

$$X = K \int_{380}^{780} S_\lambda x_\lambda R_\lambda \, d\lambda$$

$$Y = K \int_{380}^{780} S_\lambda y_\lambda R_\lambda \, d\lambda$$

$$Z = K \int_{380}^{780} S_\lambda z_\lambda R_\lambda \, d\lambda$$

$$K = \frac{100}{\int_{380}^{780} S_\lambda y_\lambda \, d\lambda}$$

where K normalizing factor for tristimulus values for representing Y value as 100 for perfect white diffuser, S_λ relative spectral power distribution of the illuminant, which is defined as the ratio of spectral concentration at a given wavelength (S_λ) to the concentration of a reference wavelength ($S_{\lambda 0}$).

$$S_\lambda = \frac{S_{\lambda m}}{S_{\lambda 0}}$$

x_λ, y_λ, z_λ color-matching functions for CIE 2° standard observer, R_λ spectral reflectance of specimen.

2.9.1.4 Chromaticity Coordinates

The color can be represented into (1) brightness and (2) chromaticity. The chromaticity defines the hue and saturation, but it does not consider lightness (light/dark color). The xyz chromaticity coordinates are calculated using XYZ tristimulus values:

$$x = \frac{X}{X + Y + Z}$$

$$y = \frac{Y}{X + Y + Z}$$

$$z = \frac{Z}{X + Y + Z} = 1 - x - y$$

The *xy* chromaticity diagram can be plotted, which represents the colors with two derived parameters. These parameters *x* and *y* represent the normalized values of all three tristimulus values. The pure colors are available along the edges of the diagram. Other colors are being produced by the mixing of pure color in various proportions, which can be represented on the chromaticity diagram. In case two colors are mixed in equal intensities, the resulting color is represented by the middle value of the line joining the colors. In case the intensity of one color is higher than the other color, the resulting color is shifted toward the higher-intensity color according to the proportion.

2.9.1.5 Hunter L, a, b Color Scale

The Hunter L, a, b color scale came into practice during the year 1950 to overcome the problem for an apt identification of color based on XYZ values. The scale has more uniformity than XYZ color scale. The color difference can be easily estimated by identifying the coordinates of different colors. The Hunter L, a, b color scale can be represented in a cubical coordinate system, which has originated at the center of the horizontal base (lower face) of the cube (Fig. 2.32).

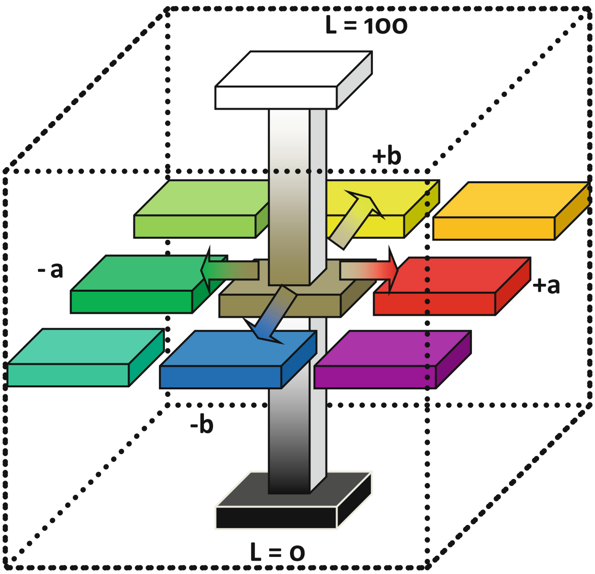
The axis, which represents lightness and darkness, is represented by central vertical axis. The axis starts from "$L = 0$" value which indicates black color and ends vertically at the top of face "$L = 100$," which indicates white color. The "a value" on the positive side indicates red color, while negative "a value" represents green color. The remaining horizontal axis indicates yellow and blue colors for positive and negative "b values," respectively.

The values of L, a, and b can be represented by the following expressions [22].

$$L = 100 \times \sqrt{\frac{Y}{Y_n}}$$

$$a = K_a \left(\frac{X/X_n - Y/Y_n}{\sqrt{Y/Y_n}} \right)$$

Fig. 2.32 Hunter L, a, b color scale



$$b = K_b \left(\frac{Y/Y_n - Z/Z_n}{\sqrt{Y/Y_n}} \right)$$

The X, Y, and Z represent CIE tristimulus values, while X_n, Y_n, and Z_n indicate tristimulus values for the illuminant. The value of Y_n is 100.0, and K_a and K_b are the chromaticity coefficients and can be obtained from the illuminant specification provided by the manufacturer, e.g., the values of X_n, Z_n, K_a, and K_b for D65 illuminant are 95.02, 108.82, 172.30, and 67.20, respectively, for 2° standard observer.

The change in color by adding any ingredient or due to the processing of ingredients or combination of both can be identified by observing the change in "L," "a," and "b" values as ΔL, Δa, and Δb values. The tolerance limit for a specific raw material or processed produce may be decided by giving consistent quality to the consumers, e.g., the redness of the product is specified by "a value," which can be controlled by operating parameters, ingredients, and processing conditions. The desired/ideal value of the sample may be considered as standard. These values are calculated according to the following expression:

$$\Delta L = L_{\text{sample}} - L_{\text{standard}}$$

$$\Delta a = a_{\text{sample}} - a_{\text{standard}}$$

$$\Delta b = b_{\text{sample}} - b_{\text{standard}}$$

$$\Delta E = \sqrt{\Delta L^2 + \Delta a^2 + \Delta b^2}$$

The positive values of ΔL, Δa, and Δb of processed samples indicate that samples are lighter, redder, and yellower from the standard. Similarly, the negative values of ΔL, Δa, and Δb of processed samples indicate that samples are darker, greener, and bluer, respectively, from the standard.

2.9.1.6 CIELAB Color Scale

The scale was recommended by the International Commission on Illumination, Austria, in 1976 with a view to provide standard for maintaining the uniformity in color values. Its representation is similar to the Hunter Lab color scale and is represented in cubical coordinate system, which has originated at the center of the horizontal base (lower face) of the cube (Fig. 2.33). The Hunter L, a, b scale indicates more contraction in yellow region and overexpansion in blue region, while CIELAB is designed for more uniformity, but small overexpansion in yellow region occurs. The CIELAB provides better approximation especially in very dark colors [23].

The CIELAB scale is as meaningful as the Hunter L, a, b scale; however, CIELAB values for "L^*," "a^*," and "b^*" are estimated using cube roots in place of square roots in the Hunter L, a, b scale. The values of L^*, a^*, and b^* can be represented by the following expressions [24].

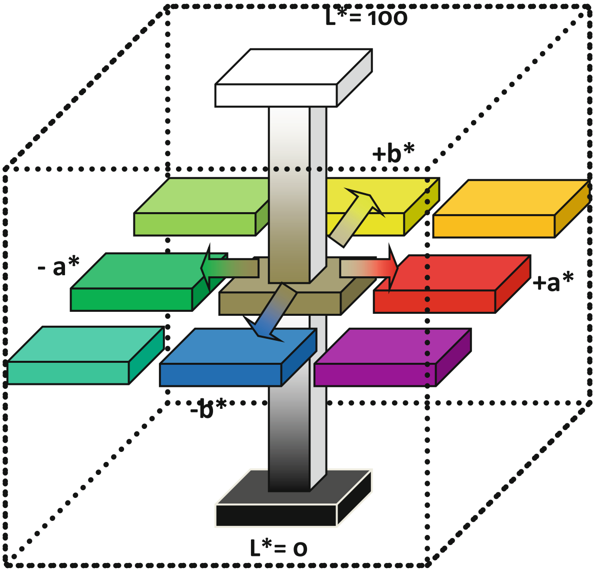


Fig. 2.33 CIELAB color scale

Case I: All values of X/X_n, Y/Y_n, and $Z/Z_n > 0.008856$

$$L^* = 116\sqrt[3]{Y/Y_n} - 16$$

$$a^* = 500\left(\sqrt[3]{X/X_n} - \sqrt[3]{Y/Y_n}\right)$$

$$b^* = 200\left(\sqrt[3]{Y/Y_n} - \sqrt[3]{Z/Z_n}\right)$$

Case II: Any value of X/X_n, Y/Y_n, and $Z/Z_n \leq 0.008856$

$$L^* = 903.3\sqrt[3]{Y/Y_n}$$

$$a^* = 500\,[\,f(X/X_n) - f(Y/Y_n)]$$

where:

If $f(X/X_n) > 0.008856$, then $f(X/X_n) = \sqrt[3]{X/X_n}$
If $f(X/X_n) < 0.008856$, then $f(X/X_n) = 7.87\,\frac{X}{X_n} + \frac{16}{116}$
If $f(Y/Y_n) > 0.008856$, then $f(Y/Y) = \sqrt[3]{Y/Y_n}$
If $f(Y/Y_n) < 0.008856$, then $f(Y/Y_n) = 7.87\,\frac{Y}{Y_n} + \frac{16}{116}$

$$b^* = 200\,[\,f(Y/Y_n) - f(Z/Z_n)]$$

where:

If $f(Z/Z_n) > 0.008856$, then $f(Z/Z_n) = \sqrt[3]{Z/Z_n}$
If $f(Z/Z_n) < 0.008856$, then $f(Z/Z_n) = 7.87\,\frac{Z}{Z_n} + \frac{16}{116}$

The X, Y, and Z represent CIE tristimulus values, while X_n, Y_n, and Z_n indicate tristimulus values for the illuminant. The value of Y_n is 100.0. The X_n and Z_n indicate tristimulus values for the illuminant and can be obtained for the illuminant source, e.g., the values of X_n and Z_n for D65 illuminant are 95.02 and 108.82, respectively, for 2° standard observer.

The change in color by adding any ingredient or due to the processing of ingredients or combination of both can be identified by observing the "L^*," "a^*," and "b^*" values. The desired/ideal value of sample may be considered as standard. The changes in "L^*," "a^*," and "b^*" values can be obtained as:

$$\Delta L^* = L^*_{\text{sample}} - L^*_{\text{standard}}$$

$$\Delta a^* = a^*_{\text{sample}} - a^*_{\text{standard}}$$

$$\Delta b^* = b^*_{\text{sample}} - b^*_{\text{standard}}$$

$$\Delta E^* = \sqrt{\Delta L^{*2} + \Delta a^{*2} + \Delta b^{*2}}$$

CIELCh Color Scale

The CIELCh/CIEHLC color scale has similar color space as in CIELAB, but cylindrical coordinates are used in place of rectangular coordinates. The change in chroma, ΔC^*, and hue angle, ΔH^*, can be estimated using the following expression [24]:

$$\text{Chroma}, C^* = \sqrt{a^{*2} + b^{*2}}$$

$$\Delta C^* = C^*_{\text{sample}} - C^*_{\text{standard}}$$

$$\text{Hue angle}, H = \tan^{-1}\frac{b^*}{a^*}$$

$$\Delta H* = \sqrt{\Delta E^{*2} - \Delta L^{*2} - \Delta C^{*2}}$$

The specific correction factors were applied to non-uniformities for estimating the total color difference in CIE94 standard by incorporating compensation for lightness, chroma, and hue. Similarly, for handling the perceptual uniformity effectively, hue rotation and correction factors for the compensation of natural color were also added for estimating the total color difference in the CIEDE2000 standard.

2.9.1.7 Munsell Color System

The Munsell color system has a series of color charts. It defines Munsell hue (H) as a measure of hue, Munsell value (V) as a measure of lightness, and Munsell chroma (C) as a measure of saturation.

2.9.1.8 Other Color Spaces

The CIELUV color space is also used for the measurement of color and defined as uniform color spaces in the year 1976. It uses L^*, u^*, and v^* values for representing the color. Similarly, the CIE 1976 UCS diagram was also developed in the year 1976, which uses u' and v' values and provide uniform color spacing in measurements at same luminance. It is extensively used in computer graphics.

2.9.2 Estimation of Important Color Parameters

2.9.2.1 Browning Index

It is an important characteristic of food, which is changed with respect to processing and storage. The quality of product can be accessed by estimating the change in browning of food material. It can be estimated using the following expression [25]:

$$\text{Browning index, BI} = \left(\frac{X - 0.31}{0.17}\right) \times 100$$

$$X = \frac{(a^* + 1.75 \times L^*)}{(5.645 \times L^* + a^* - 3.012b^*)}$$

2.9.2.2 Whiteness Index

This index represents the measurement of white color of food products. This may be used for the discoloration of product during drying. The whiteness also remains an important factor for cheese, flours, breads, etc. The whiteness index can be estimated using the following expression [26]:

$$\text{Whiteness index, WI} = 100 - \sqrt{(100 - L^*)^2 + a^{*2} + b^{*2}}$$

2.9.2.3 Yellowness Index

The yellowness of the product may occur due to the degradation of food product due to light, processing, and exposure to some chemicals. The yellowness index can be estimated using the following expression [26]:

$$\text{Yellowness index, YI} = \frac{142.86 \times b^*}{L^*}$$

2.9.3 Color Measurement Working Principle

The instrument used for measuring the color is known as colorimeter/chromameter. There are two principles, which are commonly employed for the measurement of colors of food samples.

2.9.3.1 Colorimeter with 8° Illumination

The portable colorimeter generally uses 8° illumination (8°/D) sphere principle. The sphere is illuminated by the incident light, which undergoes through refraction and reflection and becomes uniform. The detector is placed at an angle of 8° from the center axis to receive the reflected light from the sample. The integrating sphere is an integral part of the colorimeter and affects the accuracy of color measurement. A good-quality integrating sphere assures the accuracy as well as lower maintenance of the instrument (Fig. 2.34). The equipment may have 2° or 10° viewing angle according to the standard or supplementary standard [20].

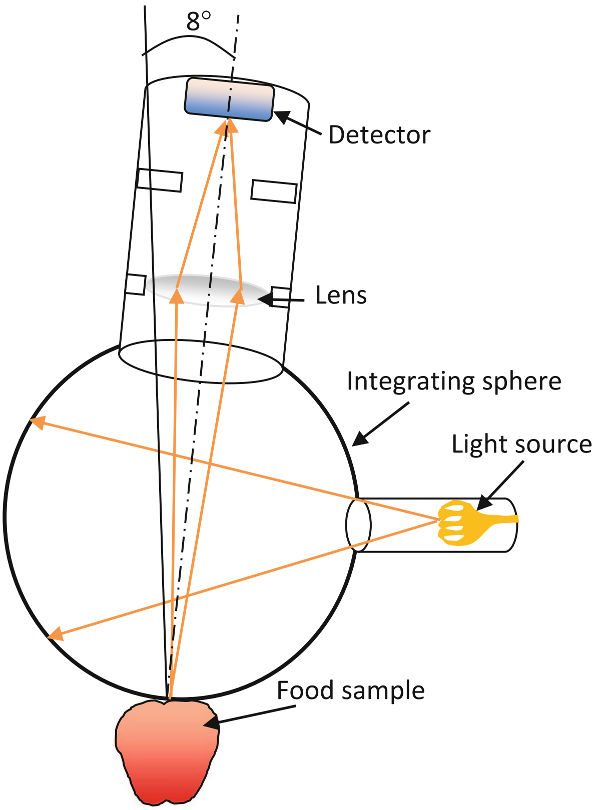


Fig. 2.34 Colorimeter with 8° illumination

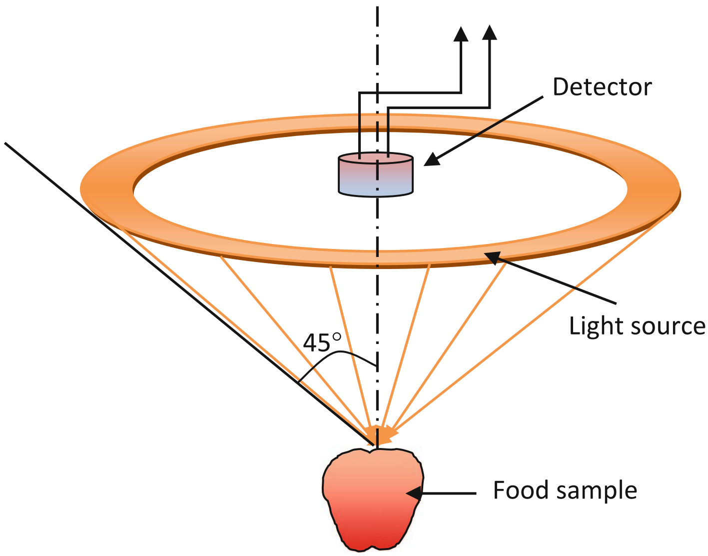


Fig. 2.35 Colorimeter with 45° annular ring illumination

2.9.3.2 Colorimeter with 45° Annular Illumination

The colorimeter can have 45° annular ring illumination (45°/0) as the light source illuminates the energy from all directions and makes an angle 45° to the sample. The reflected light from the sample is captured by the detector. The detector is kept at the central axis, which receives the reflected rays (Fig. 2.35). The received spectral light provides signal to the electronic circuit for processing and displays CIELAB L^*, a^*, and b^* values, which can also be stored using data logger or attached computer.

2.10 Thermal Properties

Thermal properties of food play an important role in various food processing operations. Either the heat is given to the food material in processing operations like drying, evaporation, thermal processing, cooking, and extrusion, or heat is extracted from the food material in refrigeration or freezing. A number of thermal properties exist, which affect the rate of heat transfer. However, thermal conductivity, specific heat, and thermal diffusivity are the most important properties, which are used in designing of various thermal processing operation and storage structures.

2.10.1 Thermal Conductivity

The flow of heat in a food material through conduction is dependent on the thermal conductivity of food. Generally, the metals show higher thermal conductivity due to

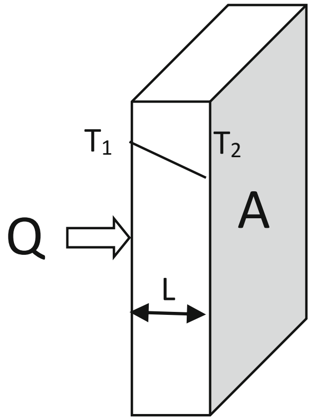


Fig. 2.36 Heat transfer through flat surface

the presence of free-moving electrons, which vibrate faster and freely flow through the metal lattices to transfer the energy. That is why, the metals are utilized in the manufacturing of heat transfer surfaces in a variety of thermal processing equipment. Non-metals have lower thermal conductivity, which are also used to act as insulators in the manufacturing of cabinets for refrigeration units and ovens to minimize the loss of energy.

Fourier's law of heat transfer is applied to estimate the heat transfer through conduction, which is also utilized to estimate the thermal conductivity of material in steady-state condition.

$$Q = -k \times A \times \frac{T_2 - T_1}{L}$$

where Q is the rate of heat transfer (W), k thermal conductivity (W/mK), A cross-sectional area normal to the direction of flow, m^2, T_1 temperature of the surface on the higher side (K), T_2 temperature of the surface on the lower side (K), and L thickness of the material along the flow of heat (Fig. 2.36).

The negative sign indicates the direction of heat flow as heat always moves from higher temperature to lower temperature.

2.10.1.1 Prediction of Thermal Conductivity Using Compositional Criteria

The structure and composition of the foods affects the thermal conductivity of food. It can be estimated using the water content of the food using the following expression [27]:

$$k = k_w X_w + k_s (1 - X_w)$$

where X_w is the mass fraction of water and k_w and k_s are the thermal conductivity of water (0.591–0.598 W/m K at 20 °C) and solids (approximately 0.259 W/m K), respectively.

Table 2.4 Constants for the determination of thermal conductivity of different components in food [28, 29]

S. no.	Component	a_k	b_k	c_k
1.	Water	-6.7306×10^{-6}	0.0017625	0.57109
2.	Ice	1.0154×10^{-4}	−0.0062489	2.2196
3.	Protein	-2.7178×10^{-6}	0.0011958	0.1788
4.	Fat	-1.7749×10^{-7}	−0.0027604	0.1807
5.	Carbohydrate	-4.3312×10^{-6}	0.0013874	0.2014
6.	Fiber	-3.1683×10^{-6}	0.0012497	0.1833
7.	Ash	-2.9069×10^{-6}	0.001401	0.3296

The composition of food material in terms of carbohydrate, protein, fat, fiber, ash, and water is used for the thermal conductivity estimation of food. It can be estimated for the different components/constituents on the basis of temperature using the following expression in the range of −40 to 150 °C [28]:

$$k = a_k t^2 + b_k\, t + c_k$$

where k is the thermal conductivity of different components (W/mK), t is the temperature of food material (°C); and a_k, b_k, and c_k are the constants based on different components (Table 2.4).

The composition of known and popular foods can be estimated using the proximate composition from Food Data Central or Other Standards [30]. The thermal conductivity is usually estimated according to the mass fractions of material using the following expression:

$$k = X_w k_w + X_i k_i + X_p k_p + X_f k_f + X_c k_c + X_{fi} k_{fi} + X_a k_a$$

where X and k represent the fraction of components and thermal conductivity of components and subscripts w, i, p, f, c, fi, and a represent water, ice, protein, fat, carbohydrate, fiber, and ash, respectively.

Q3. If the food grain contains various constituents according to the following table, (1) estimate the thermal conductivity of grain at 20 °C. (2) If the food grain is heated from 20 °C to 60 °C, estimate the increase in the thermal conductivity of grain. Consider the loss of moisture during heating as negligible.

Component	Water	Protein	Fat	Carbohydrate	Ash
Percentage (%)	13.1	12.61	1.54	71.18	1.57

Ans. The thermal conductivity of components at 20 °C is calculated as:

$$k = a_k t^2 + b_k\, t + c_k$$

$$k = a_k \times 20^2 + b_k \times 20 + c_k$$

Putting the values of constants from table:

$$k_w = -6.7306 \text{ x } 10^{-6} \times 20^2 + 0.0017625 \times 20 + 0.57109 = 6.0365 \times 10^{-1}$$

$$k_p = -2.7178 \text{ x } 10^{-6} \times 20^2 + 0.0011958 \times 20 + 0.1788 = 2.0163 \times 10^{-1}$$

$$k_f = -1.7749 \text{ x } 10^{-7} \times 20^2 - 0.0027604 \times 20 + 0.1807 = 1.2452 \times 10^{-1}$$

$$k_C = 4.3312 \text{ x } 10^{-6} \times 20^2 + 0.0013874 \times 20 + 0.2014 = 2.2742 \times 10^{-1}$$

$$k_a = -2.9069 \text{ x } 10^{-6} \times 20^2 + 0.001401 \times 20 + 0.3296 = 3.5646 \times 10^{-1}$$

The thermal conductivity of the food at 20 °C is calculated as:

$$k = 0.131 \times k_w + 0.1261 \times k_p + 0.0154 \times k_f + 0.7118 \times k_c + 0.0157 \times k_a$$

S. no.	Component	Temp. (°C)	k at 20 °C (W/mK)	Proportion (%)	k (W/mK)
(1)	(2)	(3)	(4)	(5)	(6) = (4) × [(5)/100]
1	Water	20	6.0365×10^{-1}	13.1	7.9078×10^{-2}
2	Ice		–	–	–
3	Protein		2.0163×10^{-1}	12.61	2.5425×10^{-2}
4	Fat		1.2542×10^{-1}	1.54	1.9315×10^{-3}
5	Carbohydrate		2.2742×10^{-1}	71.18	1.6187×10^{-1}
6	Fiber		–	–	–
7	Ash		3.5646×10^{-1}	1.57	5.5964×10^{-3}
Total				100.00	0.273905488

The thermal conductivity of the grain at 20 °C is 0.273905488 ≈ 0.274 w/mK. Similarly, conductivity of various components is calculated for 60 °C as:

$$k_w = -6.7306 \text{ x } 10^{-6} \times 60^2 + 0.0017625 \times 60 + 0.57109 = 6.5261 \times 10^{-1}$$

$$k_p = -2.7178 \text{ x } 10^{-6} \times 60^2 + 0.0011958 \times 60 + 0.1788 = 2.4076 \times 10^{-1}$$

$$k_f = -1.7749 \text{ x } 10^{-7} \times 60^2 - 0.0027604 \times 60 + 0.1807 = 1.4437 \times 10^{-2}$$

$$k_C = 4.3312 \text{ x } 10^{-6} \times 60^2 + 0.0013874 \times 60 + 0.2014 = 2.6905 \times 10^{-1}$$

$$k_a = -2.9069 \text{ x } 10^{-6} \times 60^2 + 0.001401 \times 60 + 0.3296 = 4.0320 \times 10^{-1}$$

Similarly, the thermal conductivity of the grain at 60 °C is estimated as 0.3139157 ≈ 0.314 w/mK. Therefore, the increase in thermal conductivity = 0.314 − 0.274 = 0.04 w/mK.

It can be noted from the estimated value that the thermal conductivity increases for water, protein, carbohydrate, and ash per unit mass of individual constituent with the increase in temperature. Generally, increase in thermal conductivity in cereals is observed with the increase in temperature due to the predominating presence of carbohydrates, whereas the thermal conductivity of fat decreases with the increase in temperature. The decrease in the thermal conductivity of edible oil with the increase in temperature has been reported [31].

2.10.1.2 Determination of Thermal Conductivity Under Steady State

The thermal conductivity determination under steady state requires more time to determine to establish the equilibrium; however, the determination offers advantages of being simpler, higher precision, and ease of controlling environmental conditions. Some of the methods are discussed as follows.

Longitudinal Heat Flow Method

This method works on the principle of Fourier's law. It is suitable for the food materials, which can be kept in slab/slice form. A heat source is used to maintain the constant temperature of hot plate, while other cold plate is placed in a heat sink (Fig. 2.37). The electric power is switched on for heating the hot plate to maintain the higher temperature. The guard plates around the samples are placed to avoid lateral heat transfer. The temperatures of hot and cold plates are noted after maintaining the steady-state condition, i.e., temperature difference between both the plates $(T_1 - T_2)$

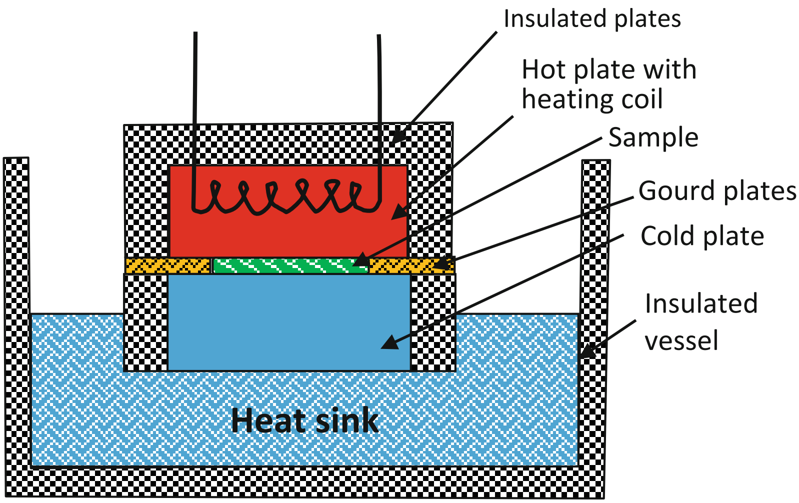


Fig. 2.37 Longitudinal heat flow apparatus

becomes constant. The following equation is used for the determination of thermal conductivity (k):

$$k = \frac{Q \times L}{A \times (T_1 - T_2)}$$

where Q, L, T_1, T_2, and A are the heat transfer rate (W), sample thickness (m) temperatures of hot and cold plates (°C), and cross-sectional area of sample (m^2). The heat transfer rate in terms of electrical energy is estimated by measuring the electricity consumption using voltmeter and ammeter display provided in the apparatus.

Radial Heat Flow Methods

Concentric Cylinder Method

It is suitable for liquid material, which is filled between two concentric cylinders. The outer cylinder is heated by heaters placed at the outer cylinder, and coolant flows through the inner cylinder (Fig. 2.38). The temperature is noted after establishing the steady-state condition (temperature difference between the surface of outer cylinder and inner surface of inner cylinder (T_1-T_2) becomes constant). The conductivity (k) can be estimated using the following expression:

$$k = \frac{Q \ \ln\left({r_2}/{r_1}\right)}{2\pi L(T_1 - T_2)}$$

where Q, r_1, r_2, T_1, T_2, and L are the heat transfer rate (W), outer cylinder radius (m), inner cylinder radius (m), temperatures of surface of outer cylinder and inner surface of inner cylinder (°C), and length of cylinder (m^2). The heat transfer rate in terms of

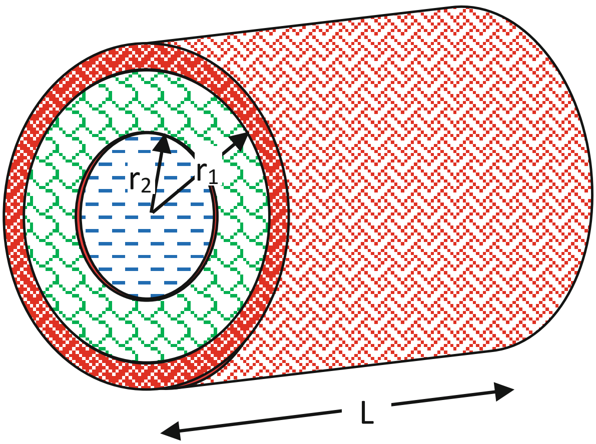


Fig. 2.38 Concentric cylinder apparatus

electrical energy is estimated by measuring electricity consumption using voltmeter and ammeter display provided in the apparatus.

The concentric cylinder with central heating source may also be used for the determination of thermal conductivity of sample by comparing with the standard sample of known thermal conductivity.

Sphere with Central Heating Source Method

It is used to measure the thermal conductivity of granular material. A central heating source is placed at the center of sphere, and the granular material is filled in the spherical cavity. The heat source is switched on till the steady state is maintained. The temperature difference between the inner and outer surface of the sample (T_1-T_2) becomes constant at steady state and is noted for the estimation of thermal conductivity (k, W/mK) using the following expression:

$$k = \frac{Q\left(\frac{1}{r_1} - \frac{1}{r_2}\right)}{4\pi(T_1 - T_2)}$$

where Q, r_1, r_2, T_1, and T_2 are the heat transfer rate (W), outer central heater radius (m), outer sphere radius (m), and temperatures of surface of sample at inner surface and outer surface (°C).

2.10.1.3 Determination of Thermal Conductivity Under Unsteady State

The thermal conductivity determination of a food material under unsteady state requires less time in comparison to steady-state methods. Some of these methods are thermal conductivity probe method, point heat source method, comparative method, etc.

Thermal Conductivity Probe Method

The thermal conductivity probe is popular in estimating thermal conductivity in unsteady state. It requires small sample and takes less time. The probe is made up of stainless steel, which has a heating wire inside to heat the probe (Fig. 2.39). The heat generated during the heating of the probe is transferred to grains surrounding the probe. A thermocouple is placed inside the probe, which is used to measure the temperature at different times.

The thermal conductivity can be expressed as:

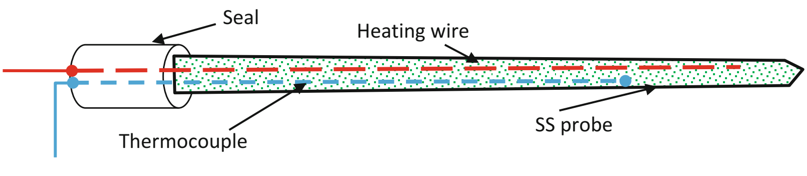


Fig. 2.39 Thermal conductivity probe

$$\Delta T = \frac{Q \times \ln t_2/t_1}{4\pi k} = \frac{\left(I^2 \times R\right) \ln t_2/t_1}{4\pi k}$$

The expression can be written as:

$$k = \frac{2.3 \times I^2 \times R \log t_2/t_1}{4\pi \Delta T}$$

where I, R, t_1, t_2, and ΔT are the electrical current (A), electrical resistance of wire (Ω/m), heating time at first observation (s), heating time at second observation (s), and temperature difference between the observations (°C).

2.10.2 Specific Heat

It is defined as the amount of energy required to raise the temperature by 1 °C of 1 kg of material. The expression of heat transfer during the increase in temperature is expressed as:

$$Q = m\, C_p \Delta T$$

or

$$C_p = \frac{Q}{m\Delta T}$$

where Q is the amount of energy required (J), C_p specific heat (J/kg °C), m mass of the material (kg), and ΔT temperature difference.

The specific heat of food mainly depends upon the moisture content. The specific heat of the food material can be estimated using the following expression [32]:

$$Cp = 837.36 + 3349\, X_w$$

where C_p is the specific heat (J/kgK) and X_w is the mass fraction of water.

Similar approach for considering the composition of food material in terms of water, protein, fat, carbohydrate, fiber, and ash is used for the estimation of specific heat. The specific heat of different components on the basis of temperature can be estimated using the following expression in the temperature range of −40 to 150 °C [33]:

$$C = a_c t^2 + b_c\, t + c_c$$

where C is the specific heat of different components (J/kg K); t is the temperature of food material (°C), and a_c, b_c, and c_c are the constants based on different components (Table 2.5).

Table 2.5 Constants for the determination of specific heat of different components in food [28]

S. no.	Component	a_c	b_c	c_c
1.	Water[a]	9.9516×10^{-1}	−5.3062	4.0817×10^3
	Water[b]	5.4731×10^{-3}	−0.090864	4.1762×10^3
2.	Ice	0.00	6.0769	2.0623×10^3
3.	Protein	-1.3129×10^{-3}	1.2089	2.0082×10^3
4.	Fat	-4.8008×10^{-3}	1.4733	1.9842×10^3
5.	Carbohydrate	-5.9399×10^{-3}	1.9625	1.5488×10^3
6.	Fiber	-4.6509×10^{-3}	1.8306	1.8459×10^3
7.	Ash	-3.6817×10^{-3}	1.8896	1.0926×10^3

[a] For temperature range of –40 to 0 °C
[b] For temperature range of 0 to 150 °C

The composition of food material is estimated using the proximate analysis, or composition of standard materials can be obtained from FoodData Central or other standards [30]. The specific heat of food material is estimated according to the fractions of material using the following expression:

$$Cp = X_w C_w + X_i C_i + X_p C_p + X_f C_f + X_c C_c + X_{fi} C_{fi} + X_a C_a$$

where X and C represent fraction of components and specific heat of components and subscripts w, i, p, f, c, fi, and a represent water, ice, protein, fat, carbohydrate, fiber, and ash, respectively.

Q4. If the food grain contains various constituents according to the following table, (1) estimate the specific heat of grain at 20 °C. (2) If the food grain is heated from 20 °C to 60 °C, estimate the increase in specific heat of grain. Consider the loss of moisture during heating as negligible.

Component	Water	Protein	Fat	Carbohydrate	Ash
Percentage (%)	13.1	12.61	1.54	71.18	1.57

Ans. The specific heat of components at 20 °C is calculated as:

$$C = a_c t^2 + b_c\, t + c_c$$

$$C = a_c \times 20^2 + b_c \times 20 + c_c$$

Putting the values of constants from table:

$$C_w = 5.4731 \times 10^{-3} \times 20^2 - 0.090864 \times 20 + 4.1762 \times 10^3 = 4.1766 \times 10^3$$

$$C_p = -1.3129 \ \text{x}\ 10^{-3} \times 20^2 + 1.2089 \times 20 + 2.0082 \times 10^3 = 2.0319 \times 10^3$$

$$C_f = -4.8008 \ \text{x}\ 10^{-3} \times 20^2 + 1.4733 \times 20 + 1.9842 \times 10^3 = 2.0117 \times 10^3$$

$$C_C = -5.9399 \text{ x } 10^{-3} \times 20^2 + 1.9625 \times 20 + 1.5488 \times 10^3 = 1.5857 \times 10^3$$

$$C_a = -3.6817 \text{ x } 10^{-3} \times 20^2 + 1.8896 \times 20 + 1.0926 \times 10^3 = 1.1289 \times 10^3$$

The specific heat of the food at 20 °C is calculated as:

$$C = 0.131 \times C_w + 0.1261 \times C_p + 0.0154 \times C_f + 0.7118 \times C_c + 0.0157 \times C_a$$

S. no.	Component	Temp. (°C)	C	Proportion (%)	Specific heat (J/kg K)
(1)	(2)	(3)	(4)	(5)	(6) = (4) × [(5)/100]
1	Water[a]	20	4.3736×10^3	–	–
	Water[b]		4.1766×10^3	13.1	5.4713×10^2
2	Ice		2.1838×10^3	–	–
3	Protein		2.0319×10^3	12.61	2.5622×10^2
4	Fat		2.0117×10^3	1.54	3.0981×10^1
5	Carbohydrate		1.5857×10^3	71.18	1.1287×10^3
6	Fiber		1.8807×10^3	–	–
7	Ash		1.1289×10^3	1.57	1.7724×10^1
Total				100.00	1980.735268

[a] For temperature range −40 to 0 °C
[b] For temperature range 0 to 150 °C

The specific heat of grain at 20 °C is 1980.73528 ≈ 1980.74 J/kg K = 1.98 kJ/kg K.

Similar to the specific heat of grain at 20 °C, specific heat is calculated at 60 °C as:

$$Cp = 0.131 \times C_w + 0.1261 \times C_p + 0.0154 \times C_f + 0.7118 \times C_c + 0.0157 \times C_a$$

Similarly, the values obtained for C_w, C_p, C_f, C_c, and C_a at 60 °C are 4.1905×10^3, 2.0760×10^3, 2.0553×10^3, 1.6452×10^3, and 1.1927×10^3, respectively.

The specific heat of the grain at 60 °C is 2032.140678 ≈ 2032.14 J/kg K = 2.03 kJ/kg K. Therefore, the increase in specific heat = 2.03 − 1.98 = 0.05 kJ/kg K.

2.10.2.1 Measurement of Specific Heat

In this, the known quantity of sample (m_2) is kept in a cup (m_1). The temperature of the cup along with the sample is raised by several degrees (T_i). Thereafter, the known quantity (m_3) of water maintained at specific lower temperature (T_w) is added in the

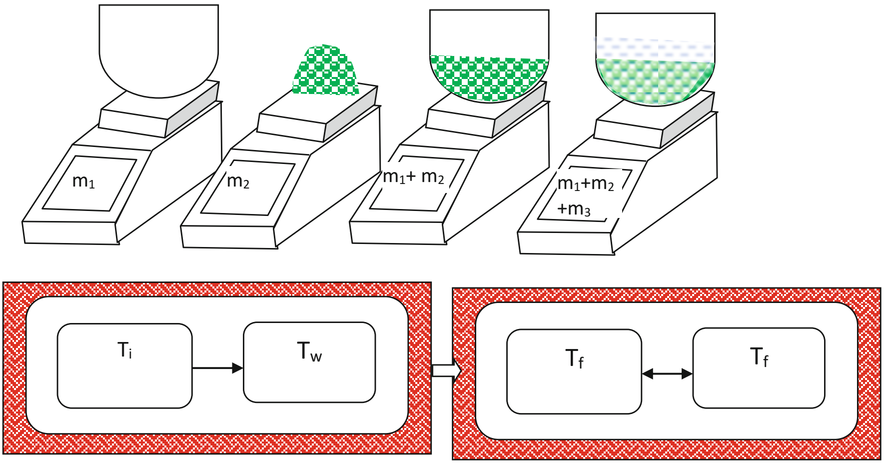


Fig. 2.40 Determination of specific heat. m_1 mass of the cup (kg), C_{p1} specific heat of the cup (J/kg K), m_2 mass of food sample (kg), C_{p2} specific heat of food sample (J/kg K), m_3 mass of water (kg), C_{p3} specific heat of water (J/kg K), T_i initial temperature of sample and cup (K), T_w initial temperature of water (K), T_f final temperature of sample, cup, and water (K)

cup and kept in the insulated surroundings for negligible heat loss (Fig. 2.40). At equilibrium, the cup is filled with sample, and water reaches at a final temperature (T_f). The final temperature of sample is noted, and specific heat of material is estimated using the energy balance.

The energy balance equation can be written as:

$$m_1 c_{p1}\left(T_i - T_f\right) + m_2 c_{p2}\left(T_i - T_f\right) = m_3 c_{p3}\left(T_f - T_w\right)$$

$$c_{p2} = \frac{m_3 c_{p3}\left(T_f - T_w\right) - m_1 c_{p1}\left(T_i - T_f\right)}{m_2\left(T_i - T_f\right)}$$

2.10.3 Thermal Diffusivity

Thermal diffusivity is a measure of the ability of material to conduct heat. It is a material specific to characterize unsteady-state heat conduction. It is estimated by dividing the thermal conductivity by the product of density and specific heat. The high value of diffusivity indicates higher heat transfer rates.

$$\alpha = \frac{k}{\rho\, C_p}$$

where α is the thermal diffusivity of different components (m^2/s), k thermal conductivity (W/mK), ρ density (kg/m^3); and C_p specific heat of the sample (J/kgK).

Table 2.6 Constants for the determination of thermal diffusivity of different components in food [33]

S. no.	Component	a_α	b_α	c_α
1.	Water	-2.4022×10^{-12}	6.2477×10^{-10}	1.3168×10^{-7}
2.	Ice	9.5037×10^{-11}	-6.0833×10^{-9}	1.1756×10^{-6}
3.	Protein	-1.4646×10^{-12}	4.7578×10^{-10}	6.8714×10^{-8}
4.	Fat	-3.8286×10^{-14}	-1.2569×10^{-11}	9.8777×10^{-8}
5.	Carbohydrate	-2.3218×10^{-12}	5.3052×10^{-10}	8.0842×10^{-8}
6.	Fiber	-2.2202×10^{-12}	5.1902×10^{-10}	7.3976×10^{-8}
7.	Ash	-1.2244×10^{-12}	3.7321×10^{-10}	1.2461×10^{-7}

The thermal diffusivity of food can be determined by considering the composition of food material in terms of carbohydrate, protein, fat, fiber, ash, and water. The thermal diffusivity of different components is estimated using the following expression in the temperature range of −40 to 150 °C [33]:

$$\propto = a_\propto t^2 + b_\propto t + c_\propto$$

where α is the thermal diffusivity of different components (m^2/s), t is the temperature of food material (°C), and a_α, b_α, and c_α are the constants based on different components (Table 2.6).

The composition of food material is estimated using the proximate analysis, or the composition of standard materials can be obtained from FoodData Central or other standards [30]. It can be estimated according to the fractions of the material using the following expression:

$$\propto = X_w \propto_w + X_i \propto_i + X_p \propto_p + X_f \propto_f + X_c \propto_c + X_{fi} \propto_{fi} + X_a \propto_a$$

where X and α represent the fraction of components and thermal diffusivity of components and subscripts w, i, p, f, c, fi, and a represent water, ice, protein, fat, carbohydrate, fiber, and ash, respectively.

2.10.4 Differential Scanning Calorimeter (DSC)

The differential scanning calorimeter is a prevalent method to determine the specific heat of samples. For measuring the specific heat, a cylindrical or similar shaped sample is kept in a sample pan, while the other end is connected to a sink maintained at constant temperature. The sample is heated at a specific rate. The heat flow is observed with respect to change in temperature, which is proportional to the specific heat. The thermal scan for an empty pan is done to obtain a base line. Again, thermal scans for standard and food sample are performed. The deflection of food material and sample from base line is estimated from the thermogram, which is proportional to the amount of energy needed to maintain the temperature. The following equation can be used to estimate the specific heat of the sample:

$$C_p = \frac{d \times m'}{d' \times m} \times C'_p$$

where C_p and $C_p{}'$ are the specific heat of samples and standard, d and d' are the deflection value (W) of sample and standard in thermogram, and m and m' are the mass of sample and standards, respectively. For measuring thermal conductivity, the sample gets heated for a specific time and temperature. The difference in heat flow can be obtained from the thermogram, and thermal conductivity is calculated based on Fourier's equation.

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Material Handling and Transportation Devices

3

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Abstract

In this chapter different material handling and transportation devices are discussed. The principle, importance, and selection criteria of material handling and transportation devices are also explained. Conveyor systems are used to move a large quantity of materials at a quicker pace and lower cost than manual labor. Conveyors generally utilized for transportation of solid and semi-solid materials can be powerless or powered conveyors and both have their own pros and cons. Cranes, hoist, and trucks are also utilized to transport material required for movement in agriculture sector and food processing industries. For fluid transportation different types of pumps are used and are broadly classified under two categories, i.e., positive displacement pump (reciprocating pumps and rotary pumps) and centrifugal pump. Other liquid handling devices, viz. valves, pipes, and pipes fitting and joint are discussed with schematic diagrams and figures. During transportation of solid, semi-solid, or liquid material the hygienic considerations for proper material handling operation are of utmost importance and should be given proper consideration to avoid contamination issues. The chapter presents the overall picture of the material handling and

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transportation systems used in food processing operations with schematic diagrams.

Keywords

Material handling devices · Powerless conveyors · Powered conveyors · Fluids transportation · Valves · Pipes and pipe fitting joints · Hygienic considerations

3.1 Introduction

3.1.1 Principles of Material Handling Devices

Conveyor systems are used to move a large quantity of materials at a quicker pace and lower cost than manual labor. In a food manufacturing unit, about 30% of its labor is required for material handling [1]. Conveyors can be installed conveniently anywhere to move material of all shapes, sizes, and weights. Conveyors can be used in a variety of ways in a food processing plant such as:

- Transporting raw materials into silos, bins, and other storage devices.
- Moving out the same raw materials out of storage devices for further processing into the industries.
- To transport the finished product from the production line to the packaging line.
- Finally, to move packaged products from the packaging line to the shipment area.

There are many types of conveyors available commercially, which are used in the manufacturing process. About 80 different types of conveyor system have been described by the Conveyor Equipment Manufacturers Association (CEMA), situated in Naples, Florida (www.cemanet.org) [2]. CEMA embodies American manufacturers and designers and provides engineering standards as well as specifications required for design aspects and safety of different types of the conveyor systems.

3.1.2 Importance of Material Handling Devices

Efficient material handling is related to five elements: movement, time, place, quantity, and space. Effective material handling is movement in the most efficient way at the correct place in the required quantity with the maximum economy of space [3].

The advantages of material handling and transportation (solids and fluids) are uncountable in food processing. The handling methods are required in view of bulk transport of the materials and also to ensure hygiene. The advantages of the handling devices may:

- Help to organize your products and materials.
- Transport material for packaging and processing.
- Provide better utilization of labor, equipment, and space.
- Reduce handling costs.
- Improve working condition and operational errors.
- Improve customer service.
- Minimize the distance moved, by adopting the shortest routes.
- Improve the utilization of men, machines, and storage space.
- Reduce the material wastage and damage.
- Improve control and rotation of stock.

This results in higher productivity, improved product quality, reduced damage, and errors.

3.1.3 Selection Criteria for Conveyor Systems

The purchaser should review the following key points for the selection of the conveying system prior to procurement:

- Type of product, material to be conveyed. The properties such as bulk density, particle size, terminal velocity, abrasiveness, moisture content, fluidity, dustiness, flammability, explosiveness, the flowability of the material should be taken into consideration.
- Type of material to be handled (liquid, semi-solid, and solid)
- Source from which material is being transported (Such as silos, bulk bag, etc.)
- Place where the material to be moved (such as a mixer, feeder, mill, etc.)
- Orientation at which material to be conveyed (horizontally, vertically, the route with bends)
- The amount of material to be conveyed per unit time, per unit area.
- To avoid handling damage, the material strength should be known (whether fragile, delicate, hard, etc.)
- Area for cleaning and maintenance of conveying systems.

3.2 Powerless Material Handling Devices

3.2.1 Gravity Conveyors

Gravity conveyor does not require any external power to operate, utilizes gravity force to transport materials in a downward direction. In an inclined runway, a gravity chute conveyor is used to move articles with the required weight to move downwards unassisted and is unpowered as shown in diagrammatic representation of top view of typical gravity roller conveyor in Fig. 3.1. This conveyor is multipurpose and cost-effective. It transports large amount of material quickly in a downward

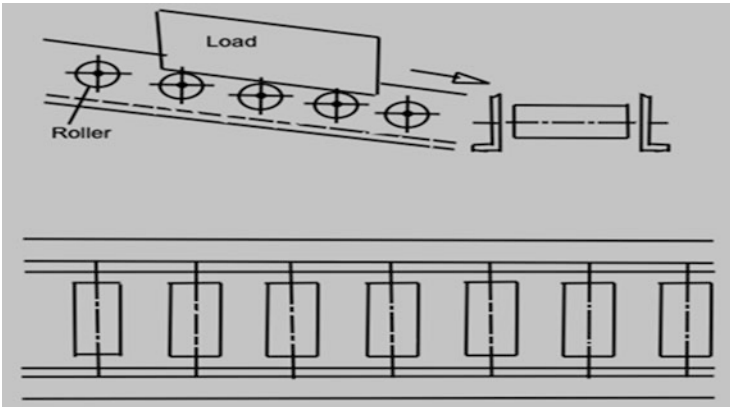


Fig. 3.1 Line diagram showing top and side view of typical gravity roller conveyor

direction with less efforts and expenses and mostly used in case of a material having a firm or flat surface at the bottom. It can be used where the natural flow of gravity is present and also over a level line where the movement of material can be accomplished by pushing and hence it can be utilized in both applications, i.e. fixed and portable.

3.2.2 Functions and Design Considerations

Gravity roller conveyors are used to divert spurs on automatic sorting lines, transfer lines between order packing, and dispatch areas to move picking bins and containers, etc. The optimum decline angle that suits the type and weight of the load being handled is the most important parameter for better efficiency of gravity roller conveyor. Load must be at rigid bases and their length should cover at least three carrying rollers as shown in Fig. 3.1. To decelerate and halt bins/boxes at the end of the decline, rollers can be replaced with a static brake plate, or electrically or pneumatically operated brakes [4].

3.2.3 Advantages

- Economical.
- No operational cost as it uses the natural flow of gravity for its operation.
- Ease of installation and environmentally friendly.
- Negligible maintenance requirement.
- Low operational noise levels.
- Complete systems possible with or without powered sections.

In comparison with motor-driven conveyor systems, a system using gravity roller conveyors is a highly efficient and energy saving alternative. Gravity roller conveyors can be integrated into high speed powered conveyor systems which can considerably reduce the project cost.

3.3 Powered Conveyors

3.3.1 Roller Conveyors

Roller conveyors design can be as a straight or curved. These power operated roller conveyors can be classified based on their driving mechanism. The following are the types of roller conveyor:

3.3.1.1 Belt Driven Roller Conveyors

These can be controlled via a programmable logic controller (PLC) for high flexibility and speed. Through the division into drives, the product is separated and transported easily The belt driven conveyor consist of power drive pulley to move the material in forward direction as shown in Fig. 3.2. Contact rollers are mounted over the drive belts to convey the material. This offers many advantages to transport and sorting applications in a limited space.

3.3.1.2 Toothed Belt Driven Roller Conveyors

Roller conveyors with toothed belt drive are appropriate for the transportation of boxes as shown in Fig. 3.3. Pressing the belt against the rollers and with single motor material can be transported to a large distance. These are well suited for on-off or transit transport due to modular design.

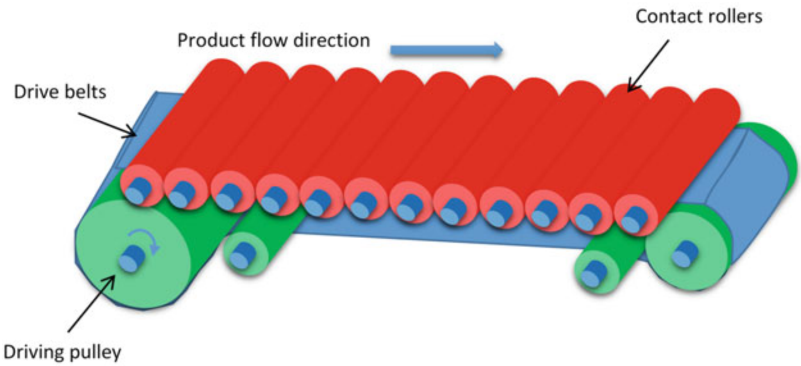


Fig. 3.2 Belt driven roller conveyors

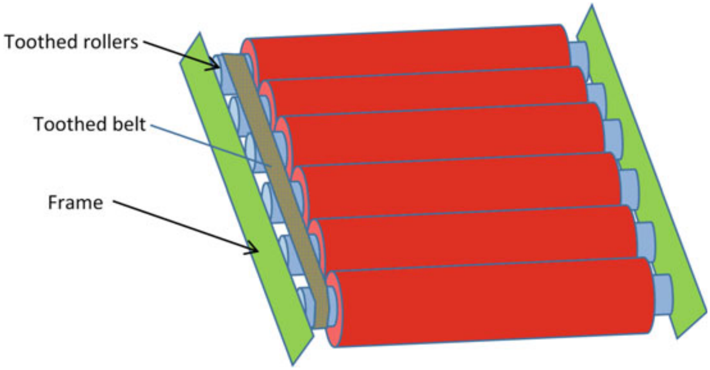


Fig. 3.3 Toothed belt driven roller conveyors

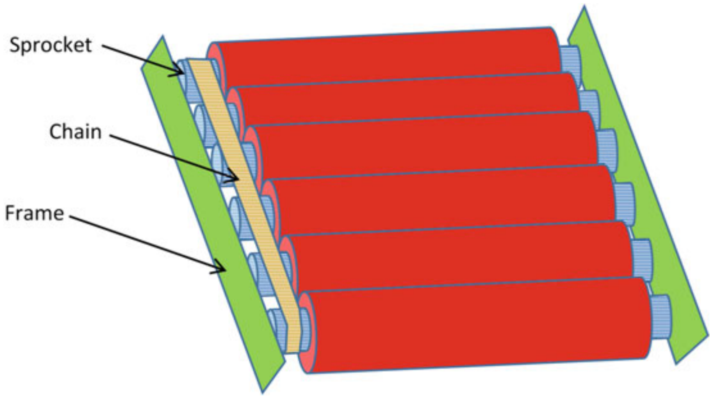


Fig. 3.4 Chain driven roller conveyors

3.3.1.3 Chain Driven Roller Conveyors

It is utilized in case of the transportation of heavy crates. To achieve sturdy construction mostly stainless steel is used but depends on the requirement as well (Fig. 3.4).

3.3.2 Belt Conveyor

It is an unending belt moving between two or more pulleys and the drive pulley is responsible for the continuous movement of the belt over the pulleys. The belt and its load may ride over an immobile flat surface, but usually, idlers are used to reduce friction, between the belt and flat surface and to increase the wrap contact area. Most belts are made from solid woven rubber and stitched. The drive pulley is typically equipped with motors to rotate the whole belt conveyor. Generally, three idlers set are typically used, one horizontal and two side idlers, which may be tilted at angles

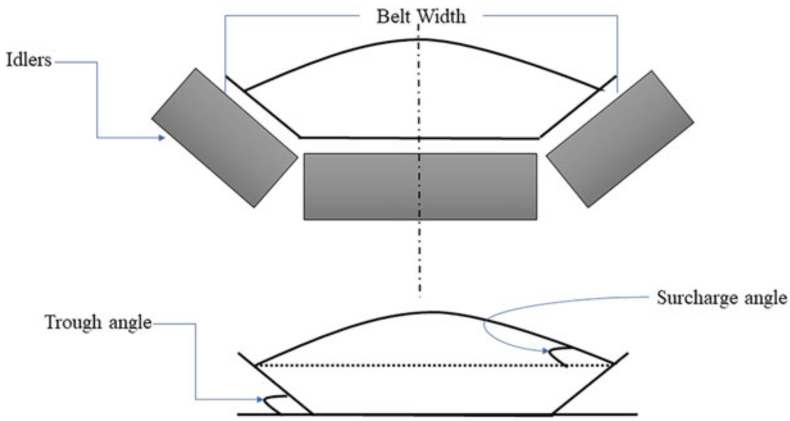


Fig. 3.5 Trough and Surcharge angle of belt conveyor

up to 45° to form a trough as shown in Fig. 3.5. Belt speed is an important parameter for transporting material, which can vary with variations of belt width.

It is an effective conveying system but a comparatively costly way of conveying material in the bulk. Due to the absence of relative motion between grain and belt surface, the grain damage is negligible, therefore widely utilized in conditioning and processing seed. It is also used in flour mills, feed processing mills, oil and fats mills, starch mills, mines, and chemicals, etc. Mostly belt conveyors are used for large conveying capacities and grains can be transported to a large distance in belt conveying system. One of the limitations is the low angle of elevation (below 15–20°) [5], although it can be overcome by equipping the belt with cups or ribs, which may be used to increase the elevation angle.

Capacity is directly proportional to the cross-sectional area and speed of the belt. The cross-sectional area depends upon the type of roller. Among the three rollers, the center rollers are kept horizontal whereas the remaining two are kept at an inclined position or trough angle (20° to 45° angle), as can be seen in Fig. 3.5. For paddy, it is found that a trough angle of 20° is well suited as surcharge angle of 20° is formed by paddy. For less capacity, flat belts may be used. Belt width is based on power requirements, speed of conveyor, and angle of inclination.

The power requirement for this conveyor is driven by the need [6]:

- To overcome the frictional forces related to the movement of the belt
- To adjust the speed as per the required capacity
- To lift the material if there is any elevation

The capacity of belt conveyor can be calculated using the following equation:

$$\text{Capacity}\left(\frac{\text{m}^3}{\text{h}}\right) = \text{Area of crosssection}\left(\text{m}^2\right) \times \text{belt speed}\left(\frac{\text{m}}{\text{min}}\right) \times 60 \tag{3.1}$$

Horsepower (hp) requirement for belt conveyor

$$\text{hp} = \text{Capacity of belt coveyor}\left(\frac{\text{t}}{\text{h}}\right) \times \frac{0.48 + 0.01\text{L}}{100} \tag{3.2}$$

where L is the length of the belt conveyor.

Example 1 What will be the horsepower required for operating a belt conveyor whose capacity is 80 t/h. and its length is 120 m.

Solution:

$$\text{Belt conveyor capacity} = 80\ \text{t/h}$$

$$\text{Length} = 120\ \text{m}$$

Therefore,

$$\text{hp} = \text{Capacity of belt coveyor}\left(\frac{\text{t}}{\text{h}}\right) \times \frac{0.48 + 0.01\text{L}}{100}$$

$$\text{hp} = 80\left(\frac{\text{t}}{\text{h}}\right) \times \frac{0.48 + 0.01 \times 120\ \text{m}}{100}$$

$$\text{hp} = 1.344.$$

3.3.3 Chain Conveyors

These conveyors are durable, sturdy, rugged, and utilized to carry the products along the process line. It can be used to transport heavy material that could not be moved over the roller conveyor. Most commonly utilized to move heavy racks, boxes, pallets, big containers, and any article with a sturdy or flat bottom surface. These systems can be seen in numerous warehouses and distribution centers where it is needed to handle heavy and large items.

3.3.4 Vibratory Conveyor

For conveying the particulate and granular ingredients, vibratory conveyor system is most effective and efficient. It has wide applications in the manufacturing process involving the particulate material [7]. In vibratory conveyor, the process of material conveyance takes place due to recurrent micro-displacements of particles.

True natural frequency conveyors are equipped with mechanical drives while the electromagnetic conveyors are equipped with electromagnetic drives. Frame-mounted drives and spring arm assemblies are used to dispense energy to the frequency and electromagnetic conveyors, which produce a diagonal, harmonic motion that results in the forward movement of the product. Mechanical drives are used in traditional vibratory conveyors which generates a high amplitude, low-frequency movement. On the other hand, electromagnetic shakers at higher frequencies generate lower conveying pan amplitudes, which make them ideal for a wide variety of products.

Vibratory conveyors are naturally cleaner and are made of stainless steel which remains in contact with products as compared to belt conveyors. The latest vibratory shaker with a drive system requires low maintenance. Specific applications of vibratory conveyors are given below:

- For dewatering purposes, as shaking may cause loosening the bond between surface moisture and agricultural product such as potato, green beans, carrots, leafy greens, apples, and guava, etc.
- For sizing purposes of specific produce. A series of sieves with different sizes can be fitted from top to bottom and different size material can be collected from each level.
- For hand sorting of a wide range of products such as grapes in the wine production line, apple in the juice production line, etc. for a thorough inspection.
- For removal of dust, husk and other impurities from grains and blower can be attached to remove dust efficiently.

A vibratory conveyor is useful, where product orientation is important such as feeding to cutter/slicer which ultimately improves the effectiveness of the operation.

3.3.4.1 Conveying Principles

Sliding A crankshaft mechanism is used to move the deck horizontally with asymmetric forward and backward motions. Along with the deck, the trough surface also moves horizontally with a product that always remains in contact with the surface and is conveyed forward relative to the deck by a stick-slip drag.

Throwing During conveying, when vertical component of acceleration is higher than gravity force then the material is forced to perform ballistic flight as the product loses contact with the surface.

Ratcheting In this new transport mechanism, granular particulates can be conveyed horizontally with the vertical vibratory system.

3.3.4.2 Design Limitations

- It is not suitable for a wide range of materials to be transported.
- It is not a positive type of conveyor; conveying speed may vary with the product type.

- Limitation in the degree of slope for conveying.
- The requirement of a solid foundation, supporting structure, is required for maintaining the unbalanced forces.
- Limitation in length of conveyor per drive.

3.3.5 Pneumatic Conveying

In a pneumatic conveying system, dry bulk materials or powders are transported by using ambient air from one point to another. Transportation of products is due to the collective force of pressure and the airflow in an enclosed conveying pipeline [8]. Positive displacement blowers or vacuum pumps are used to generate pressure and airflow. Therefore, the capacity and distance to be conveyed can be adjusted by manipulating the pressure differential and airflow. Pneumatic conveyors are utilized in different manufacturing plants because of the effectiveness and to ensure that materials are transported safely.

These systems are reasonable and economical as compared to other mechanical systems. As this conveyor works in an enclosed loop, it protects conveyed material from insects, rodents, and other foreign matters. The pneumatic conveying systems can be classified as a dilute phase and dense phase conveying systems. In both types of systems, material can be conveyed either by pressure or a vacuum.

3.3.5.1 Dense Phase Pneumatic Conveying Technique

In this technique, the bulk material to be transported is not generally suspended in the air. The material can be transported by either pushing (pressure) or pulling (vacuum) particles. In dense phase conveying, the materials are transferred at low velocity and high pressure. According to the operating principle, it is further classified into two main types of dense phase conveying technique, which are described below:

Dense Phase Pressure Conveying

It can be used to convey rough-surfaced and fragile materials at extremely low speeds over the long distances. The materials commonly conveyed by this method are candies, cereal, cocoa beans, and glass particles. Firstly, the material is loaded into a pressure vessel. Once the vessel is filled, air inlet valve and material vent are closed. With the help of a blower, compressed air is pushed into the vessel. This compressed air pushes the material out from the vessel into the conveying line to the desired place. Once all the material in the vessel and line is conveyed completely, the cycle/process can be started again. To boost the conveying, the jets or air injectors can be fixed over the length of the conveying line as shown in Fig. 3.6.

Dense Phase Vacuum Conveying (DPVC)

It can be used to convey rough-surfaced and fragile materials at low speed over a short distance. DPVC is commonly used to unload materials in a fluidized state and the material is transported by vacuum. The vacuum pump is used to create a vacuum, which sucks the material from the source and discharge to the destination.

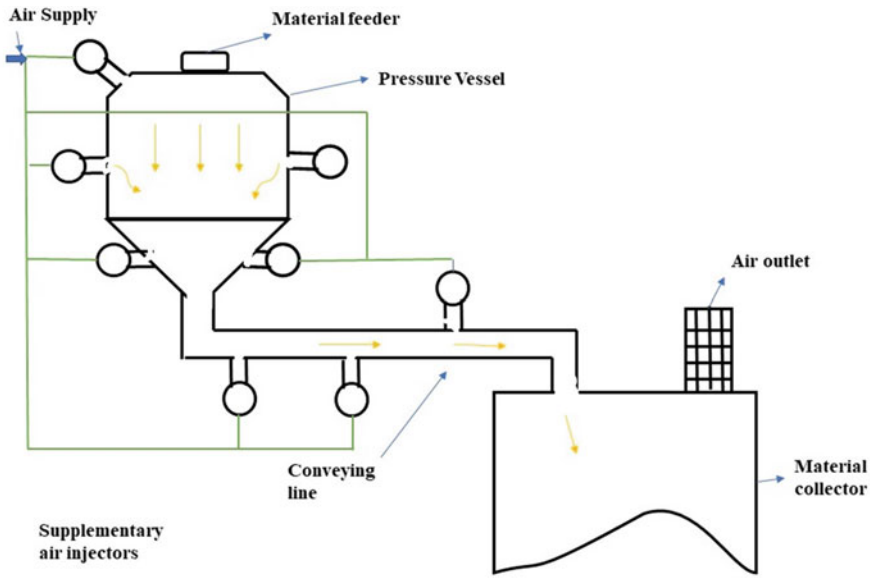


Fig. 3.6 Dense Phase

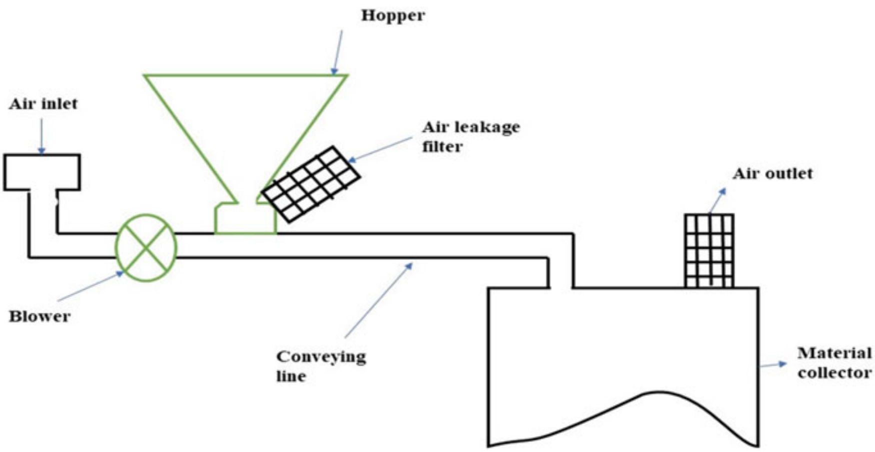


Fig. 3.7 Dilute phase

3.3.5.2 Dilute Phase Pneumatic Conveying

In this technique, the bulk material to be transported is generally suspended in the air (Fig. 3.7). The material can be transported by either pushing (pressure) or pulling (vacuum) particles. In dilute phase conveying, materials are transferred at high velocity and low pressure. According to the operating principle, it can be further classified into the following two main types of dilute phase conveying techniques.

Dilute Phase Pressure Conveying

It is generally used for dry materials, which are nonabrasive and resilient with a low bulk density over long distances. Plastic grains, sugar, and flour are a few examples of the materials that can be conveyed by this method. At the start of the system, a positive displacement blower is fixed which supplies low-pressure air in a high volume. Next to the blower, the material is feed from the feeder. As the materials enter into the line from the feeder, the blower pushes and suspends the particles from where they are conveyed to the desired place as shown in Fig. 3.7.

Dilute Phase Vacuum Conveying (DPVC)

It can be used to convey rough-surfaced and fragile materials over long distances at high speed. DPVC is generally used to unload materials in a fluidized state. It can be used to convey materials from rail cars and multiple trucks to a silo or single location. A DPVC system uses a positive displacement vacuum pump to create negative pressure which ultimately pulls material from a storage hopper. By controlling the vacuum through a vacuum relief valve the quantity of the material to be conveyed can be controlled.

3.3.6 Screw Conveyor (SC)

SC is a mechanism in which rotating helical screw blade usually rotates inside a U-shaped or circular tube to move bulk materials [5] (Fig. 3.8a). It consists of helical flights, i.e., screw mounted over a cylindrical shaft. Bulk materials move along the bottom of the rotating blade, which is why it does not remain fill completely. The distance between two screw flights is known as pitch which may be constant with in the conveyor or may vary depending upon the application. In this system, the bulk material conveyed can be well controlled by adjusting the rotation of the helix. They are widely utilized in a variety of unit operations and have wide applications in the transportation of bulk agriculture materials (i.e., mixing grain in storage, and loading-unloading of grains from the bin), and in food manufacturing units [9]. It is mostly used for transporting free-flowing materials. Screw conveyors give good throughput control, have a simple design, high efficiency, require less maintenance, and are cost-effective. But they are not suitable for long-distance transportation due to high power consumption. The size of conveyors may vary from 75 to 400 mm and 1 to 30 m in diameter and length, respectively.

The increase in rotational speed and screw diameter clearance (Figure 3.8b) significantly increases specific power requirement of a designed screw conveyor. Similarly, the net power requirement can be enhanced significantly with an increase in screw rotational speed and decreased with an increase in screw diameter clearance. Enhancing both parameters, i.e., screw rotational speed and diametric clearance significantly reduces volumetric efficiency of the conveyor.

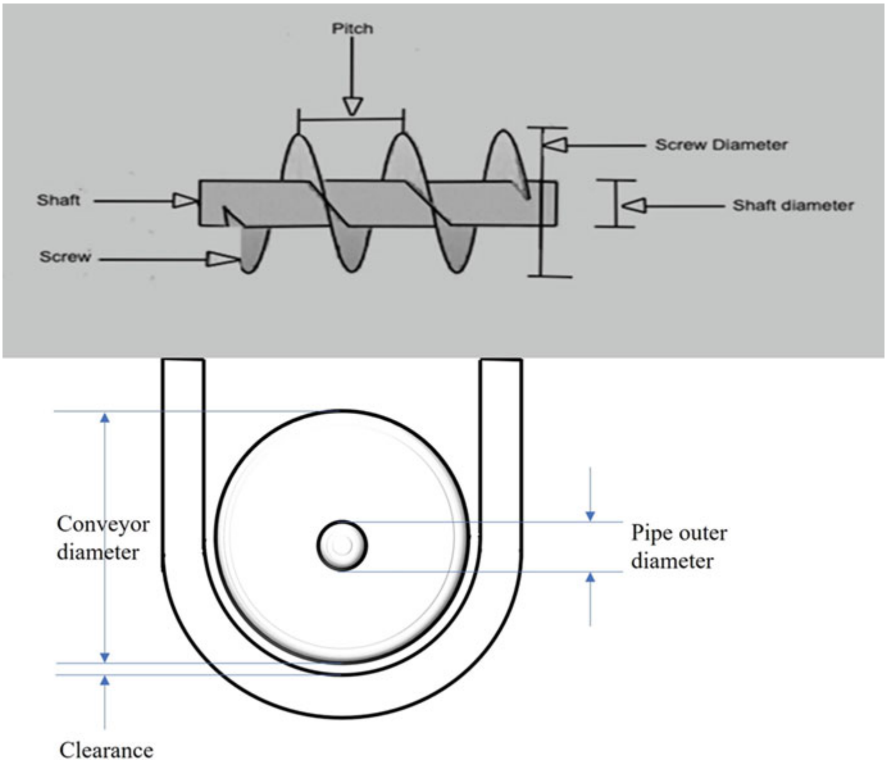


Fig. 3.8 (**a**) Screw Conveyor Shaft. (**b**) Screw Conveyor side view

Advantages of Screw Conveyor systems:

- Completely closed from dusty, corrosive environmental conditions.
- Ideal for conveying free-flowing dry powdered materials to semi-solid bulk materials.
- Cost-effective because of the low maintenance required as compared to the belt conveyor system.
- It has multiple inlets and discharges points for effectively distributing the materials at different locations.

Theoretical conveyance capacity and power can be calculated by the following equation [10]

$$\text{Capacity}\left(\frac{\text{m}^3}{\text{h}}\right) = \left[\frac{\pi}{4}(\text{screw diameter})^2 - (\text{shaft diameter})^2\right](\text{m}^2) \times \text{pitch}\,(\text{m}) \times \text{rpm} \quad (3.3)$$

$$\text{hp} = \text{Capacity of conveyor}\left(\frac{\text{m}^3}{\text{h}}\right) \times \text{conveyor length (m)}$$
$$\times \text{bulk material weight}\left(\frac{\text{kg}}{\text{m}^3}\right) \times \text{material factor} \tag{3.4}$$

Example 2 If the screw diameter is 3 m, shaft diameter, 1 m and its pitch length is 3 m with a running speed of 1 rpm, what will be the capacity of a screw conveyor?

Solution:

$$\text{screw diameter} = 3\text{ m}$$

$$\text{Pitch length} = 3\text{ m}$$

Therefore,

$$\text{Capacity}\left(\frac{\text{m}^3}{\text{hr}}\right) = \left[\frac{\pi}{4}(\text{screw diameter})^2 - (\text{shaft diameter})^2\right](\text{m}^2) \times \text{pitch (m)} \times \text{rpm}$$
$$= 0.78\left(3^2 - 1^2\right) \times 3 \times 1$$
$$= 18.8\text{ m}^3/\text{min} \quad \text{Or} \quad 0.314\text{ m}^3/\text{s}$$

3.3.6.1 Types of Screw Conveyors

Horizontal Screw Conveyors (HSC)

HSC are extensively used and preferred to transport bulk materials from one place to another. Another advantage is the availability of different sizes (diameters and length), configurations as well as the range of materials to be used for construction [11].

Inclined Screw Conveyors (ISC)

ISC generally operate below 45° angle to the horizontal position. Above 45° angle, an ISC is considered a vertical screw conveyor. With an increase in the degree of inclination, conveying efficiency decreases and horsepower requirements increase due to the effect of gravity. Conveying efficiency is affected by the angle of inclination, screw pitch, type of screw conveyor trough, and the characteristics of the specific bulk material. It is recommended to design screw conveyors, having lowest possible degree of inclination to attain maximum efficiency.

Shaftless Screw Conveyors

Shaftless helix is used in this design which results in smooth movement of bulk materials without any clogging. To handle bulk materials with high moisture, shaftless screw conveyor is the best solution. The following are the advantages of shaftless screw conveyors.

- Good for handling sticky and sluggish bulk materials.
- Very flexible and can be shifted according to plant layout.
- Less wear and tear because of the elimination of internal bearings.

Vertical Screw Conveyors

The vertical screw conveyors are at an inclination (over 45° angle) from the horizontal surface or completely vertical. Due to the compact design, cost-effectiveness of screw conveyors, installation in a variety of processing industries is easier for conveying bulk material.

Advantages of vertical screw conveyors are as follows.

- They are considered well suited for conveying the dry to semi-fluid commodities.
- They can handle material with capacities up to 6000 cubic feet/h.
- Bulk material can be elevated up to 30 feet.
- Completely enclosed design to prevent dust, corrosion, or hazardous environment.

3.3.7 Hydraulic Conveying

Hydraulic conveying is emerging as a widely adopted method due to the capability to transfer material over long distances with higher capacity. It also does not have the limitations of other conveying systems. As it has a large capacity and transport product with minimum wear and tear, demand for hydraulic conveying systems in the food and petrochemical industries is increasing. Earlier this conveying system was mostly used for coal transportation.

Hydraulic conveying also involves transporting of solid material in the moving liquid (Fig. 3.9). It is operated as a closed loop system [12] and for the separation sediments and fines from water, high-duty filter units are used to achieve the highest purity. After hydraulically carrying the material, centrifugal or fluidized-bed driers are used to dry the commodity depending upon the properties of the product. Advantages of hydraulic conveying are:

- The purity of product is maintained. It also renders minimum abrasion to the product as it flows through the water.
- The system can convey commodities over long distances and has huge capacities nearly unlimited.
- The process saves energy up to 60–80% as compared to other conveyors for the same capacity.
- Low noise emission.
- Even small diameters of pipe are required for high capacities.

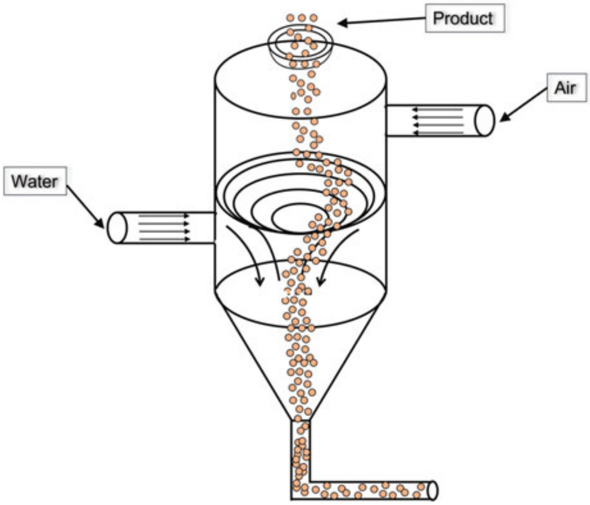


Fig. 3.9 Hydraulic conveying system

3.3.8 Bucket Elevators

Food elevators are designed to transfer food materials efficiently by many systems in continuous movement in a vertical direction. The bucket elevator is used to elevate the variety of bulk material in the food processing industry. It lifts the solid food material either vertically or inclined. It consists of steel or malleable iron buckets carried on an endless belt or on a chain. The bucket elevators carry the material in a closed system. The free-flowing solids are fed at the bottom continuously by means of some feeding arrangement into the bucket under the feeding movement point. As the bucket moves upward, the bottom bucket occupies the position of feeding point, thus it render continuous movement.

Centrifugal Discharge Elevator It is used in grain processing facilities at the farm level since a long time. The centrifugal force is used in this elevator for the free discharge of the product. The food grains are collected into the bucket and discharge through spout mounted at the elevator head.

Continuous Discharge Elevator It is used for the removal of the sticky and hygroscopic food product. Generally, it handles the food material at a slower speed to reduce the losses. Furthermore, it can be a positive discharge elevator and flight elevator.

In the case of a positive discharge elevator, the buckets are used for lifting crunchy and soft food products where the structure and texture are important parameters for their quality. These elevators work by double-strand chain by which is held in place by two pins and because of this bucket can easily turn around a point. The bucket is mechanically turned for emptying but because of this, the

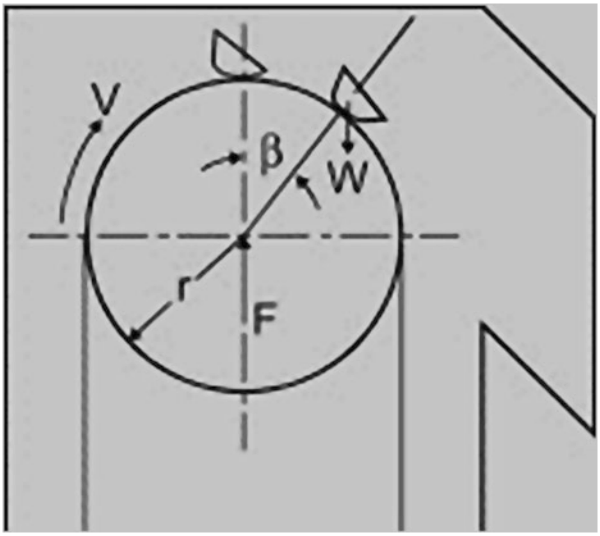


Fig. 3.10 Bucket elevators

bucket position goes parallel to the floor and upright. Flight elevators are used for all-purpose lifting food materials whose shapes like gooseneck to straight and curved, but particularly used for elevating granular/powdery material.

Belt speed is the important parameter, and it is generally in the range of 1.5–1.8 m/s. The speed of the belt is dependent upon the speed of head pulley. The discharge of the grains becomes difficult, if the belt speed is too low and the buckets are not fed well, if the speed is too high. When grain is thrown at the top of the head pulley (Fig. 3.10), at this point the gravity and centrifugal force are balanced.where,

W is the weight of grain (kg); V is the tangential belt velocity (m/min); β is the angle from top dead center; r is the radius of pulley (m), and F is the centrifugal force (kg).

The capacity of bucket elevator [14]

$$\text{Capacity}\left(\frac{\text{m}^3}{\text{h}}\right) = \text{Bucket capacity}\left(\text{m}^3\right) \times \text{number of bucket per meter of belt belt speed}\left(\frac{\text{m}}{\text{min}}\right) \times 60 \quad (3.5)$$

Theoretical horsepower (hp) requirement for bucket elevator [14]

$$\text{hp} = \text{Capacity of bucket elevator}\left(\frac{\text{kg}}{\text{min}}\right) \times \text{lift of elevator}\,(\text{m}) \times \text{factor} \quad (3.6)$$

Factor = 1.2 and 1.5 for elevators loaded on the bottom side and upside respectively.

Example 3 What will be the capacity of a bucket elevator if the capacity of each bucket is 0.60 m^3 and there are four buckets in the 1-meter length of belt and its speed is 1.2 m/min

Solution:

$$\text{Bucket elevator capacity} = 0.60\ \text{m}^3$$

$$\text{Number of buckets} = 1$$

$$\begin{aligned}\text{Capacity}\left(\frac{\text{m}^3}{\text{hr}}\right) &= \text{Bucket capacity}\left(\text{m}^3\right)\\ &\times \text{number of bucket per meter of belt belt speed}\left(\frac{\text{m}}{\text{min}}\right)\times 60\\ &= 0.60\times 4\times 1.2\times 60 = 172.8\ \text{m}^3/\text{h}\end{aligned}$$

3.4 Other Movable Material Handling Devices

3.4.1 Cranes

Harvested crops, grains as well as foods that are manufactured in the industry have to move from one place to another place. Therefore, it should be ensured that food cannot be contaminated or damaged during transportation.

Cranes are the mechanical devices that are used for lifting and lowering a load, also for horizontal movement, where the hoisting mechanism is applied. There are various types of cranes such as manually or power-operated. They are exempted from stackers, hoist trolleys, lift trucks, power shovels, backhoes, or excavators [10].

3.4.2 Hoist

Hoists are commonly used for loading or unloading heavily loaded material. The overhead-traveling cranes are used for the storage of big bags filled with cane sugar. The important characteristics of space-saving of cranes make them easy for installation in any production line.

The cranes have an important task in the beverage industry as well as in large scale dairy industry for the lifting of heavy cartons. The heavyweight pallets are lifted by cranes from one place to another. Also, it provides convenience for transportation of packed beverages and packaged food which ultimately saves labor energy.

Table 3.1 Different types of trucks used in industries

S. No.	Type	Details
1	Hand trucks	Hand trucks are commonly called a dolly. They have l-shaped and box-moving handcarts with handles at one end. On the base side, they have wheels and a ledge for the objects.
2	Pallet jacks	Pallet jacks are a simple form of a forklift. They are used for lifting and moving pallets in a warehouse.
3	Pallet trucks	They can be operated manually or automatically.
4	Walkie stackers	Walkie stackers or straddle stackers are known as pedestrian walk-behind pallets with a mast to lift pallets to heights
5	Platform trucks	Platform trucks are the same as a two-wheeled dolly and contain an extended deck.
6	Order picker	These are electrically operated lift trucks mainly used for filling single customer demand. It picks up piece-part rather than unit loads or full pallets.
7	Side loader	Side loader loads and unloads automatically, like a forklift from the side of the machine rather than the front

3.4.3 Trucks

Forklifts (powered industrial trucks) are used for the movement of large materials or large capacity of materials on the floor of the company. They are used effectively for loading and unloading big materials onto delivery trucks [10]. Conveyors are replaced by these industrial trucks where minimum flow volume is processed. Following are the examples of industrial trucks as shown in Table 3.1.

3.5 Transportation of Fluids

Pumps, valves, and pipework are mainly used for the transportation of liquid food materials from lower to higher level as well as from one place to another place. The fluids are pumped to increase the potential energy or kinetic energy of the fluids by various types of mechanical pumps. The fluid quantities are regulated through valves or measured by means of various measuring instruments. The fluid may easily pass through bends, elbows, and T-joints in the pipeline which may be smooth or rough.

3.5.1 Pumps

Pumps are generally used for displacement of liquid food material for transportation against gravity and friction or increasing the kinetic energy or pressure energy of the fluids.

In the food industry, centrifugal pumps are commonly used and the criteria for selection of a particular pump include the following:

- Product type, based on rheology
- Temperature, pressure, and product flow rate
- Type of mixing devices (impeller)
- Speed and size of the motor
- Seal type on pump outer body and motor shaft
- Type of couplings and other fittings

3.5.1.1 Classification of Pumps

Wide varieties of pumps are designed for different applications. The different types of pumps, used for fluid transportation are mainly classified under two categories, i.e., positive displacement pump (reciprocating pumps and rotary pumps) and centrifugal pump (Fig. 3.11) [13].

Reciprocating Pumps

These types of pumps transport the liquid linearly through piston or plunger. The movement of liquid in a closed stationary cylinder is carried out by piston or plunger. Reciprocating pumps consist of a piston pump, plunger pumps, and diaphragm pumps. Mechanical efficiency of these pumps with small and large capacity varies from 40 to 50% and 70 to 90%, respectively. They are more commonly used as metering devices because the volumetric efficiency is almost constant with increase in discharge pressure. Only slight drop could be observed due to leakage.

Piston Pump

It is also a positive displacement pump in which a high-pressure seal reciprocates with the piston. This pump consists of piston-cylinder arrangement in which liquid material is collected by inlet check valve into cylinder by the withdrawal of piston. Liquid is then forced out through discharge check valve on delivery stroke [14]. On forward stroke, the fluid filled inside the cylinder is compressed which in turn opens the delivery valve for the delivery of liquid on the return stroke. They can develop maximum discharge pressure up to 50 atm.

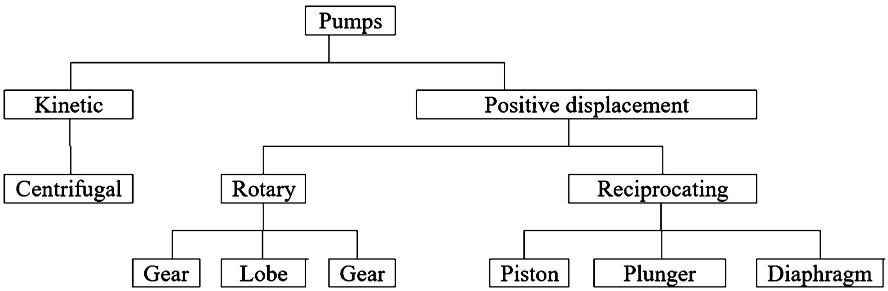


Fig. 3.11 Different types of pumps

Plunger Pump

Plunger pump is a type of reciprocating pump and mostly used for discharge of high-pressure liquid. The construction and working principle are similar to a single-acting piston pump with a plunger in place of a piston. A cylinder with small diameter has a plunger fitted into it. The plunger pump is single acting and driven by a motor and contain check valves in the discharge line which develop pressure up to 1500 atmosphere.

Diaphragm Pump

It uses combination of the reciprocating action of a rubber, thermoplastic, and suitable valves for the pumping of liquid [14]. The outputs of this pump are always low with the upper limit being approximately 500 ppm. They can pump against pressure, 100 atmospheres. Instead of a plunger or piston moving in a cylindrical chamber as in the case of reciprocating pumps, the diaphragm just vibrates, and sucks the fluid in one direction of vibration and delivers in the other direction of vibration as shown in Fig. 3.12. The diaphragms are made of some flexible materials (plastic, rubber, or some soft material of metal alloys). These pumps can be used for fluids that are toxic or non-corrosive in nature [13].

Rotary Pumps

Rotary pump is also positive displacement pump where rotary motion is applied instead of reciprocating motion as shown in Fig. 3.12 These pumps are designed with very small clearances between and stationery and rotating parts to minimize leakage. To maintain this clearance, it is designed to operate at relatively low speeds. Hence, valve arrangements like reciprocating pumps are not needed in rotary. In this, two gears, which adjust each other, create rotary motion in opposite direction. They are used for transporting liquid with moderate viscosity.

Spur Gear Pump

Spur gear pump utilizes two intermeshing gears (Fig. 3.13) enclosed in a casing with close clearance. The actual working is caused through the toothed gears. The fluid

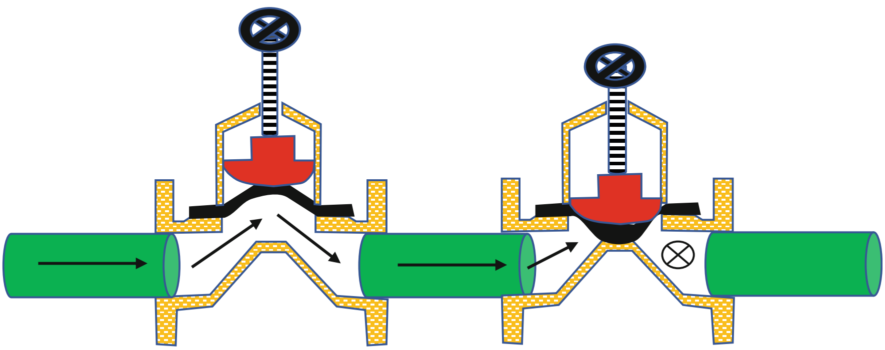


Fig. 3.12 Diaphragm pump

Fig. 3.13 Spur gear pump

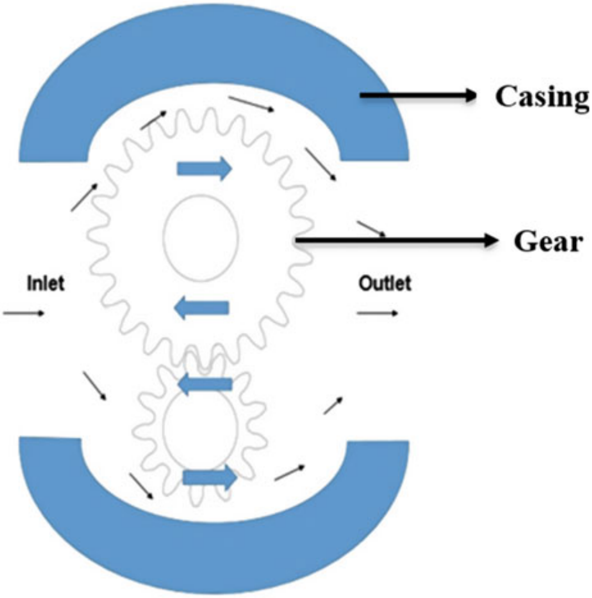
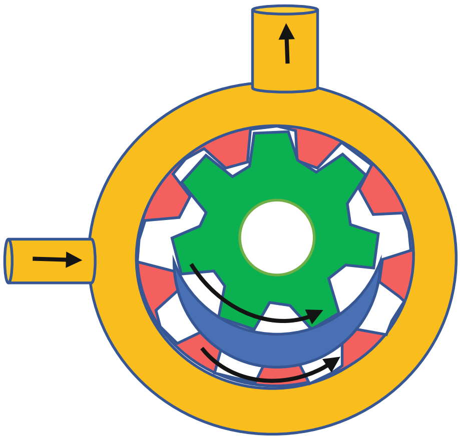


Fig. 3.14 Internal gear pump



enters through suction point, i.e., the inlet and is carried by the spaces in between gear and casing and is forced out toward the outlet. Short circuit of flow is prevented by the close intermeshing of the gears at the center. The regulation of flow is affected by the volume of the cavity between the teeth, gears speed, and fluid quantity that slips back to the inlet [13].

Internal Gear Pump

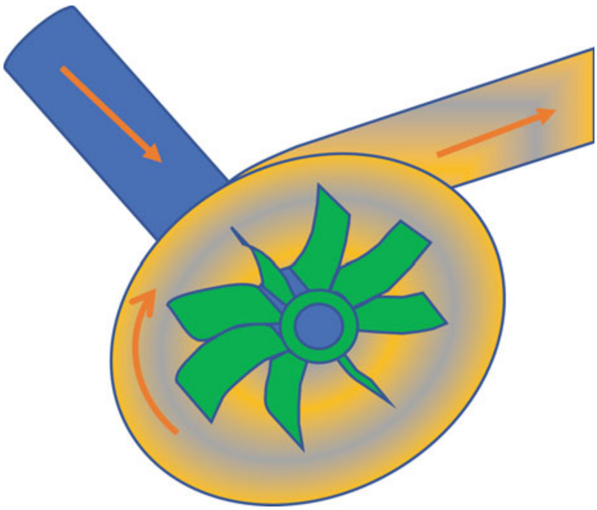
It creates flow by a gear having external-cut teeth within it and meshed with a gear with internally-cut teeth, as shown in Fig. 3.14. The liquid forcefully pumps out the discharge port when gears come out of mesh on the inlet side. The inlet volume is separated by a crescent-shaped partition which discharges volume between the two gears. These pumps can be used for many industrial applications such as handling of oils and viscous chemicals.

Centrifugal Pump
In this pump, centrifugal force is used to enhance the fluid pressure. The pump consists of an impeller driven by motor which revolves inside the casing. Fluid enters at the center of impeller rotation and due to the creation of centrifugal force fluid is moved toward impeller periphery. At this stage fluid experience maximum pressure and is moved toward the exit opening at the casing side as shown in Fig. 3.15. These types of pumps are commonly applied to move liquids through a piping system having low viscosity, e.g., supply of water, large discharge through a smaller opening, processing of milk in a dairy plant and for fruit juices. Discharge through these pumps is steady. These are not preferred to transport highly viscous product as high velocity is not achieved due to high viscous forces.

3.5.2 Valves

Valves are electro-mechanical or mechanical devices which are used to regulate the movement of flowing materials (gases, powders, and liquids) through tubes or pipes or from tanks or containers. Two varieties of valves are designed, such as on–off varieties and another which causes the very smooth flow of media through pipes for better control. On–off varieties are used for either allowing or preventing the flow of fluid.

Fig. 3.15 Centrifugal Pump



3.5.2.1 Butterfly Valves

These valves are more demandable due to their important characteristic such as easy construction, lightweight, and compact. Butterfly valves have a face-to-face dimension which makes them smaller and consists of a pivoting disc that is closed to a food-grade seal [15]. They can sustain pressures up to 1 MPa. A schematic representation is shown in Fig. 3.16.

3.5.2.2 Single and Double Seat Valves

Single and double seat valves contain inside stainless steel ball which is moved into a respective seat using an actuator [15]. These valves are more compatible to pressure up to 0.5 MPa. The double seat valves find their application in CIP because they permit two fluid streams to pass through the valve without mixing.

3.5.2.3 Diaphragm Valves

These valves use a flexible diaphragm to stop the fluid flow by "pinching" method. Also, they have an elastomer membrane or stainless steel bellows which prevent the product from valve shaft contact. These valves are used, where high-temperature fluid passes through pipes and these can sustain product pressures of 0.4 MPa.

3.5.2.4 Ball Valves

These valves have important characteristics such as good shut-off capabilities. This is because of a simple quarter-turn (90°) which opens or closes the valve easily. The size of the valve (Fig. 3.17) path is as big as that of the pipe itself. The pressure is very low and the flow of slurries or suspension is easier [15].

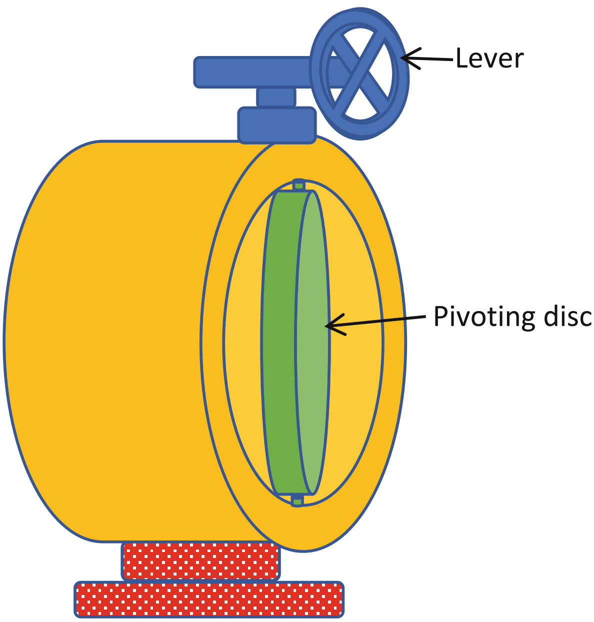


Fig. 3.16 Butterfly valves

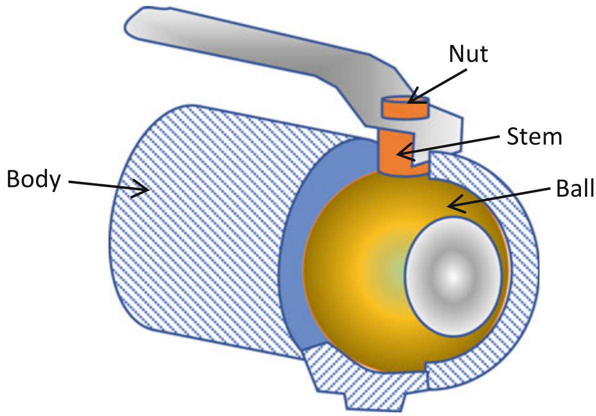


Fig. 3.17 Ball valve

3.5.2.5 Other Valves

These include the following:

- Safety valves: They are applied where large amount of pressure is generated in pressure vessels.
- Vacuum valves: They prevent the vessel from collapsing under unwanted vacuum created during transportation.
- Modulating valves: These valves are used to allow the accurate control of product throughputs.
- Sampling valves: These valves are used especially in the fermenter or in biomass production equipment for safe sampling during an ongoing process without contamination [15].

3.5.3 Pipes

The flow of fluid through pipes is an interesting phenomenon with varying velocity profile. Pipes generally are those which have large diameters and higher wall thickness. The diameter ranges at least start from ¼ inch (6 mm) and goes up to 25.4 mm. Since the wall thicknesses are high, they have a definite length, usually 10 ft. (3.048 m) or 20 ft. (6.096 m). Some important practices that need to know about fluid flow in pipelines are as follows [13]:

- The fluid pipeline should be straight as far as possible to reduce pressure drop during fluid flow.
- The direction of the flow of fluids should be indicated in the pipelines.
- Standard notation of coloring should be painted on the pipes containing different fluids.
- The pipes should be joined with coupling or union joints, with a gasket so that dismantling is easier in case of blockage and leakage.

- The valves and other accessories should be approachable and should be kept in a vertical position as far as possible.

3.5.4 Pipe Fitting and Joints

Pipe fitting and joints are the parts of piping which help in changing the direction of flow of liquid like tees and elbows. The reducers are used to convert the pipe, which increases the flow of liquid (Fig. 3.18). Couplings are used to connect the different components and caps are used to stop the flows [13]. Types of pipe fittings like elbow, tee, union, coupling, cross, cap, and nipple are summarized as under:

3.5.4.1 Elbow

It is used for connecting to more pipe fittings and available in standard degree of 45° and 90°. These elbows give the flexibility to change the pipe direction.

3.5.4.2 Bend

Bends are used for fluid movement where pigging is required. They have a long radius which changes the smooth direction of the fluid and due to this pipeline inspection gauge (PIG) flow control is possible. Bend creates very less pressure drop in flowing fluid.

3.5.4.3 Tee

Tees mainly applied for the collection of the liquid from the running pipe. They are small pipe having a 90° branch at the center such as equal/straight tee and reducing/ unequal tee.

3.5.4.4 Reducers

Reducers are used to change the size of pipe at one end so that we can attach another pipe with having a small diameter. They are available in two forms like concentric reducer and eccentric reducer.

3.5.4.5 Union

They are alternative to flanges connection generally in low-pressure small-bore piping, where dismantling of the pipe is more often needed. Unions can be threaded or socket weld type. Union consists of three pieces, a nut, a male end and a female end. The nuts provide the necessary pressure to seal the joint, when the male and female ends are joined.

3.5.4.6 Coupling

They are commonly used for connecting the same diameter pipes and sometimes for joining the leakage or broken pipes. Coupling can be either compression or slip coupling. Compression coupling is common and it is used between two pipes which prevents leakage. Slip coupling can be installed easily and it contains two pipes,

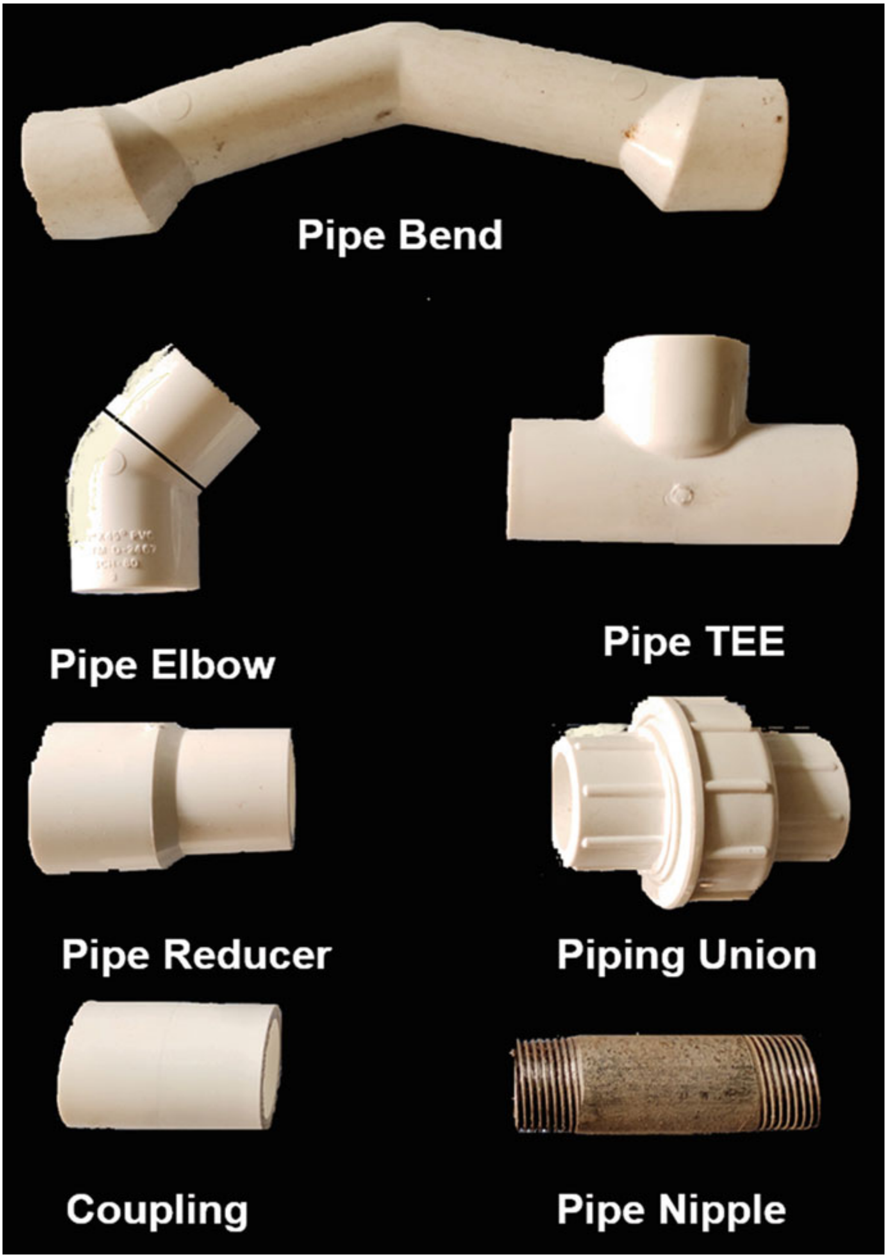


Fig. 3.18 Different types of pipe fitting

which are arranged as one into other. The inner pipe can slide up to certain length [13]. Hence, slip coupling can fix long length damaged pipe.

3.5.4.7 Nipple

Nipple consists of small male pipe having both sides' threads through which two other fittings can be connected. They are applied in low-pressure piping for joining pipe, hoses, and valves.

3.6 Hygienic Considerations During Material Handling

Material handling is a typical transport operation where hygiene plays a very important role. The contamination problem is common in batch or continuous process. To avoid the contamination issues in entire processing operation care must be taken. The possible source of contamination to occur is dirty raw material, foreign bodies hopping on the food materials, enzymatic action causing degradation of the raw materials, etc. The hygienic considerations for proper material handling operation are as follows:

- Transport the raw materials in as pure form as possible. If the raw materials are dirty, they need to clean at the farm level or the processing plant.
- Material and equipment parts coming in contact with the food materials should be rust –free.
- The surface comes in contact with the food material that should be smooth and polished. The pitches and crevices on any rough surface are potential source of undesirable microorganisms.
- The equipment and machinery used in material handling should be routinely cleaned at periodic intervals.
- The equipment design of food conveying machines should be smooth, easy to clean; otherwise, there is a deposition of dust on the surface which causes the hazard. If scratches or cuts are present on equipment, then it can create problems for cleaning surfaces.

3.7 Exercise

1. What is the importance and need of material handling and transportation devices in different unit operations?
2. What are the advantages and disadvantages associated with powerless material handling devices?
3. What are the differences between dense and dilute phase pneumatic conveying techniques?
4. What are requirements for using pump in food industry? Classify different types of pumps used for fluid transportation.

5. What are the differences between positive displacement pump and centrifugal pump?
6. Discuss the mechanism of spur gear rotary pump.
7. State the application of valves in food industry and classify them.
8. What are the different types of pipe fittings used in various unit operations in food industries?
9. What will be the horsepower required for operating a belt conveyor whose capacity is 40 t/h. and its length is 6000 cm. [Answer: 0.432]
10. What will be the capacity of a screw conveyor, if the screw diameter is 200 cm and the shaft diameter is 1 m and its pitch length is 200 cm and running speed is 1 rpm? [Answer: 4.68 m^3/min]
11. What will be the capacity of a bucket elevator if the capacity of each bucket is 0.60 m^3 and there are four buckets in the one-meter length of belt and its speed is 150 cm/min. [Answer: 288 m^3/h].

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Design of Material Handling Systems

4

Navneet Kumar and Harish Kumar Sharma

Abstract

The chapter deals with the concepts related to the design of material handling equipment. A systematic design of belt conveyor, which includes the types of conveyors, class and selection of belt conveyors, capacity of conveyor, speed of belt, driving forces and power requirements, is discussed. The design of length, capacity and power requirements is explained through worked examples. The design of bucket conveyors that includes selection of type, capacity, estimation of chain or belt tension, spacing between the buckets and power requirements is also illustrated. In the screw conveyor design, the calculation/selection of capacity, inclination and power requirement is also explained. The important information required in designing the conveyors, viz. classification of materials on the basis of handling characteristics, mechanical properties of agricultural produce and specification of screw conveyor, are also included. The design of the conveyors provides basic understanding to design an effective material handling system, which on the other hand improves the efficiency of agro-processing operations.

Keywords

Belt conveyor design · Bucket elevator design · Screw conveyor design

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4.1 Introduction

The material handling systems play an important role from the receiving section to the packaging and transportation of finished food products. The general cost during handling and transportation influences the processing cost of food material. The movement/transportation route also plays an important role in handling cost. An efficient material handling system eventually reduces the cost per unit volume of processed product and assures timely supply of material safely in all the unit operations till the dispatch of the final product.

The efficient and effective design in material handling is needed for the enhancement of productivity. It also contributes to minimizing the cost involved in handling. Some of the most important considerations for designing material handling systems are:

1. The idle time for the system should be made negligible by designing the continuous flow of material.
2. Simple mechanisms should be designed to ensure the lower cost of equipment.
3. Application of gravity flow should be exploited up to the maximum extent to minimize the cost involved in the operation of motors.
4. The dead mass of machine to the mass of food material to be conveyed should be minimum.

4.2 Belt Conveyor

The belt conveyor components are designed to meet the demand of material to convey. Nomenclature of various parts of bucket elevator is presented in Fig. 4.1. The designed capacity and dimension of components should be accurately monitored during the fabrication to ensure efficient operations. Major components/specification in designing the belt conveyors are capacity, speed of operation, dimension of rollers, belt tension, power requirement, idlers' spacing, diameter of pulley, motor, type of driving unit, pulley location and arrangement, mode of control and indented application.

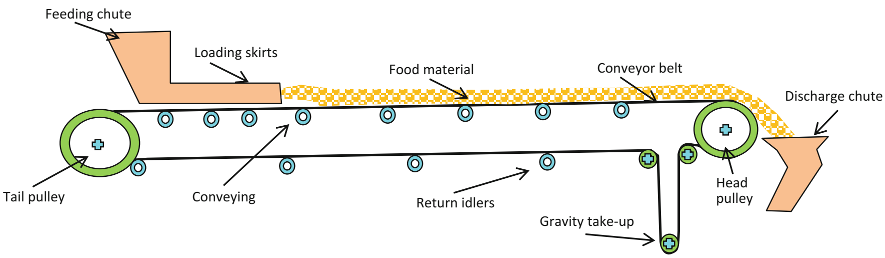


Fig. 4.1 Nomenclature of belt conveyor

4.2.1 Types of Belt Conveyors

The belt conveyor is of two types: (1) flat conveyor and (2) troughed conveyor. These can be arranged in horizontal (flat), inclined or declined orientation. Sometimes, curvature is provided vertically. The troughed conveyors usually have more than one roller, i.e. two, three and five rollers. The troughed angle may vary from 15 to 45°, while the maximum 15° troughed angle is used in troughed conveyors with two rollers only. The return rollers usually have troughing angle of about 0, 10 and 15°.

4.2.2 Selection of Belt Conveyors

The flat belt conveyors are used for handling material at a lower capacity and low speed. These are preferred for the material having smaller lumps with a higher angle of repose. These can work up to an inclination of 6° and are not preferred for the downward motion. The troughed belt conveyors are used for higher capacity and higher speed, handling the presence of bigger lumps, with or without vertical curvature in flow path and for inclination or declination travel path.

4.2.3 Design of Belt Conveyor

The configuration and layout of conveyor should be finalized initially. The material to be conveyed should be kept in two broad categories:

1. *Classified material* – The ratio of the largest lump size ($a_{\max}$) to the lowest lump size ($a_{\min}$) should remain lesser or equal to 2.5. These materials are defined by $a_{\max}$ and $a_{\min}$ values.
2. *Non-classified material* – The ratio ($a_{\max}/a_{\min}$) of the largest lump size ($a_{\max}$) to the lowest lump size ($a_{\min}$) should remain greater than 2.5. These are defined by complete sieve analysis.

Where 'a' indicates the largest (diagonal) dimension of any lump. The average lump size can be estimated by taking the mean of maximum and minimum values [1].

A material can be classified according to the size, flowability and other characteristics as given in Table 4.1 [2]. The code of the material is used to represent the characteristics of material, e.g. Code C represents granular material (maximum lump size 0.5–10 mm), Code CI represents granular material (0.5–10 mm) with medium bulk density (0.6–1.6 t/m^3) and Code CI2 represents granular material (maximum lump size 0.5–10 mm with medium bulk density (0.6–1.6 t/m^3) and free-flowing characteristics (angle of surcharge −10° and angle of repose between 20 and 30°).

Table 4.1 Classification of materials on the basis of product handling characteristics [2]

S. no.	Description	Parameter value/limitations		Class
Characteristics: Lump size (a_{max})				
1.	Dusty material	Up to 0.05 mm		A
2.	Powdered material (fine sand)	0.05–0.50 mm		B
3.	Granular material (grain)	0.5–10 mm		C
4.	Small-sized lumpy (crushed)	10–60 mm		D
5.	Medium-sized lumpy	60–200 mm		E
6.	Large lump material	200–500 mm		F
7.	Especially large lump size (such as stone, boulder, etc.)	Over 500 mm		G
Characteristics: Bulk density				
8.	Light material	Up to 0.6 t/m^3		H
9.	Medium	Over 0.6 to 1.6 t/m^3		I
10.	Heavy	Over 1.6 to 2.0 t/m^3		J
11.	Very heavy	Over 2.0 to 4.0 t/m^3		K
Characteristics: Flowability				
(measured as the angle of surcharge and angle of repose)		Angle of surcharge	Angle of repose	
12.	Very free flowing (uniform, very small rounded particles)	5°	$0° \leq \theta \leq 20°$	1
13.	Free flowing (rounded, dry particles)	10°	$20 < \theta \leq 30°$	2
14.	Average flowing (irregular, granular or lumpy material)	20°	$30 < \theta \leq 35°$	3
15.	Average flowing (common material)	25°	$35 < \theta \leq 40°$	4
16.	Sluggish (irregular, fibrous and interlocking material)	30°	$40° < \theta$	5
Abrasiveness				
17.	Non-abrasive	–		6
18.	Abrasive	–		7
19.	Very abrasive	–		8
20.	Very sharp	Can cut belt covers		9
Miscellaneous characteristics				
21.	Aerates and develops fluid (or dual operating) characteristics	–		L
22.	Contains explosive dust	–		M
23.	Sticky	–		N
24.	Contaminable	–		P
25.	Degradable	–		Q
26.	Gives off harmful fumes/dust	–		R
27	Highly corrosive	–		S
28	Mildly corrosive	–		T
29.	Hygroscopic	–		U
30.	Oil/chemicals	May affect rubber products		W
31.	Packs under pressure	–		X
32.	Very light and fluffy	May be swept by wind		T
33.	Elevated temperature	–		Z

Table 4.2 Material properties of several produce and maximum inclination [2]

S. no.	Material	Average bulk density, kg/m^3	Angle of repose, degree	Maximum inclination recommended
1.	Barley	600	23	10–15
2.	Buck wheat	640–672	25	11–13
3.	Clover seeds	768	28	15
4.	Corn shelled	720	21	10
5.	Corn meal	600–640	35	19
6.	Dry cottonseed	290–400	35	19
7.	Dry delinted cottonseed	400	29	16
8.	Cottonseed meal	560–640	35	22
9.	Flax seed	720	21	12
10.	Fuller's earth raw oil filter	560–640	35	20
11.	Linseed meal	680	34	20
12.	Oats	416	21	10
13.	Rice, hulled or polished	720–768	20	8
14.	Rye	704	23	8
15.	Coarse common salt, dry	720–800	30–45	18–22
16.	Fine common salt, dry	1120–1280	25	11
17.	Soybean, cracked	510–580	35	15–18
18.	Soybean, whole	720–800	21–28	12–16
19.	Soybean cake	640–688	32	17
20.	Soybean meal, cold	640	32–37	16–20
21.	Starch	720	24	12
22.	Wheat	720–768	28	12

4.2.3.1 Width of Conveyor Belt

The width of belt may be selected according to the maximum uniform-sized material or maximum dimension of unsized material. The belt width varies from 300 to 2000 mm for maximum uniform-sized lumps of 75–500 mm and maximum unsized lumps of 100 to 1020 mm. The specific size of belt width may be selected from the standards [3].

The width of belt can also be decided according to the capacity required, angle of surcharge and troughing angle. The larger value of belt width required for conveying the lump size and the capacity is selected for belt conveyor.

4.2.3.2 Conveyor Inclination

The maximum inclination for various agricultural produces is provided in Table 4.2. The angle of surcharge is assumed to be the angle of pile surface from the horizontal at rest and is considered about 15–20° lesser than the angle of repose [2].

4.2.3.3 Width of Material on Conveyor Belt

The belt width is decided based on lump size and the capacity of the equipment. The standard widths of belt are 300, 400, 500, 600, 650, 800, 1000, 1200, 1400, 1600, 1800 and 2000 mm [3]. The width of material on the belt can be estimated using the following expressions:

$$if\ B < 2\ \text{m then} \rightarrow b = 0.9\ B - 0.05$$

$$if\ B > 2\ \text{m then} \rightarrow b = B - 0.25$$

where B is the width of belt in mm and b width of material on the belt.

Q.1. What will be the width of material on the belts having width of the belt 600, 1400, 2200 and 2400 mm?

Answer: In the case of width of belt less than 2 m:

$B = 600\ \text{mm} = 0.60\ \text{m}$

$b = 0.9\ B - 0.05 = 0.9 \times 0.6 - 0.05 = 0.49\ \text{m}$

$B = 1400\ \text{mm} = 1.40\ \text{m}$

$b = 0.9\ B - 0.05 = 0.9 \times 0.1.4 - 0.05 = 1.21\ \text{m}$

In the case of width of belt greater than 2 m:

$B = 2200\ \text{mm} = 2.20\ \text{m}$

$b = B - 0.25 = 2.20 - 0.25 = 1.95\ \text{m}$

$B = 2400\ \text{mm} = 2.40\ \text{m}$

$b = B - 0.25 = 2.40 - 0.25 = 2.15\ \text{m}$

4.2.3.4 Roller Diameter

Rollers are used to support the belt and facilitate free rotation of belt (Fig. 4.2). The width of the roller is designed to cover the belt width and should be selected correctly. The roller diameter can be estimated using the following expression [4]:

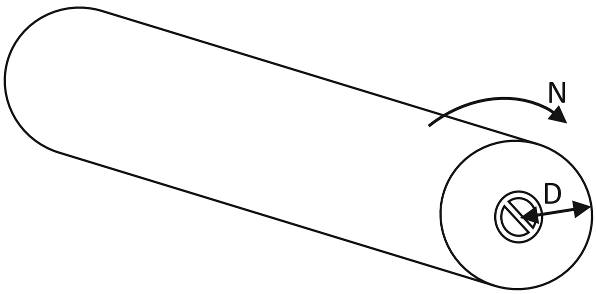


Fig. 4.2 Belt conveyor roller

$$D = \frac{v \times 1000 \times 60}{\pi \times N}$$

where D is the diameter of the roller (mm), v speed of the belt (m/s) and N number of revolutions per minute.

4.2.3.5 Length of Conveyor Belt

The length of conveyor belt can be estimated using centre-to-centre distance between the end pulleys, i.e. the length of belt conveyor and the diameter of pulleys (Fig. 4.3). The pulley dimensions are designed to minimize the stresses on the belt.

$$L = 2C + \frac{\pi}{2}(D_1 + D_2)$$

where L is the length of the belt (mm), C is the distance between centres of pulleys and D_1 and D_2 are the diameters of pulleys.

In the case of inclined belt at an angle θ, the conveyor length *(Y)* can be estimated as (Fig. 4.4):

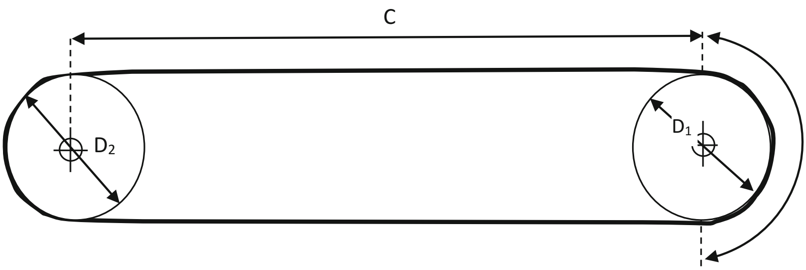
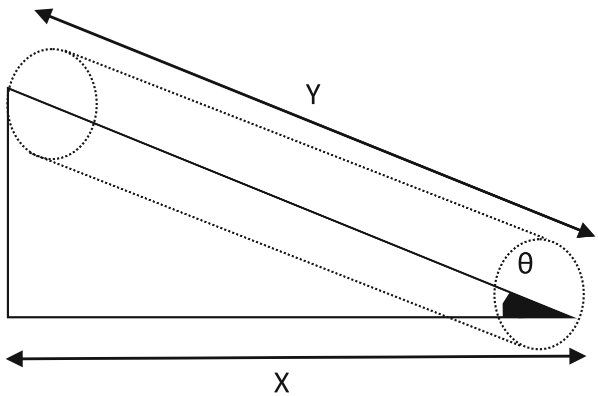


Fig. 4.3 Dimension of belt in conveyor

Fig. 4.4 Measurement of inclined conveyor length



$$Y = \frac{X}{\cos\theta}$$

where X is the horizontal distance between the centre of rollers and θ angle of inclination.

The belt length can be measured along the internal surface of the endless non-tensioned belt [5]. The net length of endless belt is calculated by subtracting the product of thickness of belt and π.

$$\text{Net length}, L_1 = L - \pi \times t$$

where L_1 is the net length, m; L measured length, m; and t thickness of belt, m.

Q.2. The length of a conveyor is 5 m, and the diameters of rollers on extreme ends are 0.4 m and 0.5 m, respectively. Estimate the length of belt required for the installation.

Answer:

$$L = 2C + \frac{\pi}{2}(D_1 + D_2) = 2 \times 5 + \frac{\pi}{2} \times (0.5 + 0.4) = 11.41\ \text{m}$$

Q.3. The length of a conveyor is 4.5 m, and the diameters of rollers on extreme ends are 0.3 m and 0.5 m, respectively. Estimate the minimum length of space required for the installation of belt conveyor at an angle of 30°.

Answer: The length of conveyor (Y) is equal to the addition of distance between the pulley centers (C) and radius of both the pulleys.

$$Y = C + \frac{1}{2}(D_1 + D_2) = 4.5 + \frac{1}{2} \times (0.3 + 0.5) = 4.90\ \text{m}$$

$$X = Y \times \cos\theta = 4.90 \times \cos 30 = 4.24\ \text{m}$$

Q.4. The length of a conveyor is 8 m, and the diameters of rollers on extreme ends are 0.35 m and 0.45 m, respectively. If the thickness of belt is 5 mm, estimate the length of belt required for the installation of belt conveyor at an angle of 25°.

Answer:

$$L = 2C + \frac{\pi}{2}(D_1 + D_2) = 2 \times 8.0 + \frac{\pi}{2} \times (0.35 + 0.45) = 17.26\ \text{m}$$

$$\text{Net length}, L_1 = L - \pi \times t = 17.26 - \pi \times 0.005 = 17.24\ \text{m}$$

$$Net\ Length\ of\ belt = 17.24\ m$$

4.2.3.6 Conveyor Pulley Diameter

Pulleys are fabricated in a vast range of sizes. The choice of pulley takes into consideration the wrap angle (180°), speed of belt, medium of belt strain, tension of belt, width of belt and type of splice of conveyor belt. The minimum diameter of pulley is decided based on the ply separation or actual fractures in the belt. The diameter of pulley can be taken from standard value [6]. Generally, the belts are made of cotton, polyamide, and polyester. The thickness of belts varies from 1.2 to 20.0 mm, 1.1–20.0 mm, and 0.9–18.5 mm for cotton, polyamide, and polyester belts respectively. The driving and snub pulley diameters range from 200 to 1600 mm, which can be selected according to the requirement and as per the specification provided in IS 8531:1986 [6].

4.2.4 Capacity of Belt Conveyor

4.2.4.1 Cross-Sectional Area of Single Horizontal Roller Belt Conveyor

In the case of flat belt, if the angle of surcharge is θ (Fig. 4.5),

$$\tan\theta = \frac{h}{b/2} = \frac{2\,h}{b}\ OR\ h = \frac{1}{2} \times b \times \tan\theta$$

Now, the area of triangle formed:

$$A = \frac{1}{2} \times b \times h = \frac{1}{2} \times b \times \frac{1}{2} \times b \times \tan\theta = \frac{1}{4} \times b^2 \times \tan\theta$$

where b is the width of material on the belt, m, and θ is the dynamic angle of repose/surcharge.

The heap of grains forms a curvature on the belt of conveyor. The cross-sectional area can be measured using curvature of repose. In practice, for simplicity in calculations, it is assumed that the shape formed is triangular.

Q.5. The width of the conveyor belt is 1400 mm, and the angle of surcharge of grain is 25°. Estimate the cross-sectional area of grains on the belt, if single roller belt conveyor is used.

Answer: The width of belt is less than 2 m, therefore:

$B = 1400$ mm $= 1.40$ m $b = 0.9\,B - 0.05 = 0.9 \times 1.4 - 0.05 = 1.21$ m

$$A = \frac{1}{4} \times b^2 \times \tan\theta = \frac{1}{4} \times 1.21^2 \times \tan 25 = 0.171\ \text{m}^2$$

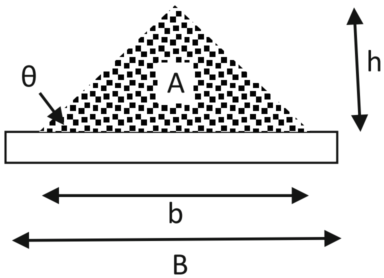


Fig. 4.5 Cross-sectional area of material on single roller belt conveyor

4.2.4.2 Cross-Sectional Area of Triple Roller Troughed Belt Conveyor

Troughing angle is another important factor for the determination of belt capacity (Fig. 4.6). The belts are troughed to allow more material for transportation. The trough angle varies between 15 and 45°, and most common trough angle is 35° for standard three idler rollers with equal length. The angle of surcharge also affects the cross-sectional area. The angle of surcharge depends on the friction between the material and the conveying belt and method of loading material on the belt.

In the case of flat belt, $\tan\theta = \frac{h}{b/2} = \frac{2h}{b}$ $OR\ h = \frac{1}{2} \times b \times \tan\theta$.

Let b be the length of material on the belt, $L =$ length of roller and $a =$ length of material covered on inclined belt on each side.

$$b = L + 2 \times a$$

$$a = \frac{b - L}{2}$$

Let the angle of inclination of roller be λ; then:

$$h_1 = a \times \sin\lambda = \frac{b - L}{2} \times \sin\lambda$$

$$c = a \times \cos\lambda = \frac{b - L}{2} \times \cos\lambda$$

$$\text{Area of part } C = \frac{1}{2} \times (L + (L + 2c)) \times h_1$$

$$\Delta C = \frac{1}{2} \times (2L + 2c) \times h_1$$

$$= \frac{1}{2} \times \left(2L + 2 \times \frac{b - L}{2} \times \cos\lambda\right) \times \left(\frac{b - L}{2} \times \sin\lambda\right)$$

$$= \frac{1}{2} \times (2L + (b - L) \times \cos\lambda) \times \left(\frac{b - L}{2} \times \sin\lambda\right)$$

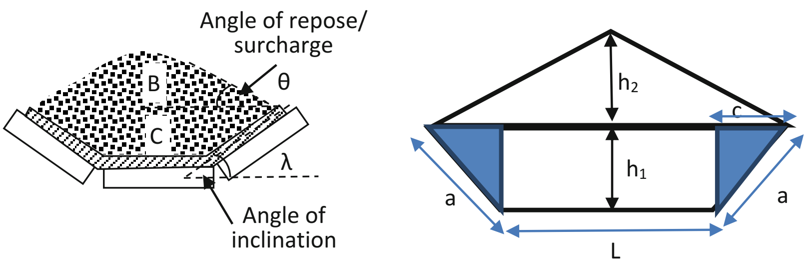


Fig. 4.6 Cross-sectional area of material on triple roller troughed belt conveyor

$$\mathbf{\Delta C} = \frac{1}{4} \times (2L + (b - L) \times \cos\lambda) \times (b - L) \times \sin\lambda$$

Let the dynamic angle of repose/surcharge be θ.

$$h_2 = \frac{1}{2} \times (L + 2c) \times \tan\theta$$

$$\text{Area of part B} = \frac{1}{2} \times (L + 2c) \times h_2$$

$$\Delta B = \frac{1}{2} \times (L + 2c) \times \frac{1}{2} \times (L + 2c) \times \tan\theta$$

$$\Delta B = \frac{1}{4} \times (L + 2c)^2 \times \tan\theta$$

$$\Delta B = \frac{1}{4} \times (L + (b - L) \times \cos\lambda)^2 \times \tan\theta$$

$$\textbf{Total cross sectional area} = \mathbf{\Delta B} + \mathbf{\Delta C}$$

$$= \frac{1}{4} \times (2L + (b - L) \times \cos\lambda) \times (b - L) \times \sin\lambda + \frac{1}{4} \times (L + (b - L) \times \cos\lambda)^2 \times \tan\theta$$

where L is the length of roller, b width of material on the belt, θ dynamic angle of repose/surcharge and λ angle of inclination.

Q.6. The width of the conveyor belt is 2200 mm, and the angle of surcharge of grain and troughing are 25° and 30°, respectively. Estimate the cross-sectional area of grains on the belt, if three rollers of 750 mm for troughed belt conveyor are used.

Answer: The width of the belt is greater than 2.0 m, therefore:

$B = 2200\ \text{mm} = 2.20\ \text{m} \quad b = B - 0.25 = 2.20 - 0.25 = 1.95\ \text{m}$

$$\Delta B = \frac{1}{4} \times (L + (b - L) \times \cos\lambda)^2 \times \tan\theta$$
$$= \frac{1}{4} \times (0.75 + (1.95 - 0.75) \times \cos 30)^2 \times \tan 25 = 0.39\ \text{m}^2$$

$$\mathbf{\Delta C} = \frac{1}{4} \times (2L + (b - L) \times \cos\lambda) \times (b - L) \times \sin\lambda$$
$$= \frac{1}{4} \times (2 \times 0.75 + (1.95 - 0.75) \times \cos 30) \times (1.95 - 0.75) \times \sin 30$$
$$= 0.387\ \text{m}^2$$

$$\textbf{Total cross sectional area} = \mathbf{\Delta B} + \mathbf{\Delta C} = \mathbf{0.39} + \mathbf{0.387} = \mathbf{0.777}\ \text{m}^2$$

4.2.4.3 Estimation of Belt Conveyor Capacity

The capacity of belt can be estimated by multiplying the cross-sectional area of the material on the belt with velocity and bulk density. The belt capacity (kg/s) can be estimated as:

$$BC = A \times v \times \rho$$

where BC is the belt capacity (kg/s), A cross-sectional area of grains (m^2), v velocity of moving belt (m/s) and ρ bulk density of grains (kg/m^3).

The equation can be written in terms of tonnes/h:

$$BC = A \times v \times \rho \times \frac{60 \times 60}{1000}$$

$$BC = 3.6 \times A \times v \times \rho$$

where BC is the belt capacity, tonnes/h.

The quantity of conveying material is dependent on the cross-sectional area of the material conveyed over the belt. The belt should be sufficiently wide to handle the size of lump of materials.

Q.7. The width of the conveyor belt is 600 mm, and the angle of surcharge of grain is 25°. Estimate the belt capacity in tonnes per hour, if single roller belt conveyor is used. The speed of conveyor and bulk density of material are 0.05 m/s and 750 kg/m^3, respectively.

Answer: The width of the belt is less than 2 m, therefore:

$B = 600$ mm $= 0.60$ m $\quad b = 0.9\,B - 0.05 = 0.9 \times 0.60 - 0.05 = 0.49$ m

$$A = \frac{1}{4} \times b^2 \times \tan\theta = \frac{1}{4} \times 0.49^2 \times \tan 25 = 0.028\ \text{m}^2$$

$$BC = A \times v \times \rho = 0.028 \times 0.05 \times 750 = 1.05\ kg/s = 1.05 \times 3.6 = 3.78\ \text{tonnes/h}$$

Q.8. The width of the conveyor belt is 1400 mm, and the angle of surcharge of grain and troughing are 25° and 30°, respectively. Estimate the belt capacity in tonnes per hour, if three rollers of 483 mm for troughed belt conveyor are used. The speed of conveyor and bulk density of material are 0.05 m/s and 750 kg/m^3, respectively.

Answer: The width of the belt is less than 2 m, therefore:

$$B = 1400\ \text{mm} = 1.40\ \text{m} \quad b = 0.9\,B - 0.05 = 0.9 \times 1.4 - 0.05 = 1.21\ \text{m}$$

$$\Delta B = \frac{1}{4} \times (L + (b - L) \times \cos\lambda)^2 \times \tan\theta$$
$$= \frac{1}{4} \times (0.483 + (1.21 - 0.483) \times \cos 30)^2 \times \tan 25 = 0.151\ \mathrm{m}^2$$

$$\mathbf{\Delta C} = \frac{1}{4} \times (2L + (b - L) \times \cos\lambda) \times (b - L) \times \sin\lambda$$
$$= \frac{1}{4} \times (2 \times 0.483 + (1.21 - 0.483) \times \cos 30) \times (1.21 - 0.483) \times \sin 30$$
$$= 0.147\ \mathrm{m}^2$$

$$\textbf{Total cross sectional area} = \mathbf{\Delta B} + \mathbf{\Delta C} = \mathbf{0.151} + \mathbf{0.147} = \mathbf{0.298}\ \mathrm{m}^2$$

$$BC = A \times v \times \rho = 0.298 \times 0.05 \times 750 = 11.175\ kg/s = 11.175 \times 3.6 = 40.23\ \mathrm{tonnes/h}$$

4.2.5 Speed of Belt

The speed of belt can be estimated as:

$$v = \pi \times D \times N$$

where v is the speed of belt, m/s; D diameter of pulley, m; and N number of rotations per second. The belt speed should also be checked from the manufacturer specifications/standards for standard width of belts, and higher value from either estimated or standard value is selected. The speed of belt affects the loading, discharge, transfer arrangements and maintenance of belts.

4.2.6 Driving Force in Belt Conveyor

The peripheral force required for driving the pulley can be estimated considering various resistances, which are offered during movement of belt [3]. Total force on driving pulley T_E (N) can be estimated using the following expression:

$$T_E = R + R_S + R_{Sp1} + R_{Sp2} + R_{SL}$$

where R is the main resistance (N), R_S secondary resistance (N), R_{Sp1} special main resistances (N), R_{Sp2} special secondary resistances (N) and R_{SL} slope resistance (N).

4.2.6.1 Main Resistance (R)

It includes rolling resistance for carrying material return idlers and belt advancement resistance due to impression of idlers in belt and can be estimated using following expression:

$$R = \propto \times f \times L \times g\left[M_c + M_r + (2M_B + M_G)\ \cos\delta\right]$$

where:

α = numerical coefficient dependent on length, L

$= \frac{\text{Total resitance without slope\&special resistance}}{\text{Main resistance}}$ can be obtained from standards [3]

f = artificial friction coefficient

= 0.012 for belt conveyors under no load conditions.

= 0.20 for considering as basic value at normal capacity installations

= 0.30 for material with high internal friction coefficients, troughing angle above 30°, belt speed over 5 m/s, poorly aligned installations, etc.

g = acceleration due to gravity, m/s^2

L = conveyor length (distance between centres)

M_c and M_r = mass of revolving idler parts along the carrying side and return side of the conveyor, respectively, kg/m.

M_B = mass of belt, kg/m.

M_G = mass per metre of handling material, kg/m.

$= \frac{\rho \times Q}{V} \times 1000$

ρ = bulk density of material, tonnes/m^3

Q = volumetric conveying capacity, m^3/s.

V = belt speed, m/s

$\boldsymbol{\delta}$ **=** slope angle from horizontal line in the moving direction

Q.9. A belt conveyor of 12 m length has 12 and 6 rollers of 650 g each on carrying side and return side, respectively. The width of the conveyor belt is 600 mm, and the angle of surcharge of grain is 25°. Estimate the belt capacity in tonnes per hour, if single roller belt conveyor is used. The speed of conveyor and bulk density of material are 0.05 m/s and 0.750 t/m^3, respectively. The conveyor belt moves at an angle of 10° from the horizontal line (assume α = 4.8, f = 0.20 and mass of belt = 2.0 kg/m).

Answer: The width of the belt is less than 2.0 m, therefore:

$B = 600\text{ mm} = 0.60\text{ m}\ \ b = 0.9\,B - 0.05 = 0.9 \times 0.60 - 0.05 = 0.49\text{ m}$

$$A = \frac{1}{4} \times b^2 \times \tan\theta = \frac{1}{4} \times 0.49^2 \times \tan 25 = 0.028\text{ m}^2$$

$$\text{Belt Capacity, m}^3/\text{s} = A \times v = 0.028 \times 0.05 = 0.0014\text{ m}^3/\text{s}$$

$$M_c = \frac{\text{Total number of rollers on conveying side}}{\text{Length of belt}} \times \text{Mass of one roller}$$
$$= \frac{12}{12} \times 0.65 = 0.65\ \text{kg/m}$$

$$M_r = \frac{\text{Total number of rollers on return side}}{\text{Length of belt}} \times \text{Mass of one roller} = \frac{6}{12} \times 0.65$$
$$= 0.325\ \text{kg/m}$$

$$M_B = 2.0\ \text{kg/m}$$

$$\mathrm{M}_G = \frac{\rho \times Q}{V} \times 1000 = \frac{0.750 \times 0.0014}{0.05} \times 1000 = 21\ \text{kg/m}$$

$$R = \propto \times f \times L \times g\ [m_c + m_r + (2M_B + M_G)\ \cos\delta]$$

$$R = 4.8 \times 0.20 \times 12 \times 9.81 \times [0.65 + 0.325 + (2 \times 2.0 + 21)\ \cos 10]$$
$$= 2878.96\ \text{N}$$

4.2.6.2 Secondary Resistance (R_S)

It includes frictional and inertial resistances due to acceleration, friction on side walls, pulley bearing resistances and wrapping of belt on pulley and can be estimated using following expression:

$$R_S = R_s + R_{sks} + R_w + R_b$$

where:

(1) R_S
= inertial and frictional resistance (N), between the handled material and the belt, at the loading point and in the acceleration area

$$R_S = Q \times 1000 \times \rho \times (V - V_o)$$

V_0 = handled material (in the direction of belt motion) conveying speed component, m/s

(2) R_{Sks} = frictional resistance (N) in acceleration area, between handled material and the skirt plate

$$R_{Sks} = \frac{\mu_2 \times Q^2 \times 1000 \times \rho \times g \times l_2}{\left[\frac{V+V_0}{2}\right]^2 \times {b_l}^2}$$

μ_2 = coefficient of friction between skirt plates and material (depends on material of belt and material to be conveyed – measured experimentally).

l_2 = distances from the point of separation to the points situated on the tangent line from which ordinates are to be drawn, m.

b_l = inter-skirt plate width, m.

(3) R_w = wrap resistance between belt and pulley, N

$R_w = 9B \times \left[140 + 0.01 \times \frac{T_{av}}{B}\right] \times \frac{t}{D}$ – for fabric belt

$R_w = 12B \times \left[200 + 0.01 \times \frac{T_{av}}{B}\right] \times \frac{t}{D}$ – for steel cord belt

B = belt width, m.

T_{av} = average tension at the pulley, N.

T = belt thickness, m.

D = diameter of pulley, m.

(4) R_b = pulley bearing resistance except drive pulley, N

$$R_b = 0.005 \times \frac{d}{D} \times R_V$$

Rv = vector sum of two belt tensions: (1) the force acting on the pulley and (2) the forces due to the revolving parts of the pulley, N.

d = shaft diameter inside bearing, m.

D = pulley diameter, m.

4.2.6.3 Special Main Resistances (R_{sp1})

It Includes Drag Resistance Due to Tilt of Idler, Friction against the Complete Chute Flaps and Skirt Plates and Can Be Estimated Using the Following Expression

$$R_{sp1} = R_t + R_{sk}$$

where:

(1) R_t = resistance due to idler tilting, N

$R_t = g \times C_1 \times \mu_0 \times L_1 \times (M_B + M_G) \cos \delta \times \sin i$

– for idlers with three equal rollers

$R_t = g \times \mu_0 \times L_l \times (M_B) \times \cos \tau \times \cos \delta \times \sin i$

– for return idlers with two rollers

g = acceleration due to gravity, m/s^2.

C_1 = coefficient depending upon trough angle.

μo = coefficient of friction between belts and carrying idlers.

L_1 = length of installation equipped with tilted idler, m.

M_B = mass of belt per metre, kg/m.

M_G = mass of handled material on conveyor per metre, kg/m.

δ = conveyor slope angle from horizontal line in the moving direction.

τ = troughing angle of return idlers.

i = tilt angle of idler axis w.r.t. a plane normal to the longitudinal axis of the belt for self-alignment (limited to 2°–3°).

(2) R_{sk} = resistance due to friction between skirt plates and handled material, N

$$R_{sk} = \frac{\mu_2 \times Q^2 \times 1000 \times \rho \times g \times l_{sk}}{V^2 \times b_l^2}$$

μ_2 = coefficient of friction between skirt plates and material.
Q = volumetric conveyor capacity, m^3/s.
ρ = bulk density of material, tonnes/m^3.
g = acceleration due to gravity, m/s^2.
l_{sk} = length of installation equipped with skirt plates excluding loading area, m.
V = belt speed, m/s.
b_l = inter-skirt plate width, m.

4.2.6.4 Special Secondary Resistances (R_{sp2})

The special secondary resistance includes friction with belt and pulley cleaners, friction against the chute flaps and skirt plates, resistance due to inverting return stand, and installation of discharge plough and trippers. It can be estimated using the following expression:

$$R_{sp2} = R_{be} + R_p$$

where:
(1) R_{be} = frictional resistance due to belt cleaners, N

$$R_{be} = A_1 \times \rho \times \mu_3$$

A_1 = contact area between belt and belt cleaner, m^2
ρ = bulk density of material, tonnes/m^3
μ_3 = coefficient of friction between belt cleaner and belt
(2) Rp = resistance (N) at the discharge plough due to friction

$$R_p = B \times K_a$$

B = belt width, m
Ka = scrapping factor, N/m (normally 1500 N/m)

4.2.6.5 Slope Resistance (R_{sl})

It includes resistances offered due to lifting or lowering the material and trippers and can be estimated using the following expression:

$$R_{sl} = m_G \times H \times g$$

where:
M_G = mass per metre of handling material, kg/m
H = lift of conveyor between loading and discharge end, m
g = acceleration due to gravity, m/s^2

4.2.7 Power Requirement

(1) Operating Power Requirement at Drive Pulley.

The requirement of power (kW) to operate driving pulley can be estimated using the driving force and speed of the belt and can be expressed as:

$$P_{oP} = \frac{T_E \times V}{1000}$$

where:

T_E = total force on driving pulley, N

V = belt speed, m/s

(2) Absorbed Power Requirement

The power requirement (kW) may be added with additional force required for considering drive pulley loss and can be modified as:

$$P_A = \frac{T_E \times V}{1000} + \frac{(R_{Wd} + R_{bd}) \times V}{1000}$$

where:

R_{wd} = wrap resistance (N) between belt and pulley for driving pulley.

R_{bd} = pulley bearing resistance (N) to drive pulley.

R_{wd} = wrap resistance between belt and drive pulley, N

$R_{wd} = 9B \times \left[140 + 0.01 \times \frac{T_{av}}{B}\right] \times \frac{t}{D}$ – for fabric belt

$R_{wd} = 12B \times \left[200 + 0.01 \times \frac{T_{av}}{B}\right] \times \frac{t}{D}$ – for steel cord belt

B = belt width, m

T_{av} = average tension at the drive pulley, N.

T = belt thickness, m

D = diameter of pulley, m

R_{bd} = pulley bearing for drive pulley, N

$$R_{bd} = 0.005 \times \frac{d}{D} \times R_V$$

d = shaft diameter inside bearing, m

D = pulley diameter, m

Rv = vector sum of the two belt tensions: (1) the force acting on the drive pulley and (2) the forces due to the mass of the revolving parts of the drive pulley, N.

(3) Motor Output Power.

The power requirement (kW) for motor shaft can be estimated using the efficiency of various transmission elements and can be expressed as:

$$\boldsymbol{P_M = \frac{P_A}{\eta}}$$

where η is the efficiency of various transmission elements.

Q.10. A belt conveyor of 10 m length has eight and four rollers of 500 g each on carrying side and return side, respectively. The width of the conveyor belt is 1400 mm, and the angle of surcharge of grain is 25°. Estimate the belt capacity in tonnes per hour, if single roller belt conveyor is used. The speed of conveyor and bulk density of material are 0.05 m/s and 0.750 t/m^3, respectively. The conveyor belt moves at an angle of 10° from the horizontal line (assume $\alpha = 4.8, f = 0.20$ and mass of belt = 2.0 kg/m). Calculate operating power of the conveyor. The diameters of drive pulley and shaft are 20 cm and 5 cm, respectively. The fabric belt of 5 mm thickness is used in the conveyor. If the average tension of drive pulley and sum of all belt tensions are 50 N and 75 N, respectively, calculate the absorbed power requirement and motor output power at 80% efficiency.

Answer: The width of the belt is less than 2.0 m, therefore:

$B = 600\ \text{mm} = 0.60\ \text{m}\ \ b = 0.9\ B - 0.05 = 0.9 \times 0.60 - 0.05 = 0.49\ \text{m}$

$$A = \frac{1}{4} \times b^2 \times \tan\theta = \frac{1}{4} \times 0.49^2 \times \tan 25 = 0.028\ \text{m}^2$$

$$\text{Belt Capacity, m}^3/\text{s} = A \times v = 0.028 \times 0.05 = 0.0086\text{m}^3/\text{s}$$

$$M_c = \frac{\text{Total number of rollers on conveying side}}{\text{Length of belt}} \times \text{Mass of one roller}$$

$$= \frac{8}{10} \times 0.50 = 0.40\text{kg/m}$$

$$M_r = \frac{\text{Total number of rollers on return side}}{\text{Length of belt}} \times \text{Mass of one roller} = \frac{4}{10} \times 0.50$$

$$= 0.20\ \text{kg/m}$$

$$M_B = 2.0\ \text{kg/m}$$

$$\text{M}_G = \frac{\rho \times Q}{V} \times 1000 = \frac{0.750 \times 0.0086}{0.05} \times 1000 = 128.25\ \text{kg/m}$$

$$R = \propto \times f \times L \times g\ [m_c + m_r + (2M_B + M_G)\ \cos\delta]$$

$$R = 4.8 \times 0.20 \times 10 \times 9.81 \times [0.40 + 0.20 + (2 \times 2.0 + 128.25) \cos 10] = 12262.19\ \text{N}$$

$$= 122.62\ \text{kN}$$

$$P_{oP} = \frac{T_E \times V}{1000}$$

$$P_{oP} = \frac{12262.19 \times 0.05}{1000} = 0.613\ \text{kW}$$

$$R_{wd} = 9B \times \left[140 + 0.01 \times \frac{T_{av}}{B}\right] \times \frac{t}{D}$$

$$R_{wd} = 9 \times 1.4 \times \left[140 + 0.01 \times \frac{50}{1.4}\right] \times \frac{0.005}{0.2} = 44.213\ N$$

$$R_{bd} = 0.005 \times \frac{d}{D} \times R_V$$

$$R_{bd} = 0.005 \times \frac{0.05}{0.2} \times 75 = 0.094\ N$$

$$P_A = \frac{T_E \times V}{1000} + \frac{(R_{Wd} + R_{bd}) \times V}{1000}$$

$$P_A = 0.613 + \frac{(44.213 + 0.094) \times 0.05}{1000} = 0.615\ N$$

$$\boldsymbol{P_M = \frac{P_A}{\eta} = \frac{0.615}{0.80} = 0.769\ kW}$$

The programmer controllers are generally used for controlling the time of operation, conveyor speed, individual drive speed, balancing of load, etc.

4.3 Bucket Elevator

The bucket elevator can be used to move various bulk materials in an upward direction. Vertical elevators are operated by centrifugal force. This makes the materials flow into the discharge chute when it runs at high speed. Centrifugal bucket elevator has the spaced buckets with rounded bottoms. These buckets are organized on elevator either close to each other or arranged apart. Bucket elevator consists of flat chain on which the small bucket is bolted. The rubber belt and plastic bucket may also be used. Pulleys, which are driven by electric motor, are arranged on the top and bottom having specified diameter. The elevator permits the materials sent to chosen bin.

4.3.1 Types of Bucket Elevator

Bucket elevators are primarily fabricated in three different discharge configurations, viz. continuous, centrifugal and positive discharge elevators. The designs provide continuous vertical conveying. Each style performs differently with choice between the three options depending largely on the specific requirements of material.

4.3.1.1 Centrifugal Bucket Elevator (CBE)

The CBEs are better suited for faster, smoother handling applications where degradation/aeration of material is not a concern (Fig. 4.7). This type of material handling is typically used for free-flowing/powdered material. It is often used for wheat, rice, corn and other grains. In this elevator, self-loading mechanism is provided for scooping material from a hopper because it passes through the boot section. When buckets pass over the head pulley, then buckets discharge material by ‘throwing’ it into the discharge chute by centrifugal force. It operates at higher speeds and accommodates greater capacities. Therefore, these elevators are preferred choice at shipping terminals and other high-volume settings. These conveyors use type A1, A2, A3 and A4 buckets as per IS 7167:1974 [7].

4.3.1.2 Positive Discharge Elevators

The construction of positive discharge elevators is similar to centrifugal discharge elevator except installation of a sprocket for pushing the belt and buckets towards the centre of elevator (Fig. 4.8). This assures the complete discharge of materials from the buckets due to complete overturning. These are suitable for elevating lighter, dusty or sticky products, which are difficult to discharge in centrifugal bucket elevator. These conveyors also use type A1, A2, A3 and A4 buckets as per IS 7167:1974 [7].

4.3.1.3 Continuous Bucket Elevator

This elevator operates at slower speeds. It offers gentle handling for materials, which are fragile or susceptible to aeration. They are the preferred choice in applications like potash and other fertilizers where degradation/attrition is the main concern. Continuous bucket elevators are suitable choice for handling materials which are either abrasive or varying in particle size (Fig. 4.9). The handling material is to be fed from a chute into buckets while passing through the boot section. Buckets are arranged and designed in a way that the back of bucket may serve as a discharge surface for the preceding bucket by making the way for grain to discharge in chute via gravity.

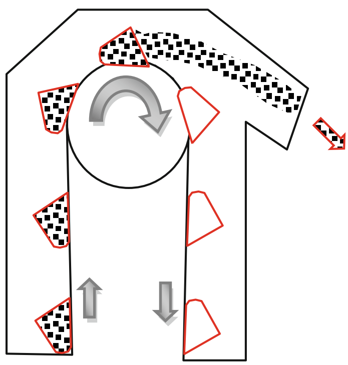


Fig. 4.7 Centrifugal bucket elevator

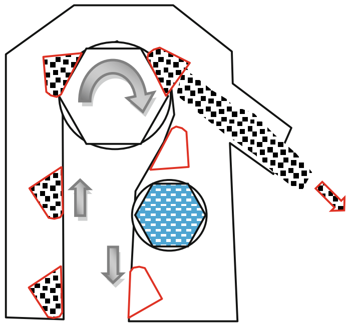


Fig. 4.8 Positive discharge elevators

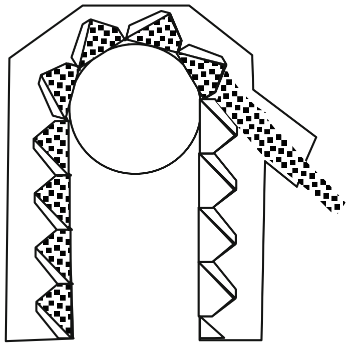


Fig. 4.9 Continuous bucket elevator

4.3.2 Selection for the Type of Bucket Elevator

The bucket elevators should be selected on the basis of properties of material to be conveyed like stickiness, bulk density and size (Appendix A: Table 1). The buckets are fixed on belts or chains. Belt-type bucket elevators (BTBE) provide a cost-effective way for applications like sand handling (a centrifugal belt-type elevator with nylon buckets provides a highly effective as well as economic option in such settings). These are preferred choice when noise is a concern. BTBE are less costly and remain less durable in comparison to chain-type bucket elevators. BTBE are lesser fit for demanding applications like at mine sites and not recommended for hot and combustible material. Further, since large particles might become wedged between bucket and belt and may cause of damage to belt, therefore, the belt-type elevator is best suitable for smaller particle sizes (i.e. roughly $\leq 1/4''$).

Chain-type bucket elevators (CTBE) are suitable for high-capacity operation, handling higher-temperature (greater than 200 °C) material or potentially combustible materials, but remain costlier in comparison to BTBE. This is also suitable for materials of larger particle size. Elevators having larger buckets typically use a dual-chain design. The belt or chains are used to transmit the power as well as carry the bucket. An electric motor is installed at the top to drive the belts, which load the material in the bucket available at the bottom section/boot of the conveyor. The screw and nut assembly are used to control the tension and alignment of the belt.

The characteristics of the materials, which affect the capacity of elevator, are geometry of bucket and speed at which the handling material is being operated. The angle of detachment is known as angle at which the material leaves the bucket. The basic criterion for designing the bucket is given as follows:

- Design of the bucket should be at an angle of 45°.
- For high capacity, tulip-shaped high curvature bucket is considered.
- The deeper buckets should not be preferred in centrifugal bucket elevator for complete discharge of material from the bucket.
- The required size of bucket may also be selected from the given standard size from the manufacturer specifications/standards.

4.3.3 Design of Bucket Elevator

4.3.3.1 Capacity

The capacity of bucket elevator can be estimated using the following expression [7]:

$$T = \frac{F \times C \times \rho \times 3600 \times V \times 10^{-4}}{100 \times S}$$

where T is the bucket elevator capacity, tonnes/h; F constant of percentage filling; C capacity of one bucket, litres; V belt/chain speed, m/s; ρ material bulk density, kg/m^3; and S bucket spacing, m. The recommended values of capacity of buckets, C, can be selected from IS 6833:1973 [8], while the constant of percentage filling, F; belt speed, V; and spacing, S, can be selected from IS 7167:1974 [7].

Q.11. Estimate the capacity of a bucket elevator, which has buckets with 0.5 litre capacities and fitted with 0.2 m distance to elevate wheat (bulk density 800 kg/m^3). The speed of the belt is 2 m/s. Consider the percentage filling constant as 0.8.

Answer: We know that

$$T = \frac{F \times C \times \rho \times 3600 \times V \times 10^{-4}}{100 \times S}$$

$$T = \frac{0.8 \times 0.87 \times 800 \times 3600 \times 2 \times 10^{-4}}{100 \times 0.2} = 20.04 \text{ t/h}$$

4.3.3.2 Selection of Buckets

The selection of the bucket is also based on the type of the material to be handled and the type of elevator. However, the types of buckets are specific to the types of elevators, viz. A-type buckets are used in centrifugal or positive discharge elevators, while B-type buckets are used for continuous discharge elevators (Appendix A: Table 2). The capacity of the bucket for various-sized buckets varies between 0.71 and 48.6 litres per bucket, and detailed specification of size is mentioned in IS 6883: 1973 [8]. The manufacturer should consider the type of bucket, length, projection, thickness of material and method of fixing as per the specification of buckets for designing a bucket conveyor.

4.3.3.3 Selection of Casing and Take-Ups

The dimension of casing should be selected from the given standard dimensions [9]. The take-ups are the arrangements for adjusting the tightness of belt using nut and bolt arrangements. These take-ups in casing of bucket conveyor are provided to make adjustments in distances between shaft centres to balance the elongation that occurred during wearing of belt and for necessary maintenance. The take-ups can be installed at the head or boot shaft. Installation at the head shaft provides advantage of storage of material for some time. It also minimizes the possibility of deterioration of material quality accumulated in the boot section and restricts the mixing of material during reuse of bucket conveyor for different material. It is also recommended for the handling of spherical-shaped material and unapproachable locations of the loading pits. The installed take-ups at the boot shaft provide advantages of easier adjustment of tension and increase the possibility of automatic take-up operations.

4.3.3.4 Selection of Chain and Belt

The chains are preferred for heavy-duty material handling processes and for the hard, hot, lumpy or corrosive material, which may affect the material of the belt. The belts are generally used for handling the grains, free-flowing material and abrasive material. The belts can run on a faster speed in comparison to chain. Any chain from bushed chains, bushed pintle chains, bushed roller chains and combination may be used in bucket elevators, while suitability and long working life of chain depend on the judicious selection.

4.3.4 Estimation of Tension in Chain/Belt

Tension due to chain/belt mass (N):

$$T_a = \text{Elevator height} \times \text{mass of chain/belt per unit length} \times \text{g}$$

where 'elevator height' and 'mass of chain/belt per unit length' are used in metre (m) and kilogramme per metre (kg/m), respectively.

Tension due to bucket mass (N):

$$T_b = \frac{\text{Elevator height} \times \text{mass of one bucket}}{\text{Spacing between the buckets}} \times \text{g}$$

where 'elevator height', 'mass of one bucket' and 'spacing between the buckets' are used in metre (m), kilogramme (kg) and metre (m), respectively.

Tension due to mass of material in buckets (N):

$$T_w = \frac{\text{Elevator height} \times \text{mass of material filled in one bucket}}{\text{Spacing between the buckets}} \times \text{g}$$

where ‘elevator height’, ‘mass of filled material in one bucket’ and ‘spacing between the buckets’ are used in metre (m), kilogramme (kg) and metre (m), respectively.

Tension due to mass of pick-up of the material (N):

$$T_f = \frac{\text{Height factor (Ho)} \times \text{mass of material filled in one bucket}}{\text{Spacing between the buckets}} \times \text{g}$$

where height factor (H_o) represents the pick-up force in metre, $H_o = 10$ m for centrifugal and positive discharge elevator and $H_o = 3$ m for continuous-type elevators, while ‘mass of filled material in one bucket’ and ‘spacing between the buckets’ are used in kilogramme (kg) and metre (m), respectively.

The maximum tension in chains (N) can be estimated using the following expression:

$$T_m = T_a + T_b + T_w + T_f$$

In the case of bucket elevators with belt, the ratio of mass of material loaded in buckets to mass of belt and empty buckets is high; the additional tension should be applied at the boot pulley for effective head pulley drive. Maximum tension in this case can be estimated as:

$$T_m = (1 + K) \times \frac{\text{Mass of material filled in one bucket (kg)}}{\text{Spacing between the buckets (m)}} \times (E\text{levator height} + \text{Height factor}) \times \text{g}$$

where ‘mass of filled material in one bucket’ is in kilogramme (kg) and ‘spacing between the buckets’, ‘elevator height’ and ‘height factor’ are used in metre (m).

Where k is 0.97 for bare pulley drive and screw powered take-up, 0.80 for lagged pulley drive and screw take-up, 0.64 for bare pulley drive with gravity take-up and 0.50 for lagged pulley and gravity take-up.

The maximum value obtained for T_m from the above-mentioned equations should be considered for the selection of belts for the conveyor.

Q.12 A centrifugal bucket conveyor has A1 buckets, which has buckets with 0.87 litre capacity and has a mass of 0.60 kg of each bucket and spaced at 0.3 m. The length of bucket is 150 mm. Estimate various stresses in the chain, if the height of elevator is 6 m. The mass of the chain is 3.5 kg/m. The elevator is used to lift the grain with a bulk density of 850 kg/m^3.

Answer:

$$T_a = \text{Elevator height} \times \text{mass of chain per unit length} \times \text{g} = 6 \times 3.5 \times 9.81 = 206.01\ \text{N}$$

$$T_b = \frac{\text{Elevator height} \times \text{mass of one bucket}}{\text{Spacing between the buckets}} \times g = \frac{6 \times 0.6}{0.3} \times 9.81 = 117.72\ N$$

$$T_w = \frac{\text{Elevator height} \times \text{mass of material filled in one bucket}}{\text{Spacing between the buckets}} \times \text{g}$$

$$= \frac{6 \times (0.00087 \times 850)}{0.3} \times 9.81 = 145.09\ \text{N}$$

$$T_f = \frac{\text{Height factor} \times \text{mass of material filled in one bucket}}{\text{Spacing between the buckets}} \times \text{g}$$

$$= \frac{10 \times (0.00087 \times 850)}{0.3} \times 9.81 = 241.82\ \text{N}$$

$$T_m = T_a + T_b + T_w + T_f = 206.01 + 117.72 + 145.09 + 241.82 = 710.64\ \text{N}$$

4.3.5 Selection of Plies in Belt

The number of plies in the belt can be estimated using the following expression:

$$\text{Number of plies} = \frac{\text{Maximum tension}}{\text{Width of Belt (cm)} \times \text{Working tension per ply (N/cm)}}$$

The minimum number of plies is dependent on the type of material and projection of the buckets used. The light powdery/free-flowing material, heavy and lump-free material, coarse materials and sticky materials have 4–6, 4–7, 5–8 and 7–10 plies, respectively, for the projections of buckets from 100 to 250 mm [7].

4.3.6 Sprocket Diameter and Speed of Elevators

The centrifugal discharge depends on the size of sprocket and speed of bucket for efficient loading of material and discharge. The recommended diameters for head sprocket and boot sprocket and speed of centrifugal discharge bucket elevators are 500–760 mm, 355–585 mm and 1.55 m/s, respectively. The recommended diameters for head sprocket, boot sprocket and snub sprocket and speed of positive discharge bucket elevators are 625–780 mm, 425–635 mm, 300–445 mm and 0.61 m/s, respectively. The recommended diameters for head sprocket, boot sprocket, and snub sprocket of continuous-type bucket elevators may range between 500–735 mm, 445–560 mm, 300–445 mm respectively, while the recommended speed of the elevator should remain between 0.5–0.9 m/s.

4.3.7 Spacing between Buckets

The spacing between buckets is dependent on bucket length and chain speed. The specification of diameters of sprocket/pulley is also provided in IS 7167:1974 [7]. The recommended bucket spacing for centrifugal discharge bucket elevators, positive discharge elevators and continuous-type bucket elevators are 320–630 mm, 500–630 mm and 150–480 mm, respectively [7].

4.3.8 Power Requirement

The power requirement at the head shaft can be estimated using the following expression:

$$\text{Power requirement at head shaft (kW)} = \frac{T_e \times V}{10}$$

where *Te* is the effective tension, *kN*, and *V* belt/chain speed, m/s. The effective tension can be estimated using the following expression:

$$T_e = (\text{Elevator height} + \text{Height factor}) \times \frac{\text{Mass of material in one bucket}}{\text{Spacing between the buckets}} \times \text{g}$$

where 'mass of filled material in one bucket' is in kilogramme (kg) and 'spacing between the buckets', 'elevator height' and 'height factor' are used in metre (m).

$$\text{Motor output, kW} = \frac{\text{Power requirement at head shaft}}{\text{Efficiency of the drive}}$$

Q.13 A centrifugal bucket conveyor has A1 buckets, which has buckets with 6.5 litre capacity. The length of bucket is 350 mm which are spaced at 500 mm. Estimate the power requirement at the head shaft, if the height of elevator is 11 m. The elevator is used to lift the grain with a bulk density of 850 kg/m^3. The speed of the belt is 1.15 m/s. If motor efficiency is 75%, estimate the motor output required to operate the bucket elevator.

Solution: We know that

$$\begin{aligned}\text{The mass of material in one bucket} &= \text{volume of bucket} \times \text{material density}\\ &= 6.5 \times 850/1000 = 5.525\ \text{kg}\end{aligned}$$

$$\begin{aligned}T_e = {} & (\text{Elevator height (m)} + \text{Height factor (m)})\\ & \times \frac{\text{Mass of material in one bucket (kg)}}{\text{Spacing between the buckets (m)}} \times \text{g}\end{aligned}$$

We know that Ho = 10 m for centrifugal and positive discharge elevator

$$T_e = (11 + 10) \times \frac{5.525}{0.50} \times 9.81 = 2276.4\text{N} = 2.276\ \text{kN}$$

$$\text{Power requirement at head shaft (kW)} = \frac{T_e \times V}{10} = \frac{2.276 \times 1.15}{10} = 0.262\ \text{kW}$$

$$\text{Motor output, kW} = \frac{\text{Power requirement at head shaft}}{\text{Efficiency of the drive}} = \frac{0.262}{0.75} = 0.35\ \text{kW}$$

4.4 Screw Conveyor

A screw conveyor (SC) comprises a circular or U-shaped tube in which a helix rotates (Fig. 4.10). The grains are pushed along the bottom of the tube by helix, which leads to easier unpacking of the tube. SC is generally used to transport and/or elevate stuff at controlled and steady rate and in many bulk materials' handling applications like agriculture (i.e. conveying of grains from transport vehicles to storage bins, mixing of grain in storage and movement of grains from bin to central unloading point), chemicals as well as food processing. SC size varies from 100 to 1250 mm in diameter, and its length varies from less than 1 m to more than 30 m [10].

4.4.1 Design Consideration

The cost, availability of material, resistance to corrosion, and resistance to wear are important parameters for designing a screw conveyor. The techno-economic viability and portability are also important factors for the users. For agricultural materials,

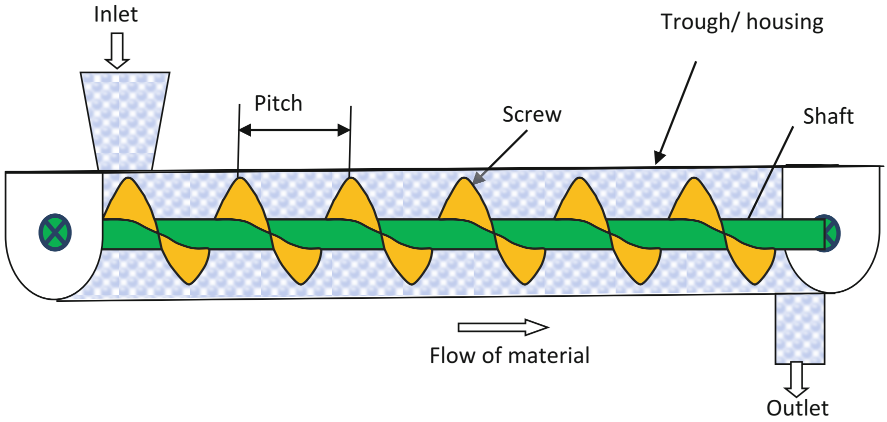


Fig. 4.10 Schematic diagram of screw conveyor

physical properties of materials/grains to be conveyed are also important to be selected.

4.4.2 Design Calculations

The nomenclature of various components is presented in Fig. 4.11, which are required to determine the capacity, selection of size and other parameters.

4.4.2.1 Nominal Size of Screw Conveyor

It represents the diameter of helical screw (*D*) in millimetres. The increase in nominal diameter increases the capacity of screw conveyor. The standard sizes are presented in Table 4.3 [10, 11], which may be selected according to the requirement.

4.4.2.2 Pitch of Screw

The pitch (*S*) is usually kept equal to the nominal size/diameter of the helical screw (*D*). However, it may vary from 0.75 to 1.0 times of nominal size of screw [12]. The pitch of screw varies from 80 to 1000 mm and can be selected from IS 5563: 1985 [10].

4.4.2.3 Shaft Diameter

The solid or tubular shafts may be used for mounting the helical screw. The shaft provides the power to helical screw; therefore, it should be adequately strong to handle the torque generated. The shaft may be hollow or solid. Generally, its diameter (*d*) is also selected according to the nominal size of the screw (Table 4.3).

4.4.2.4 Trough Height and Width

The height (a) of screw is measured from the centre of the shaft till the outer casing of the screw. It is also dependent on the nominal size of the screw. The width of the trough (*c*) also depends on the nominal size of screw and can be obtained from Table 4.3.

4.4.2.5 Radial Clearances

Radial clearances between the outer periphery of helical screw and the interior of the trough are kept for easier movement of the screw. The radial clearance is generally in the range of 5–10 mm, 5–15 mm and 5–20 mm for nominal helical screw, having a

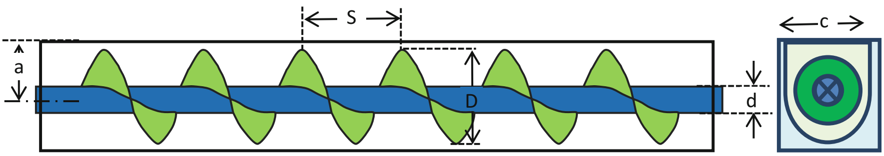


Fig. 4.11 Nomenclature of various parts of screw conveyor

Table 4.3 Specification of screw conveyors [10, 11]

S. no.	Nominal diameter (*D*), mm	Tubular shaft diameter (*d*), mm	Solid shaft diameter (*d*), mm	Trough height (*a*), mm	Trough width (*c*), mm	Radial clearances, mm	Recommended screw speed, rpm
1	100	33.7	30	63	120	5–10	23.6 to 150.0
2	125	33.7	30	75	145	5–10	23.6 to 150.0
3	160	42.4	35	90	180	5–10	23.6 to 150.0
4	200	48.3	40	112	220	5–10	23.6 to 150.0
5	250	60.3	50	140	270	5–10	23.6 to 118.0
6	315	76.1	60	180	335	5–10	19.0 to 118.0
7	400	76.1/88.9	60/70	224	420	5–15	19.0 to 95.0
8	500	88.9/114.3	70/80	280	530	5–15	19.0 to 95.0
9	630	114.3/139.7	80/90	355	660	5–15	15.0 to 75.0
10	800	139.7/152.4	90/100	450	830	5–20	–
11	1000	152.4/193.7	100/110	560	1040	5–20	–
12	1250	193.7	110	710	1290	5–20	–

diameter up to 400 mm, –800 mm and 800–1250 mm, respectively [10]. It is selected based on the properties of the material and working conditions.

4.4.2.6 Guarding

The guarding shall be provided for the revolving screw, rotating shafts, coupling, chains, gears, pulleys and driving belts. Minimum clearance between the guard and moving parts in relation to the size of opening in guards of different materials (perforated metal, woven wire or similar material) can be chosen from the specified standard values [10]. Size of opening, up to 10 mm, 10–13 mm, 13–30 mm and 30–38 mm, may have the minimum clearance of 25, 65, 100 and 130 mm, respectively [10].

4.4.2.7 Conveying Velocity

The conveying velocity of the material can be estimated by multiplying the pitch of the screw (s) with the revolutions per minute (n), and it can be expressed as [11]:

$$V = \frac{s \times n}{60}$$

where V is the conveying velocity, m/s; s screw pitch, m; and n revolutions per minute (rpm).

4.4.3 Capacity of Screw Conveyor

The SC capacity depends upon the nominal diameter of screw, diameter of shaft, pitch of the shaft and rotating speed of the screw. The theoretical conveyance capacity of the screw conveyor can be expressed as [11]:

$$Q = \frac{\pi}{4}\left(D^2 - d^2\right) \times s \times n \times 60$$

$$Q = 47.2\left(D^2 - d^2\right) \times s \times n$$

where Q is the capacity of conveyor, m^3/h; D nominal diameter of screw, m; d diameter of shaft, m; s screw pitch, m; and n revolutions per minute (rpm).

4.4.4 Effect of Inclination on Capacity of Screw Conveyor

The screw conveyors may also be used in conveying the material in inclined position (Fig. 4.12). About 10 to 50% decrease in capacity is observed during the inclination from 5 to 25°. The correction factor 'C' is taken as 1.0, 0.9, 0.8, 0.7, 0.6 and 0.5 with an inclination of 0, 5, 10, 15, 20 and 25°, respectively [11].

A supply chute with variable gate is used to load and unload the material from the screw conveyor and maintain the continuous supply. The product is usually

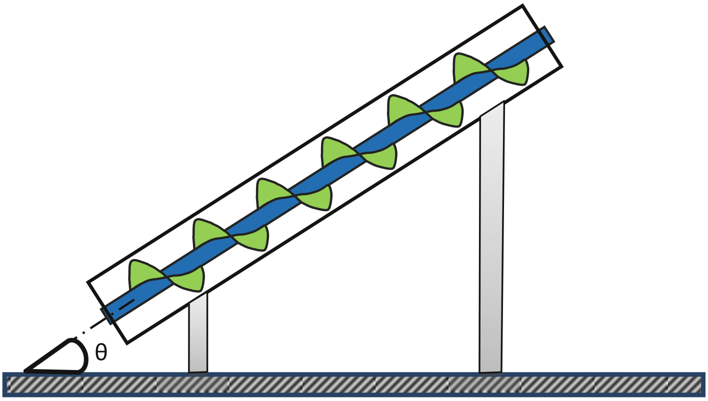


Fig. 4.12 Inclined screw conveyor

discharged from the terminating end of the conveyor; however, intermediate delivery point can also be provided to allow multiple point exit of the material.

Q.14. The dimensions of screw are measured, and it is observed that screw's diameter, pitch and shaft diameter are 31.5, 31.5 and 6 cm, respectively. The conveyor is operated at a speed of 100 rpm. Calculate the forward velocity and capacity of the screw conveyor. If the conveyer is reinstalled at an angle of 15° from horizontal, calculate its revised capacity.

Solution:

Given: D = 31.5 cm = 0.315 m; d = 6 cm = 0.06 m; s = 31.5 cm = 0.315 m; n = 100 rpm

$$V = \frac{s \times n}{60} = \frac{0.315 \times 100}{60} = 0.525\ \mathrm{m/s}$$

$$Q = 47.2 \times \left(0.315^2 - 0.06^2\right) \times 0.315 \times 100$$

$$Q = 47.2 \times (0.0992 - 0.0036) \times 0.315 \times 100$$

$$Q = 47.2 \times (0.0956) \times 0.315 \times 100$$

$$Q = 142.2\ \mathrm{m^3/h}$$

The angle of conveyer during reinstallation = 15°, which indicates correction factor = 0.7

$$Q = 142.2 \times 0.7 = 99.52\ \mathrm{m^3/h}$$

Q.15. A screw's diameter and shaft diameter are 25 and 5 cm, respectively. If the pitch is equal to the screw diameter and 105 m^3/h capacity is required for the designed capacity, estimate the approximate rpm for the purpose.

Solution:

Given: D = 25 cm = 0.25 m;
d = 5 cm = 0.05 m;
p = D = 0.25 m; Q = 105 m^3/h

$$105 = 47.2 \times \left(0.25^2 - 0.05^2\right) \times 0.25 \times n$$

$$105 = 47.2 \times (0.0625 - 0.0025) \times 0.25 \times n$$

$$105 = 47.2 \times (0.06) \times 0.25 \times n$$

$$n = 105/0.708$$

$$n = 148.3$$

$$n \approx 150\ rpm$$

Answer: The screw speed must be kept at 150 rpm for conveying material at a flow rate of 105 m^3/h.

4.4.5 Power Requirement

The power requirement for conveying the material is dependent on the mass of material handled, the flow rate and the type of material to be conveyed. The material factor for wheat, paddy, barley and corn is 0.4, while it is 0.5 and 0.7, respectively, for soybean and peanut. The theoretical power requirement for conveying the material in screw conveyor can be expressed as [11]:

$$P = \frac{Q \times L \times \rho \times F}{4560}$$

where P is the theoretical power requirement, hp.; L conveyor length, m; Q conveyor capacity, m^3/h; ρ bulk density of material, kg/m^3; and F material factor. In the case of theoretical power requirement less than 5.0 hp., to reduce downtime, minimize loss of production and overcome unforeseen conditions, it is multiplied with a correction factor to estimate the actual power requirement. The correction factor values are 2.00, 1.50, 1.25 and 1.10 for theoretical power values of less than 1.0, 1.0 to 2.0, 2.0 to 4.0 and 4.0 to 5.0, respectively.

Q.16. A screw's length, diameter, pitch and shaft diameter are 300, 40, 40 and 6 cm, respectively. The conveyor is operated at a speed of 30 rpm. Calculate the capacity for conveying paddy (material factor = 0.4, bulk density = 650 kg/m^3) and power requirement of the screw conveyor.

Solution:

Given: L = 300 cm = 3.0 m; D = 40 cm = 0.40 m; d = 6 cm = 0.06 m; p = 40 cm = 0.40 m; n = 30 rpm

$$Q = 47.2 \times \left(0.40^2 - 0.06^2\right) \times 0.40 \times 30$$

$$Q = 47.2 \times (0.16 - 0.0036) \times 0.40 \times 30$$

$$Q = 47.2 \times (0.1564) \times 0.40 \times 30$$

$$Q = 88.58\ m^3/h$$

Theoretical power requirement:

$$P = \frac{Q \times L \times \rho \times F}{4560}$$

$$P = \frac{88.58 \times 3.0 \times 650 \times 0.4}{4560}$$

$$P = 15.15 \text{ hp}$$

Since it is greater than 5.0 hp, the actual power requirement is also equal to 15.15 hp.

4.5 Exercise

1. Estimate the capacity of a bucket elevator elevating grains with a bulk density of 820 kg/m^3, which have buckets with 0.55 litre capacity and fitted with 0.3 m distance. The speed of the belt is 2 m/s. Consider the percentage filling constant as 0.7.

[Ans: 7.58 tonnes/h]

2. Estimate the capacity of a bucket elevator elevating seeds with a bulk density of 780 kg/m^3, which have buckets with 0.45 litre capacity and fitted with 0.25 m distance. The speed of the belt is 2.5 m/s. Consider the percentage filling constant as 0.75.

[Ans: 7.90 tonnes/h]

3. A centrifugal bucket conveyor has A1 buckets, which is of 1.53 litre capacity and has a mass of 0.65 kg of each bucket and spaced at 0.3 m. The length of bucket is 170 mm. Estimate various stresses in the chain, if the height of elevator is 6.5 m. The mass of the chain is 3.5 kg/m. The elevator is used to lift the grains having a bulk density of 800 kg/m^3.

[Ans: Ta = 223.18 N, Tb = 138.16 N, Tw = 260.16 N, Tf = 400.3 N, Tm = 1021.74 N].

4. A centrifugal bucket conveyor has A3 buckets, which is of 1.07 litre capacity and has a mass of 0.39 kg of each bucket and spaced at 0.28 m. The length of bucket is 130 mm. Estimate various stresses in the chain, if the height of elevator is 8 m. The mass of the chain is 2.5 kg/m. The elevator is used to lift the grain with a bulk density of 750 kg/m^3.

[Ans: $Ta = 196.2$ N, $Tb = 109.3$ N, $Tw = 224.93$ N, $Tf = 281.16$ N, $Tm = 811.60$ N].

5. A centrifugal bucket conveyor has A1 buckets, which has buckets of 6.0 litre capacity. The length of the bucket is 350 mm and is spaced at 300 mm. Estimate the power requirement at the head shaft, if the height of elevator is 10 m. The elevator is used to lift the grain with a bulk density of 750 kg/m^3. The speed of the belt is 1.10 m/s. If motor efficiency is 70%, estimate the motor output required to operate the bucket elevator.

[$T_e = 2.94$ kN, $P = 0.46$ kW].

6. The screw's diameter, pitch and shaft diameter of a screw conveyor are 29.3, 29.3 and 10 cm, respectively. The conveyor is operated at a speed of 80 rpm. Calculate the forward velocity and capacity of the screw conveyor. If the conveyer is reinstalled at an angle of 10° from horizontal, calculate its revised capacity.

[$Q = 83.91$ m^3/h, Revised $Q = 67.13$ m^3/h].

7. The dimensions of screw are as follows: screw's diameter = 31.5 cm, pitch = 30 cm and shaft diameter = 6 cm. The conveyor is operated at a speed of 60 rpm. Calculate the forward velocity and capacity of the screw conveyor. If the conveyer is reinstalled at an angle of 20° from horizontal, calculate its revised capacity.

[$Q = 81.24$ m^3/h, Revised $Q = 48.75$ m^3/h].

8. A screw's diameter and shaft diameter are 30 and 6 cm, respectively. If the pitch is equal to the screw diameter and 150 m^3/h capacity is required for the designed capacity, estimate approximate rpm for the purpose.

[$N = 123$ RPM].

9. A screw's length, diameter, pitch and shaft diameter are 250, 30, 32 and 6 cm, respectively. The conveyor is operated at a speed of 35 rpm. Calculate the capacity for conveying paddy (material factor = 0.4, bulk density = 680 kg/m^3) and power requirement of the screw conveyor.

[$P = 6.81$ hp].

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Drying

5

Navneet Kumar and Harish Kumar Sharma

Abstract

Drying is a popular technique to preserve the agricultural produce. In this chapter, the importance of drying for the enhancement of shelf life is highlighted. The basic concepts related to state of water are discussed. The material balance calculation is explained by using worked examples. The mechanism of drying, concept of moisture content and equilibrium moisture content are also presented. Various models used in the estimation of equilibrium moisture content are also explained through worked examples. The methods for determination of moisture content are also provided using simple schematic diagrams of instruments/equipment, wherever possible. The psychometrics involved in drying operation is discussed using simple worked examples. The governing heat and mass transfer rules are also presented. The drying rate viz. constant drying rate, falling rate periods are explained. Various models used for thin layer drying and estimation of effective diffusivity and activation energy are also discussed. The working of various dryer used in the industry is also elaborated. The effect of drying on agricultural produce and the advanced drying technologies reported by various researchers are also incorporated to acquaint the students with the recent developments and ignite their minds for further research in drying.

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Keywords

Drying concepts · Moisture content · Equilibrium moisture content · Heat requirements · Psychrometrics · Constant rate drying · Falling rate drying · Thin layer drying · Dryers · Advanced drying technologies

Drying is a popular technique since time immemorial to preserve the crop/food for longer duration. Several methods are available for drying viz. contact drying, forced convection drying, thin layer drying, etc. Drying methods are selected on the basis of properties of food material, viz. moisture content, shape, size, nutritional values of crops to get the desired properties of food material. According to Food and Agriculture Organization (FAO), wastage of foods is about 1.3 billion tonnes per year, which amounts to loss of resources as huge as 1/3 of the food produced globally [1]. Food security can be enhanced not only by increasing production but also with the reduction of post-harvest losses. Therefore, the emphasis is given on drying and storage of agricultural produces for food security.

The appropriate method of harvesting followed by proper transportation, suitable drying technology and adequate storage facilities are essential for the reduction of losses. Quantitative and qualitative deterioration in harvested crop do occur separately or simultaneously. This represents the real loss, which is not limited to the weight loss of the food, but also it includes the loss generated by dust, presence of insects, foreign materials and many more. The quality loss includes presence of various undesired contaminants, damaged kernels, rodent's hairs and pesticides with the produce, which lowers the price of the product. The loss of crop may be enumerated as loss of mass of food over a length of time. The viability of seed is also one of the prime criteria for accessing the germination behaviour, which is also affected during post-harvest processing and storage. The loss of nutritional and biochemical parameters may also be considered as loss of quality.

Drying of fruits and vegetables is one of the vital unit operations after harvesting for prolonged storage of the perishables, which reduces the moisture from the products to a predetermined safe limit [2]. The process of drying of high moisture foods remains a complicated process due to the occurrence of heat and mass transfer simultaneously [3]. Sometimes, drying up to standard moisture content is the need of process to get the highest yield with good quality attributes. Over drying of produce increases the shelf life; however, it may raise quality issues in deterioration of product quality.

Dehydration generally refers to expulsion of moisture to the maximum possible level or bone-dry condition, whereas drying refers to removal of excess undesirable moisture. Drying protects the grains from the attack of insects, moulds and other microorganisms by lowering the water activity and increasing the hardness of products. Harvesting of crops at higher moisture content and subsequent drying to safe moisture levels lead to the better storage stability and yield of the grains. For example, if paddy is harvested at 20–22% moisture and later on dried to 14% moisture content, it has a potential of increasing rice yield by 10% as compared to harvested paddy at 14% moisture content. Therefore, in modern agriculture, the importance of timely drying is immense.

Drying refers to the removal of free water from food products; however, dehydration refers to a process of reducing moisture of food to very low levels. The former requires less energy for decreasing the moisture content and application of heat to raise the temperature and faster evaporation of water; however, the later includes more energy, higher flow rates along with more control on temperature and humidity to remove the water to the lowest possible extent.

Benefits of Drying

Drying of produce provides several benefits like:

1. It allows the longer storage of produce without appreciable loss in quality.
2. It permits farmers to produce quality-enriched value-added product.
3. It reduces the cost of transport.
4. It permits proper planning of available resources like land, labour, etc.
5. It permits uninterrupted availability of the produce throughout the year and also confers advantage of getting higher value during off season.
6. It makes material more suitable for handling in food processing industries.
7. It enhances specific properties, viz. free-flowing nature by reducing cohesion.
8. It eliminates additional undesired moisture, which may otherwise accelerate the corrosion of machinery and storage structures.

Limitations of Drying

The limitations of the drying are:

1. There are more chances of damage of crystals in case of crystalline product.
2. Shrinkage of material and loss of flavour, colour and texture of food material.
3. Loss in nutrient composition of food material.
4. Energy loss in drying operations.

5.1 Basic Concepts

5.1.1 States and Phases of Water

Water is tasteless, odourless and colourless in its pure form. The states and phases are two terms, which are generally used interchangeably for water. The state of water refers to the form of water at a given temperature and pressure, e.g. ice in solid state, water in liquid state and vapour in gaseous state, whereas phase of water refers to the region in which water has uniform physical and chemical properties. Water is available in liquid state at normal temperature and pressure. When solidification of water takes place, its molecules move farther apart at normal pressure, which makes ice to have lesser density as compared to water and show the phenomenon of floatation over the water in liquid state.

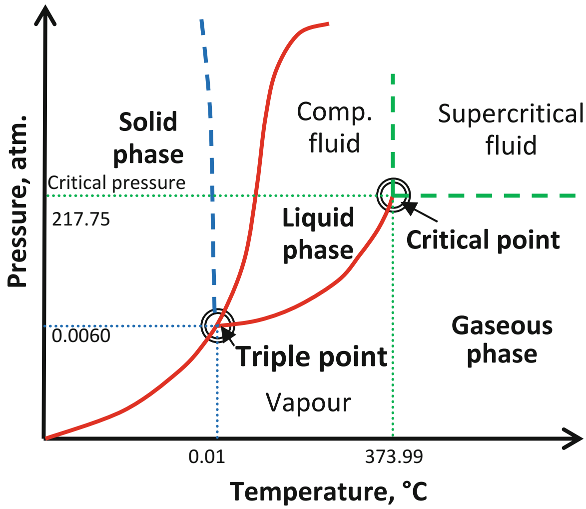


Fig. 5.1 Phase diagram of water

This phenomenon may be attributed to the arrangement of molecules with a low packing efficiency, which describes more space utilization by atoms. The packaging density refers to the ratio of volume occupied within the Van der Waals envelope and to the volumetric space used to contain the molecule. Four straight tetrahedrally oriented hydrogen bonds bound all the water molecules by keeping hydrogen of one molecule adjacent to another oxygen atom of other water molecules. The water volume goes up by about 9% during freezing at 0 °C under normal atmospheric pressure. If pressure is increased, which lowers the melting point, it can result in more increase in volume [4]. The expansion in volume of water during freezing remains responsible for the tissue damages in perishables during freezing under normal pressure condition.

Water remains as a fluid at normal temperature (0–100 °C). This is the form of water, which is the main part of life cycle. This form of water is used for day-to-day purposes including drinking, washing, etc. and used as ingredients in various processed foods. The density of water is maximum at 4 °C, and it decreases with the increase in temperature. Water is also available in the form of vapour, which is present in the air. After getting the energy from the ambience or through boiling, the liquid particles evaporate in the form of water vapour. At normal pressure, steam is created at 100 °C. The steam is used for heating, pasteurization, sterilization and other unit operation in the food processing industry.

The variation of pressure–temperature of water can be observed from the phase diagram of water (Fig. 5.1). The diagram depicts phase boundaries or equilibrium lines between all three phases of water, and the line dividing the solid and liquid phase has negative slope (dotted lines). This shows the unusual property of water having lower density in solid state.

The application of additional pressure can also change the state of water near to the melting point. The liquid phase has shorter distance among water molecules in comparison to solid state. A very rapid movement of water molecules in vapour starts at critical point (temperature of 373.99 °C). The gas phase cannot be liquified above critical temperature even at very high pressure. The pressure applied at critical temperature to make the vapour in liquid state is known at critical pressure. The value of critical pressure is 217.75 atm. The point of intersection of critical temperature and critical pressure is known as critical point.

The boundary line between liquid and gaseous phases of water ends at critical point. When the temperature and pressure are increased further, the gaseous and liquid phases of water cannot be distinguished, and the state is known as supercritical. In water, the critical point occurs at around $T_c = 374$ °C and pressure = 217.75 atm. at density $\rho_c = 322$ kg/m^3 [5].

The triple point of water refers to specific temperature and pressure at which water is available in all three states, i.e. solid, liquid and gaseous states. If the temperature and pressure are less than the triple point, water available in solid form directly sublimates to gaseous phase without the intermediate phase of liquid as water.

In the solid and liquid phases, boundary has positive slope (solid lines) for most of the substances, indicating closeness between the molecules with the increase in pressure, thereby increase in intermolecular forces. Therefore, molecules at higher temperatures have ample energy to break the intermolecular forces and transform into liquid phase. Similarly, the liquid at higher temperatures changes its phase to vapour due to availability of sufficient energy. Water is one of the several exceptions to the rule because of its specific properties.

5.1.2 Vapour Pressure of Water

The vapour pressure of water can be defined as the pressure at which water vapour maintains thermal equilibrium with its condensed state (water/ice). The partial pressure of water vapour can be expressed as the amount of pressure exerted by vapour in air (mixture of vapour and gasses). It remains as the function of temperature and may be related to the propensity of molecules to convert from liquid to gas. The saturated vapour pressure is generally the vapour pressure of a closed system having vapour and liquid in equilibrium.

Following empirical equations were developed for relating saturation vapour pressure to temperature of moist air:

For liquid water at temperature(t) > 0 °C

$$P_s(t) = 0.61121\ \exp\left\{\left(18.678 - \frac{t}{234.5}\right)\left(\frac{t}{257.14 + t}\right)\right\} \tag{5.1}$$

For ice at temperature(t) < 0 °C

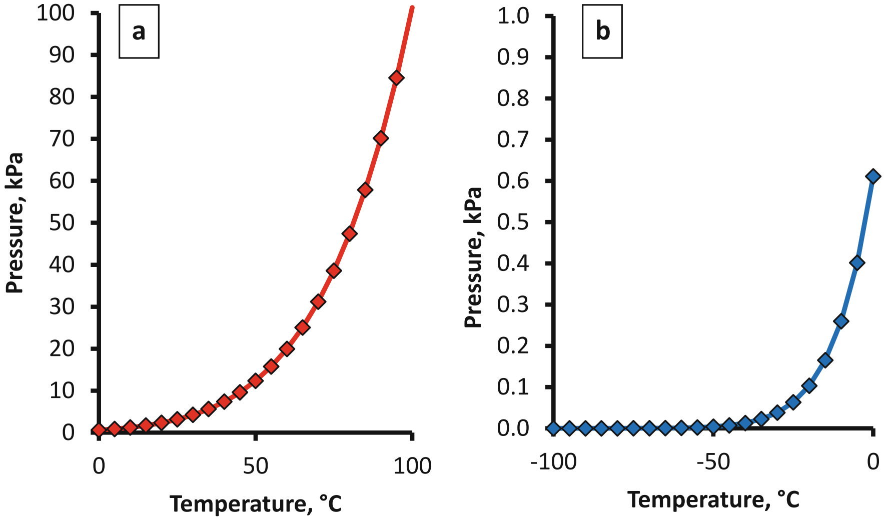


Fig. 5.2 Vapour pressure/temperature curve for (**a**) water and (**b**) ice

$$P_s(t) = 0.61115 \ \exp\left\{\left(23.036 - \frac{t}{333.7}\right)\left(\frac{t}{279.82 + t}\right)\right\} \tag{5.2}$$

where $P_s(t)$ and t are the vapour pressure in kPa and air temperature in °C, respectively.

Boiling starts on the creation of equal vapour pressure with respect to total pressure exerted on water vapour surface. Normally, boiling temperature of water is considered as 100 °C at atmospheric pressure. Water may boil at higher or lower temperatures depending upon the corresponding pressures [6]. The saturation vapour pressure and temperature curves (Fig. 5.2) indicate lower boiling points at lower pressures, which could be utilized in various processes according to retaining nutrients along with sensory characteristics.

5.2 Drying

Drying refers to decrease in moisture of food product by the action of removing water through vaporization of water from a suspension, solution, or high moisture food to reduce the moisture content up to prescribed limits for the enhancement of shelf life. The important aspect of drying is to provide heat to the food product for removal of water through evaporation and to transfer vapours to the ambience. The material balance of drying/dehydration process has two components, i.e. water and air, which are represented in Fig. 5.3:

The diagram of drying or dehydration process represents the loss of mass of food material which remains equal to amount of vapour (moisture) taken away by the hot air. The following equation can represent the mass transfer during drying:

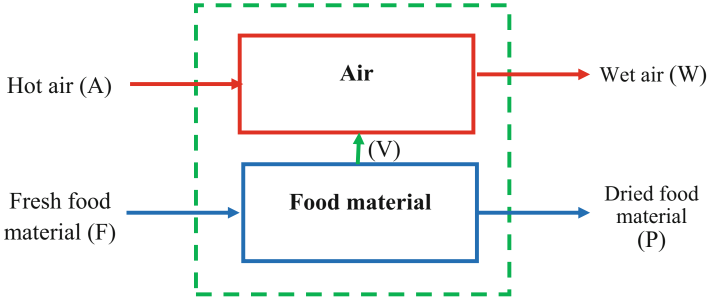


Fig. 5.3 Material balance of drying/dehydration process

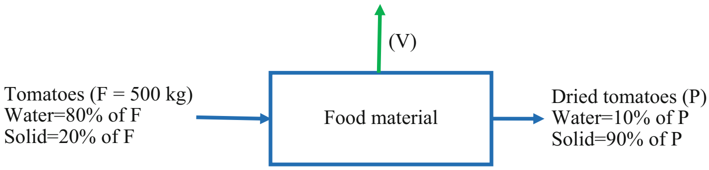


Fig. 5.4 Material balance diagram

$$\text{Total material balance}: A + F = W + P \tag{5.3}$$

$$\text{Food sub} - \text{system}: F = V + P \tag{5.4}$$

$$\text{Air sub} - \text{system}: A + V = W \tag{5.5}$$

Q.1 How much mass reduction of the 500 kg tomatoes would result, if these were dried from 80% to 10% moisture content using hot air dryer?

Solution

Let the amount of dried tomatoes and amount of water evaporated are P and V, respectively (Fig. 5.4).

$$\text{Total material balance}: \mathbf{F} = \mathbf{V} + \mathbf{P}$$

Component balance for Solid:

$$0.20 \times 500 = 0.90 \times \mathbf{P} \rightarrow \mathbf{P} = 111.1 \text{ kg}$$

By keeping the value of **F** and **P** in Total material balance:

$$500 = \mathbf{V} + 111.11 \rightarrow \mathbf{V} = 388.9 \text{ kg}$$

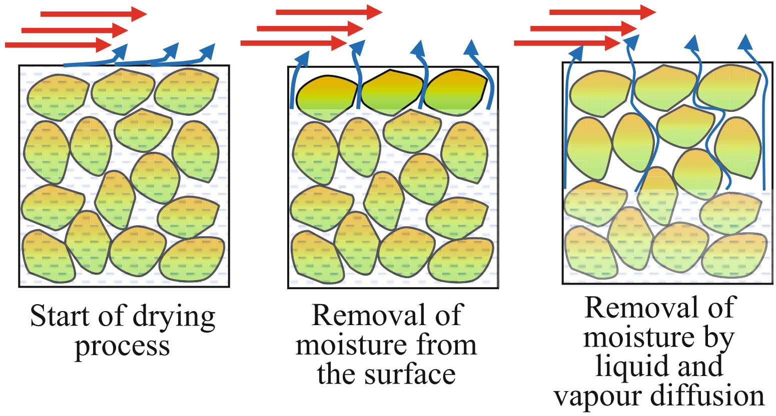


Fig. 5.5 Distribution of moisture during drying of food material

Answer The tomato mass was reduced by 388.9 kg.

During drying operation, heat is transferred through conduction, convection or radiation mode to the food material to evaporate the moisture available at surface of food. However, migration of internal moisture to drying surface occurs simultaneously (Fig. 5.5). Heat provided by drying medium accelerates the evaporation process. The movement of water molecules from higher to lower concentration also occurs due to diffusion, which is considered as the main driving factor for drying or dehydration.

The following factors alone or in combinations may be used to describe the drying behaviour.

1. *Liquid diffusion:* It is generally occurred at a temperature below the boiling point of liquid, and movement of water occurs from inner most part to the surface of the food material due to concentration gradient of water within food.
2. *Vapour diffusion:* The water is vaporized within the food material, and migration of vaporized water from the food to outer surface takes place, which moves further to the ambience due to concentration difference of vapours in the food material.
3. *Surface diffusion:* Process involving the motion (movement) of water molecules at the food material surfaces.
4. *Capillary flow:* Process of moving water through small interstices may be due to capillary action or hydrostatic pressure.

5.3 Moisture

Perishable foods are rich in moisture and nutrients and are therefore prone to microbial attack. Low-moisture foods do not permit the growth of microorganisms; therefore, measurement of moisture is a good indicator of the storage stability of the product. Moisture present in the food material also affects the economical values of the product; therefore, food moisture analysis has a significant role in agro and food processing industries.

Sometimes, the amount of water present in specific food products remains legal requirement according to the regulations. The texture and appearance of food are also dependant on the moisture content of food, which are considered as major quality factors. The storability and quality of the processed food products could also be predicted by estimating moisture content.

According to the convention, moisture contents of grains are usually measured on wet basis, which considers mass of water available per unit mass of wet grains/food product. It is represented as *x*% (wb). The alternative method for representation considers mass of moisture present in food per unit mass of dry grains/food product and represented as *x*% (db), which is the mass of moisture per unit mass of completely dried grain. Usually, the moisture content is represented on wet basis.

The moisture content on wet basis (wb) in food is the amount of moisture present in the food to the total amount of material. It can be represented by the following formula:

$$\text{Moisture content(wb)}, \% = \frac{\text{Amount of water present in food, g}}{\text{Total amount of food, g}} \times 100 \quad (5.6)$$

The moisture content on dry basis (db) in food is the amount of water present in the food to the amount of dry material. It can be represented by the following formula:

$$\text{Moisture content(db)}, \% = \frac{\text{Amount of water present in food, g}}{\text{Amount of dry material in food, g}} \times 100 \quad (5.7)$$

Conversion of Dry Basis to Wet Basis

Let total mass of sample = M, mass of water present = M_w and mass of solid content = M_s.

As we know,

$$\text{Moisture content(wb)}, \% = \frac{\text{Amount of water present in food, g}}{\text{Total amount of food, g}} \times 100$$

$$\text{Moisturecontent(wb)}, \% = \frac{Mw}{M} \times 100$$

We also know that,

$$M = Mw + Ms$$

Therefore, the equation can be written as:

$$\text{Moisture content(wb)}, \% = \frac{Mw}{Mw + Ms} \times 100$$

By inverting, the equation can be written as:

$$\frac{1}{\text{Moisture content(wb)}, \%} = \frac{Mw + Ms}{Mw \times 100}$$

$$\frac{100}{\text{Moisture content(wb)}, \%} = \frac{Mw + Ms}{Mw}$$

$$\frac{100}{\text{Moisture content(wb)}, \%} = \frac{Mw}{Mw} + \frac{Ms}{Mw}$$

$$\frac{100}{\text{Moisture content(wb)}, \%} = 1 + \frac{Ms}{Mw}$$

$$\frac{100}{\text{Moisture content(wb)}, \%} - 1 = \frac{Ms}{Mw}$$

$$\frac{100 - \text{Moisture content(wb)}, \%}{\text{Moisture content(wb)}, \%} = \frac{Ms}{Mw}$$

By inverting again,

$$\frac{\text{Moisture content(wb)}, \%}{100 - \text{Moisture content(wb)}, \%} = \frac{Mw}{Ms}$$

$$\frac{Mw}{Ms} = \frac{\text{Moisture content(wb)}, \%}{100 - \text{Moisture content(wb)}, \%}$$

Multiplying with 100 on both sides,

$$\frac{Mw}{Ms} \times 100 = \frac{\text{Moisture content(wb)}, \%}{100 - \text{Moisture content(wb)}, \%} \times 100$$

$$\textbf{Moisture content(db)}, \% = \frac{\textbf{Moisture content(wb)}, \%}{\textbf{100} - \textbf{Moisture content(wb)}, \%} \times \textbf{100} \tag{5.8}$$

Similarly, expression for moisture content on wet basis can be written as:

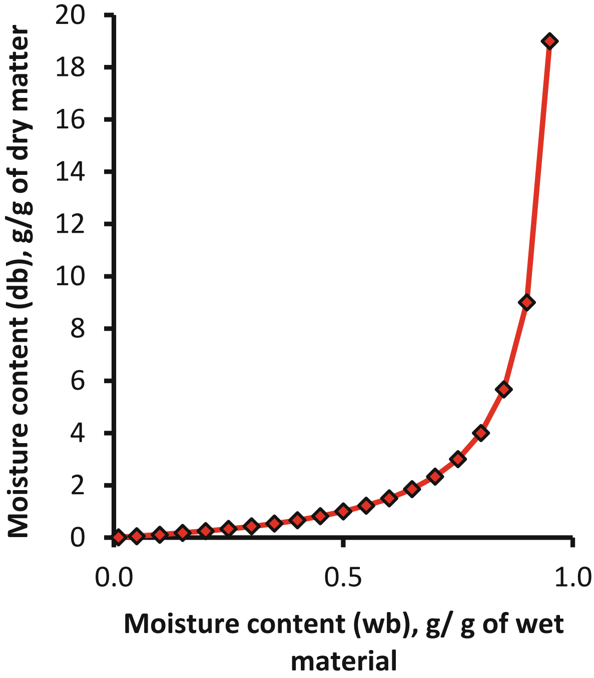


Fig. 5.6 Variation in dry basis with respect to wet basis moisture contents

$$\textbf{Moisture content(wb)}, \% = \frac{\textbf{Moisture content(db)}, \%}{\textbf{100} + \textbf{Moisture content(db)}, \%} \times \textbf{100} \quad (5.9)$$

The following conversion table for moisture content conversion may also be used from wet basis (% wb) to dry basis (% db)and vice versa. A variation of dry basis with respect to wet basis moisture content can be observed in Fig. 5.6.

Wet basis %	Dry basis %	Wet basis %	Dry basis %
1	1.0	50	100.0
5	5.3	55	122.2
10	11.1	60	150.0
15	17.6	65	185.7
20	25.0	70	233.3
25	33.3	75	300.0
30	42.9	80	400.0
35	53.8	85	566.7
40	66.7	90	900.0
45	81.8	95	1900.0

Q.2 In an experiment, a fruit having 85 g mass was dried in a tray dryer till all the water evaporated. The final mass of the fruit was 20 g. Calculate the moisture content of the fruit on wet and dry basis.

Solution

$$\text{Given}: M = 85\ \text{g and Ms} = 20\ \text{g}$$

$$\text{Now, Mw} = M - \text{Ms} = 85 - 20 = 65\ \text{g}$$

$$\text{Moisture content(wb), \%} = \frac{\text{Amount of water present in food, g}}{\text{Total amount of food, g}} \times 100$$

$$\text{Moisture content(wb), \%} = \frac{65}{85} \times 100 = 76.47\%$$

$$\text{Moisture content(db), \%} = \frac{\text{Amount of water present in food, g}}{\text{Amount of dry material in food, g}} \times 100$$

$$\text{Moisture content(db), \%} = \frac{65}{20} \times 100 = 325\%$$

Alternatively,

$$\text{Moisture content(db), \%} = \frac{76.47}{(100 - 76.47)} \times 100 = \frac{76.47}{23.53} \times 100 = 324.98\% \approx 325\%$$

5.3.1 Determination of Moisture Content

The determination of moisture content of agricultural produce may be performed by several methods based on various factors like the form of water present, relative amount of water, duration of measurement, accuracy, cost of equipment, number of samples handled, etc. Broadly, these methods can be sub-grouped into two groups based on the measurement of moisture in the food.

5.3.1.1 Direct/Primary Methods

Moisture content is determined by removing the moisture present in the sample and then by measuring mass and estimating the weight loss of the sample. These methods provide precise results, but the test duration is longer. These are quite popular in laboratory rather than field work. Following methods are used to remove the moisture from the samples using convection, microwave, and infrared radiation.

Air Oven

A hot air oven with a provision to control the temperature in the heating space up to 150 ± 1 °C, a digital weighing scale for measuring the mass, thermal resistance containers, or petri-dishes are required for determination. In case of low moisture products, viz. cereals, pulses, etc. having moisture less than 13%, 2–3 g of samples should be ground without creating much heat during grinding to avoid any loss of water at this stage. The samples are then kept in hot air oven and temperature should be set as per the requirement of the sample. After reaching the desired temperature, 1–2 h is required for the removal of moisture. Thereafter, samples should be transferred to desiccators to cool down and avoid absorption of moisture from the ambience. At least three replications are required for the determination of moisture.

In case of measuring the moisture of unground sample, about 25–30 g samples is needed, and it should be kept at 100 °C in hot air oven. About 72–96 h is required to remove the moisture completely. Thereafter, the samples should be transferred to desiccators, and the mass of dried sample is measured for the estimation of moisture contents [7].

For the determination of moisture content in dehydrated vegetables, about 5 g of ground sample is generally kept at 105 $\pm$ 1 °C for 2 h [8]. The drop in the mass of grain is measured as the amount of moisture present in the sample and can be estimated using Eqs. (5.1) and (5.2).

Vacuum Oven

About 2–3 g of ground cereals is kept in an oven at 25 mm Hg vacuum and is generally dried at 100 °C for 72 h [7]. The material having high moisture like vegetables or heat-sensitive food materials can be kept in vacuum oven at a lower temperature of 85 °C for 635 mm of Hg for 4 h for the removal of complete moisture [9]. The vacuum maintained should be released slowly for avoiding bubbling up of samples. After releasing the air into the oven, the vacuum is released followed by cooling in desiccators to ambient temperature [10].

Brown–Duvel Fractional Distillation

Distillation separates the mixture of liquids into different fractions, which differs in boiling point (Fig. 5.7). Fractional distillation of water takes place while heating the samples in oil with higher boiling points. About 100 g sample is added to 150 ml mineral oil in a flask. In this method, mineral oil is heated in the flask, and moisture determination may be completed within 30 min, which can be observed by discontinuation of flow through condenser. The moisture is evaporated, condensed in a condenser, and collected in a graduated cylinder. The amount of water can be measured. The method remains useful for the determination of moisture for volatile oil containing spices and herbs, which are dissolved in organic solvents.

Infrared Moisture Meter

Water is directly removed from the energy provided by an infrared bulb. It is mainly used for powders. The apparatus consists of infrared bulb, counter balanced pan, weighing chain and balance (Fig. 5.8). The infrared bulb is fixed on the opening cover, and the height of the bulb can be adjusted. A pre-calibrated scale for estimating moisture in percentage is placed inside the apparatus. A knob is provided to adjust the scale, which is adjusted to ‘zero’, before starting the measurement. The

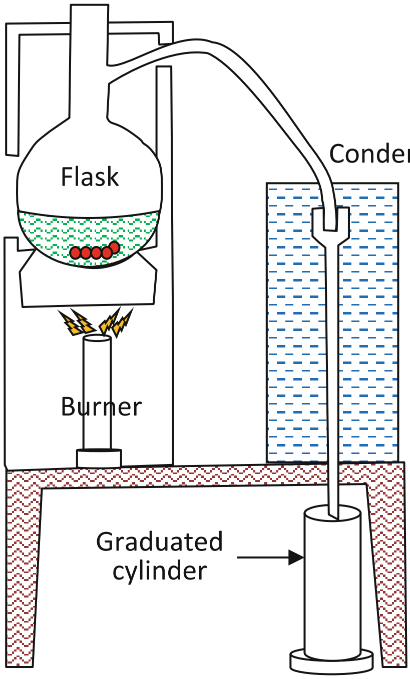


Fig. 5.7 Brown–Duvel fraction distillation apparatus

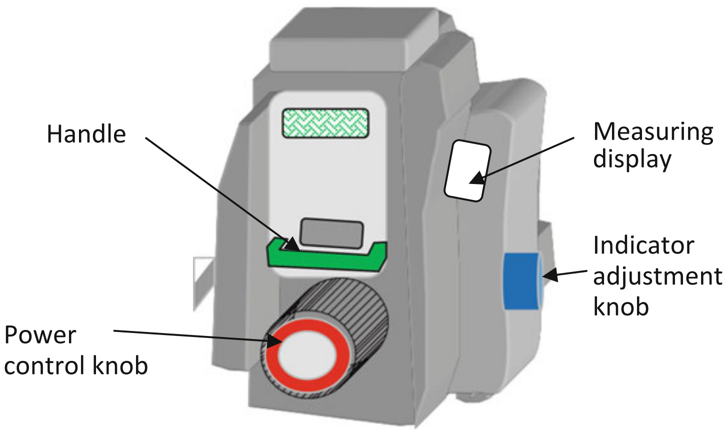


Fig. 5.8 Infrared moisture meter

moisture content reading can directly be observed after the complete evaporation of moisture from the sample.

5.3.1.2 Indirect/Secondary Methods

The methods are used to measure various properties of food, which varies with alteration in moisture content of food materials. Intermediate variable is measured and then converted into moisture content. The calibration curve/charts are prepared for the application of indirect measurements. These methods also provide fairly accurate results in a shorter period.

Chemical Method

Calcium carbide (CaC_2) is used to measure the grain moisture content. It reacts with the moisture present in the sample, which produces calcium hydroxide along with acetylene gas.

The predetermined amount of well-ground food powder is filled in an airtight bottle along with calcium carbide and metallic balls (Fig. 5.9). The bottle is shaken well for proper mixing of the ingredients. As a result of this, acetylene gas is produced, and the pressure generated in the bottle provides the deflection in the moisture gauge attached to the bottle. The moisture meter used in this chemical method is also known as rapid moisture meter due to faster measurements. The chemical reaction can be given as:

$$CaC_2 + 2H_2O \rightarrow Ca(OH)_2 + C_2H_2 \tag{5.10}$$

Electrical Resistance Method

The moisture content of the agricultural and food materials may be determined using electrical resistance or conductance of materials as these properties vary with the change in moisture. These properties can also be used for the estimation of mechanical stress and germination of agricultural produce. Conductivity can be estimated by measuring the resistance of materials of known volume by passing specific current at

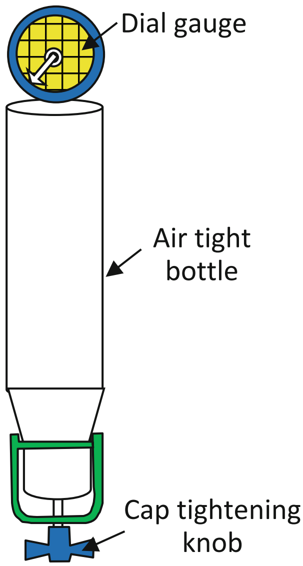


Fig. 5.9 Rapid moisture meter

specific voltage difference. It can be obtained by passing the electric current in a unit length (L) of material through a unit cross-sectional area (A) and with resistance (R) of the food sample, and it remains inverse of electrical resistivity and can be represented as [11].

$$\sigma = {}^{L}\!/_{A \times R} \tag{5.11}$$

The moisture analyser measures the electrical resistance of grains at a specific temperature and compaction level. These are calibrated for various grains and provide the moisture content directly.

Dielectric Method

The dielectric material has the capacity to store energy during the application of external field. The difference in storage of charge can be observed and quantified by placing the food material between the parallel plates of capacitor. The grains are filled in the chamber, and high-frequency current is passed for the estimation of capacitance (Fig. 5.10), which correlates with the moisture of the grain. The degree of compaction and grain temperature are important consideration, while measuring the moisture content.

Near-Infrared Method

Near infrared (NIR) spectroscopy method works on the principle of absorbing near-infrared light due to the presence of molecular bonds at specific wavelengths. The 'O-H' bond in water absorbs the wavelengths at about 970–1940 nm and is proportional to the amount of moisture present in the samples. The light strikes samples and detector measures the absorbance of light by the food sample or transmittance of light through the sample (Fig. 5.11). The detector generates the signals, which are processed according to the amount of moisture present to a specific value into a digital display. The value can be observed directly in percentage or any other specified unit. The sample requirement is about 100–200 g, which is placed in a

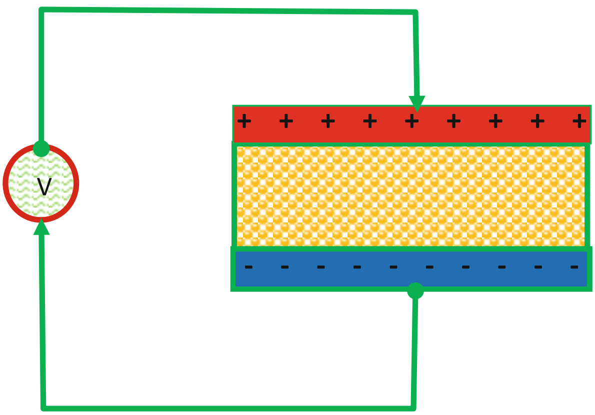


Fig. 5.10 Moisture measurement using dielectric methods

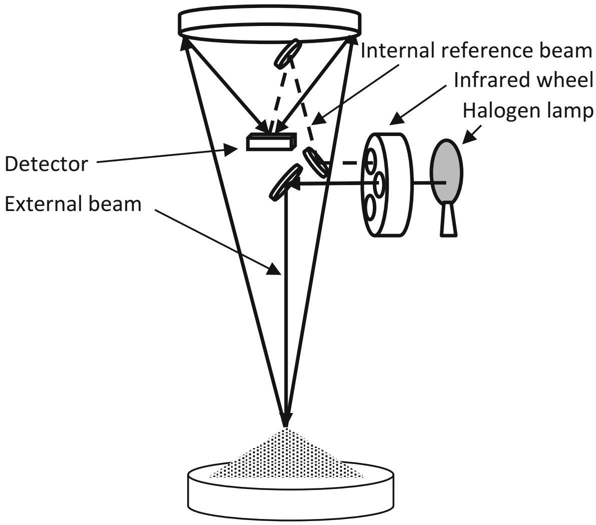


Fig. 5.11 Moisture measurement using NIR method

round sample dish ($\phi = 140$ mm) in the instrument, and the direct result is shown in percent (g/100 g).

NIR also remains useful in quantitative estimation of food elements along with moisture and requires calibration for specific component. The calibration curve prepared using known concentrations of samples make the machine to understand the concentration of unknown samples. After completing the calibration, the instrument has a capability to measure moisture content along with fat and protein simultaneously. The repeatability ranges about 0.32–0.36%, for moisture content.

5.4 Equilibrium Moisture Content

The equilibrium moisture content (EMC) can be defined as the moisture content of food material in equilibrium with the ambient air at a specific temperature and relative humidity, and the food material neither loses nor gains moisture at this condition. In this condition, the vapour pressure of the bound moisture of the food material becomes equal to the vapour pressure of the ambient air. The bound water is referred as the chemically and physically attached water to solid matrix and has lower vapour pressure in comparison to pure liquid at the same temperature. Hence, free moisture is the amount of available moisture in a food above equilibrium moisture content (Fig. 5.12). The EMC of food material is also lowered with the rise in temperature at specific relative humidity.

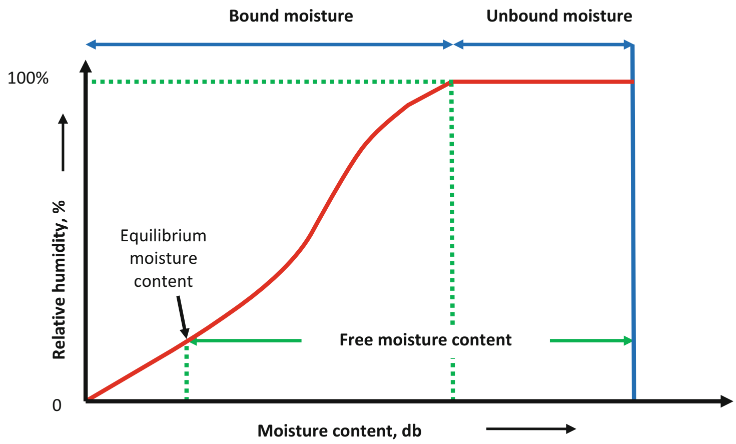


Fig. 5.12 Types of moisture based on bonding and availability

5.4.1 Estimation of Equilibrium Moisture Content

The equilibrium moisture content can be determined using static, dynamic or empirical relations. The food material is kept at specific set of temperature and relative humidity and allowed to gain/lose moisture to establish equilibrium with the ambiance.

Usually, the food material is kept in incubators at a specific temperature and relative humidity. However, food takes many days or weeks to reach its equilibrium moisture content in static condition. The food material with higher moisture gets sufficient chances to be get affected by moulds, when samples are kept at higher relative humidity. Whereas, in dynamic method, the food is kept in small closed containers/desiccators, and humidity and temperature are controlled. The containers are kept at specific temperature and humidity. The relative humidity may also be maintained by keeping the different concentration of acids (sulphuric/nitric/hydrochloric) or salt solutions. Generally, salt is preferred due to its stability, less expansive, less dangerous, and corrosive in comparison to acids.

A number of relationships between relative humidity and equilibrium moisture content have been established by various researchers using theoretical/empirical/semi-theoretical approach. Henderson (1952) as well as Chung and Pfost (1967) models are popular for the estimation of equilibrium moisture content of grains, which can be expressed ass:

Henderson's equation:

$$1 - \mathrm{rh} = \exp\left(-cTM_e{}^n\right) \tag{5.12}$$

Chung and Pfost's equation:

$$\ln(\mathrm{rh}) = \frac{-A}{RT}\ \exp\left(-BM_e\right) \tag{5.13}$$

The Chung and Pfost's equation remains valid in between 20% and 90% relative humidity.

Where RH = relative humidity, decimal; T = absolute temperature, K; M_e = equilibrium moisture content, % db; R = universal gas constant (8.315 J/K·mol); c & n = constants for Henderson's equation; A & B = constants for Chung and Pfost's equation.

Q.3 The grains are kept at a temperature of 35 °C and 40% relative humidity. The coefficients of Henderson's equations 'c' and 'n' are 1.2×10^{-6} and 1.7, respectively. Estimate the equilibrium moisture content of grain on dry and wet basis.

Solution

$$t = 35^{\circ}\mathrm{C}$$

$$T = 273 + 35 = 308^{\circ}\mathrm{K}$$

$$\mathrm{rh} = 40\% = 0.40$$

$$1 - \mathrm{rh} = \exp\left(-cTM_e{}^{n}\right)$$

$$1 - 0.40 = \exp\left(-1.2 \times 10^{-6} \times 308 \times M_e{}^{1.7}\right)$$

$$0.60 = \exp\left(-1.2 \times 10^{-6} \times 308 \times M_e{}^{1.7}\right)$$

$$\ln(0.60) = -1.2 \times 10^{-6} \times 308 \times M_e{}^{1.7}$$

$$-0.5108 = -1.2 \times 10^{-6} \times 308 \times M_e{}^{1.7}$$

$$\frac{-0.5108}{-1.2 \times 10^{-6} \times 308} = M_e{}^{1.7}$$

$$1382.1 = M_e{}^{1.7}$$

$$M_e = (1382.1)^{1/1.7}$$

$$M_e = 70.37\%, \mathrm{db}$$

$$\text{Moisture content(wb), \%} = \frac{\text{Moisture content(db), \%}}{100 + \text{Moisture content(db), \%}} \times 100$$

$$\text{Moisture content(wb), \%} = \frac{70.37}{100 + 70.37} \times 100 = 41.30\%$$

Q.4 A food material is kept at a temperature of 40 °C and 75% relative humidity. The coefficients of Chung and Pfost's equation 'A' and 'B' are 1.2×10^5 and 0.25, respectively. Estimate the equilibrium moisture content of food on dry and wet basis.

Solution

$$t = 40^{\circ}\text{C}$$

$$T = 273 + 40 = 313^{\circ}\text{K}$$

$$\text{rh} = 75\% = 0.75$$

$$\ln(\text{rh}) = \frac{-A}{RT}\ \exp(-BM_e)$$

$$\ln(0.75) = \frac{-1.2\text{x}10^5}{8.315 \times 313}\ \exp(-0.25 \times M_e)$$

$$-0.2877 = -46.1078 \times\ \exp(-0.25 \times M_e)$$

$$\exp(-0.25 \times M_e) = \frac{-0.2877}{-46.1078} = 0.00624$$

$$-0.25 \times M_e = \ \ln(0.00624)$$

$$-0.25 \times M_e = -5.0767$$

$$M_e = 20.31\%, \text{db}$$

$$\text{Moisture content(wb)}, \% = \frac{\text{Moisture content(db)}, \%}{100 + \text{Moisture content(db)}, \%} \times 100$$

$$\text{Moisture content(wb)}, \% = \frac{20.31}{100 + 20.31} \times 100 = 16.88\%$$

Q.5 A set of two experiments were conducted to estimate the coefficients of Henderson's equation 'c' and 'n' for a specific grain and values are given in the following table:

Experiment number	Temperature, °C	Relative humidity, %	Equilibrium moisture content, % db
1	45	55	11
2	50	70	14

Solution

Experiment 1:

$$t = 45^{\circ}\mathrm{C}$$

$$T = 273 + 45 = 318^{\circ}\mathrm{K}$$

$$\mathrm{rh} = 55\% = 0.55$$

$$1 - \mathrm{rh} = \exp\left(-cTM_e{}^n\right)$$

$$1 - 0.55 = \exp\left(-c \times 318 \times 11^n\right)$$

$$0.45 = \exp\left(-c \times 318 \times 11^n\right)$$

$$\ln(0.45) = -c \times 318 \times 11^n$$

$$\frac{\ln(0.45)}{318} = -c \times 11^n \tag{5.14}$$

Experiment 2:

$$t = 50^{\circ}\mathrm{C}$$

$$T = 273 + 50 = 323^{\circ}\mathrm{K}$$

$$\mathrm{rh} = 70\% = 0.70$$

$$1 - 0.70 = \exp\left(-c \times 323 \times 14^n\right)$$

$$0.30 = \exp\left(-c \times 323 \times 14^n\right)$$

$$\ln(0.30) = -c \times 323 \times 14^n$$

$$\frac{\ln(0.30)}{323} = -c \times 14^n \tag{5.15}$$

Dividing Eq. (5.14) with Eq. (5.15):

$$\frac{\ln(0.45)}{318} \Big/ \frac{\ln(0.30)}{323} = \frac{-c \times 11^n}{-c \times 14^n}$$

$$0.674 = \left(\frac{11}{14}\right)^n$$

$$0.674 = (0.7857)^n$$

$$\ln\ (0.674) = n \times\ \ln\ (0.7857)$$

$$-0.1713 = n \times (-0.1047)$$

$$n = \frac{-0.1713}{-0.1047} = \mathbf{1.6359}$$

Keeping the value of n in Eq. (14):

$$\frac{\ln(0.45)}{318} = -c \times 11^{1.6359}$$

$$\frac{-0.7985}{318 \times 11^{1.6359}} = -c$$

$$c = \frac{0.7985}{16070.94} = \mathbf{4.97 \times 10^{-5}}$$

5.5 Heat Requirements

5.5.1 Sensible Heat

The temperature of food material remains in equilibrium with the ambience. The amount of heat transfer depends upon specific heat of the food material, which is defined as the amount of heat required to raise the temperature of 1 kg material by 1 °C. The amount of heat required can be represented as

$$Q = m \times C_p \times \Delta T \tag{5.16}$$

where Cp is the specific heat of the material in kJ/kg °C.

5.5.2 Latent Heat

The energy required to vaporize the water depends upon its temperature. The latent heat of vaporization refers to the extent of energy needed for evaporating 1 kg of water, whereas latent heat of sublimation provides the energy needed to convert from ice to vapour.

$$Q = m \times \lambda \tag{5.17}$$

where λ is the latent heat of vaporization in kJ/kg.

Q.6 Tomatoes containing 94% moisture content are kept at 100 °C for drying up to 12% moisture content. The amount and initial temperature of tomatoes are 50 kg and 21 °C, respectively. Estimate the amount of required energy at atmospheric pressures for the following set of conditions: (1) The latent heat of vaporization is 2257 kJ/kg at 100 °C and specific heat capacities of the tomatoes and water can be taken as 2.02 and 4.186 kJ/kg°C, respectively. Estimate the amount of energy requirement/kg water removed too. (2) If the tomatoes are dried at 58 °C under 20 kPa abs saturation pressure in place of 100 °C and atmospheric pressure, estimate the energy needed for removal of moisture per unit mass of tomatoes. The latent heat of vaporization at 20 kPa is 2358 kJ/kg. (3) If the tomatoes are freeze dried at 0 °C, then estimate the amount of energy needed per kg of raw material at 0 °C. The latent heat of sublimation is 2838 kJ/kg.

Solution

1. *CASE I*: Initial moisture = 94%;

$$\text{Moisture content (wb)}, \% = \frac{\text{Amount of water present in tomatoes, kg}}{\text{Total amountoftomatoes, kg}} \times 100$$

$$94 = \frac{\text{Amount of water present in food, kg}}{50} \times 100$$

$$\text{Now, the amount of water present in tomatoes} = 47\ \text{kg}$$

$$\text{Amount of dry matter} = \text{Total amount of tomatoes} - \text{Amount of water present}$$

$$= 50 - 47 = 3\ \text{kg}$$

Case II: Final moisture = 10%,

$$\text{Moisture content (wb)}, \% = \frac{\text{Amount of water present in tomatoes, kg}}{\text{Total amount of tomatoes, kg}} \times 100$$

$$12 = \frac{\text{Amount of water present in tomatoes, kg } (w)}{3 + \text{Amount of water present in tomatoes, kg } (w)} \times 100$$

$$12 \times (3 + w) = w \times 100$$

$$36 + 10 \times w = w \times 100$$

$$36 = w \times 90$$

$$w = \frac{36}{90} = 0.4\ \text{kg}$$

$$\text{The amount of water available in the final product} = 0.4\ \text{kg}$$

$$\text{The amount of water that must be evaporated} \\ = \text{Initial amount of water} - \text{final amount of water} = 47 - 0.4 = 46.6\ \text{kg}$$

$$\text{Energy needed for 50 kg of tomatoes} \\ = \text{Energy needed to increase temperature up to } 100^{\circ}\text{C} \\ + \text{Latent heat (vaporization)}$$

$$= 50 \times (100 - 21) \times 2.02 + 46.6 \times 2257$$

$$= 7979 + 105176 = \mathbf{113155\ kJ}$$

$$\text{Energy needed per kg of water removed} = \text{Energy needed}/\text{Amount of water evaporated}$$

$$= 113155/46.6 = \mathbf{2428\ kJ/kg}$$

2. ***Energy required for tomatoes in vacuum drying*** = Heat needed to increase temperature up to 58 °C + latent heat (vaporization)

$$= 50 \times (58 - 21) \times 2.02 + 46.6 \times 2358$$

$$= 3737 + 109882.8 = \mathbf{113619.8\ kJ}$$

$$\text{Energy needed per kg water of removed} = \mathbf{2438\ kJ/kg}$$

3. ***Energy needed for tomatoes in freeze drying*** = *Latent heat* (*sublimation*)

$$= 46.6 \times 2838 = \mathbf{132250.8\ kJ}$$

$$\text{Energy/kg water removed} = \mathbf{2838\ kJ/kg}$$

5.6 Psychrometrics

The temperature and humidity of drying air are of prime importance for deciding the capacity of a dryer. Psychrometry deals with thermodynamic properties of moist air and is used in the analysis of humid air conditions and several food processes. In case of lower humidity air, moisture is taken away from the material and is added to the air gradually till saturation. The droplets are formed due to further addition of moisture, and the pressure exerted by water vapours equalizes with saturation vapour pressure at that temperature.

The constituent gases exert total pressure, wherein pressure exerted by any specific constituent gas is termed as partial pressure of specific constituent gas. This partial pressure relates to the number of moles available in the system (Fig. 5.13). The total pressure of gases is equal to partial pressure generated by all the gases. According to the Dalton's law:

$$P_{\text{Total}} = P_{\text{gas A}} + P_{\text{gas B}} + \ldots.. + P_{\text{gas n}} \tag{5.18}$$

The mole fraction and partial pressure of gas can be determined as:

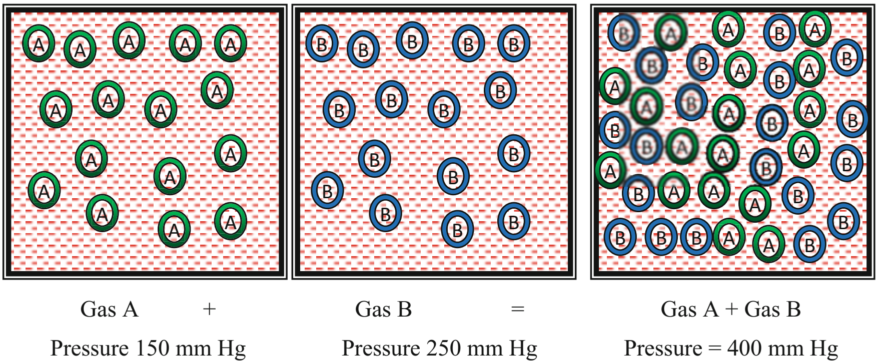


Fig. 5.13 Pressure exerted by gases

$$\textbf{Mole fraction of gas A} = \frac{\textbf{moles of gas A}}{\textbf{Total moles of gas}} \tag{5.19}$$

$$\textbf{Partial pressure of gas A} = \textbf{mole faction of gas A} \times \boldsymbol{P}_{\textbf{Total}} \tag{5.20}$$

The absolute humidity is represented in kg water/kg of dry air can be written as:

$$\textbf{Absolute humidity}, \boldsymbol{H} = \frac{\textbf{18} \times \boldsymbol{P}_{\textbf{water}}}{\textbf{29}\ (\boldsymbol{P}_{\textbf{Total}} - \boldsymbol{P}_{\textbf{water}})} \tag{5.21}$$

The relative humidity (RH) can be represented by following equation.

$$\textbf{RH} = \frac{\boldsymbol{P}_{\textbf{water}}}{\boldsymbol{P}_{\textbf{Saturation}}} \times \textbf{100} \tag{5.22}$$

Q.7 The total pressure and humidity of wet air are 124 kPa and 0.04 kg/kg, respectively. (1) Calculate partial pressure exerted by vapours. (2) If the saturation pressure remains 12.5 kPa, estimate relative humidity. (3) If the temperature of air is 65 °C, estimate relative humidity. (4) What should be the partial pressure and relative humidity at 65 °C and at dew point.

Solution

1. *Molecular weight of air and water are* 29 *and* 18*, respectively*,

$$\text{mole fraction of water} = \frac{\text{moles of water}}{\text{Total moles of air and water}}$$

$$\text{Mole fraction of water} = \frac{\text{mass of water}/\text{mol.wt.of water}}{\left(\text{mass of air}/\text{mol.wt.ofwater} + \text{mass ofwater}/\text{mol.wt.ofwater}\right)}$$

$$\text{Mole fraction of water} = \frac{0.04/18}{\left(1/29 + 0.04/18\right)} = 0.0605$$

$$\text{Hence, vapour pressure} = 0.0605 \times 124 = 7.5\ \text{kPa}$$

2. Relative humidity = P/Ps = 7.5/12.5 = 0.600 = 60%.
3. Ps at 65 °C = 25.04 (from steam table)

$$\text{Relative humidity} = P/Ps = 7.502/25.04 = 0.2996 = 29.96\%$$

4. The pressure will remain the same at 65 °C = 25.04 kPa; and relative humidity = 100%.

Q.8 The humidity of air is 0.03 kg/kg at total pressure of 100 kPa, estimate partial vapour pressure and relative humidity in case of saturation vapour pressure at 70 °C is 31.2 kPa.

Solution
The molecular weight of water and air are 18 and 29, respectively.

$$\textbf{Mole fraction of } \boldsymbol{A} = \text{Moles of } A / (\text{Moles of } A + \text{Moles of } B)$$

where Moles = Mass/Molecular weight

$$\textbf{Mole fraction of water} = \frac{0.03}{18} \Big/ \left(\frac{1.00}{29} + \frac{0.03}{18}\right) = \mathbf{0.046}$$

The partial pressure of water = 0.046 × 100 = 4.6 kPa

$$\mathbf{RH} = \frac{P_w}{P_S} \times \mathbf{100} = \frac{\mathbf{4.6}}{\mathbf{31.2}} = \mathbf{14.74\%}$$

The drying process invariably needs air for the removal of moisture, and the capacity of moisture removal is dependent on temperature and humidity of drying air. The change in the properties of air during drying can be studied using psychrometry. Important terminology related to psychrometrics is discussed below:

5.6.1 Dry Bulb Temperature

The thermometer reading under ambient conditions provides dry bulb temperature. These values are represented on the horizontal axis, and the dry bulb line remains parallel to the vertical axis (Fig. 5.14).

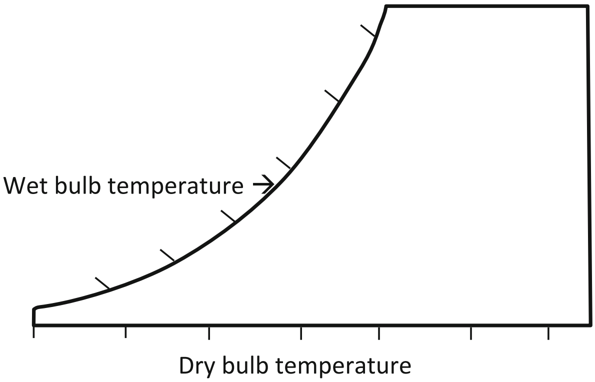


Fig. 5.14 Schematic view of psychrometric chart indicating dry and wet bulb temperature

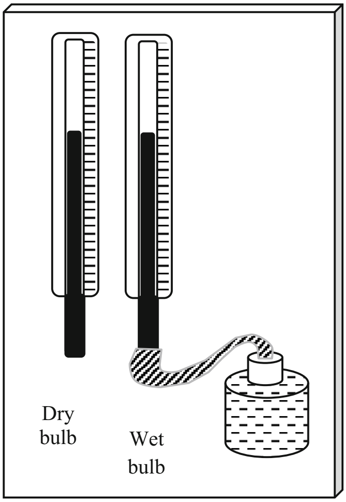


Fig. 5.15 Dry and wet bulb apparatus

5.6.2 Wet Bulb Temperature

The wet bulb temperature of air indicates the temperature of air in completely saturated ambient condition. It is represented by the uppermost curved axis (Fig. 5.14). It is interesting to note those dry and wet bulbs are equal at 100% relative humidity due to complete saturation of the surrounding air.

Measurement of Dry and Wet Bulb Temperatures
The dry and wet bulb temperatures can be measured by using dry and wet bulb thermometer apparatus (Fig. 5.15). The dry bulb temperature is the normal ambient temperature, which is measured by a thermometer, whereas wet bulb thermometer remains covered with a cotton wick, which remains constantly dipped in water on the other end to provide capillary water to rise up to bulb of thermometer and maintain saturation condition. The apparatus is generally hanged in rooms/storage structures,

where the measurement is to be taken. Similar set of thermometers are fixed on a rotating arm, which rapidly maintains the equilibrium with the ambiance by rotating swiftly. The rotating apparatus is known sling phychrometer. The dry and wet bulb temperatures are used as input for estimating the relative humidity of the ambiance using phychrometic chart.

5.6.3 Dew Point Temperature

Dew point is the temperature, at which dew formation takes place. It can be obtained by cooling the air till it becomes saturated. The temperature at which the water vapour present in air starts condensing in the form of dew is termed as dew point temperature. The condensation of water vapours occur as the ambient air comes in contact with the surface, which is colder than air, and as a result, dew is formed on the wind screen of car during cool weather outside. Dew point temperature is temperature shown along the line of 100% relative humidity line or curved axis and the value of dew point temperature can be obtained by drawing a horizonal line towards the saturation curve.

5.6.4 Humidity

Humidity refers to the amount of water present in the ambient air. It is represented in two ways, namely absolute and relative humidity.

5.6.4.1 Absolute Humidity/Humidity Ratio

It is the amount of mass of water vapour per unit mass of dry air. The unit is represented by kg of water per kg of dry air. This is also designated as humidity of air, which is similar to the moisture content of food material on dry basis. Absolute humidity/humidity ratio can be noted from right side vertical axis in a psychrometric chart.

5.6.4.2 Relative Humidity

The relative humidity refers to the ratio of the partial pressure of the water vapour (P_w) to the partial pressure of saturated water vapour (P_s) at the same temperature (Fig. 5.16). The relative humidity values can be obtained from the curved lines.

5.6.5 Measurement of Humidity

The dry and wet bulb temperature thermometers are used to estimate humidity using psychrometric chart. The hygrometers are also used to measure the humidity.

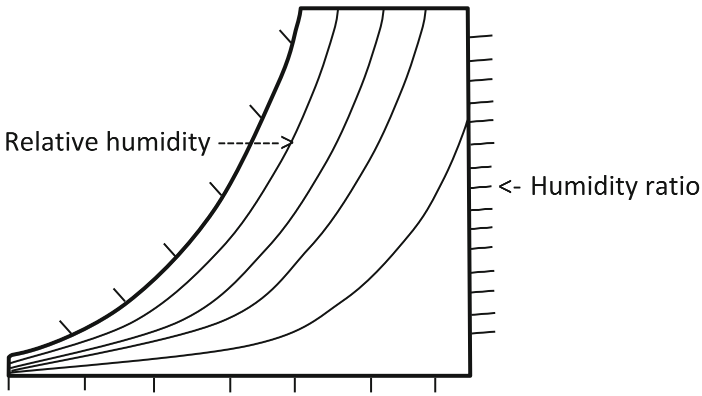
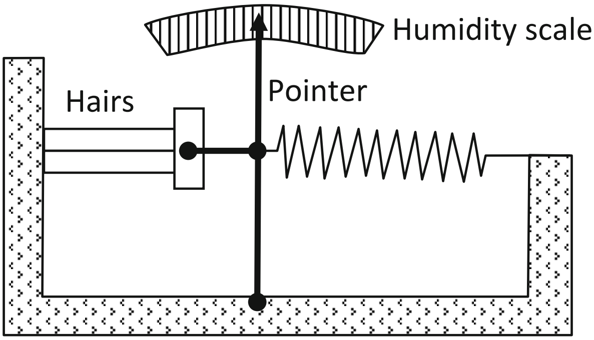


Fig. 5.16 Schematic view of psychrometric chart for humidity ratio and relative humidity

Fig. 5.17 Hair hygrometer



5.6.5.1 Wet and Dry Bulb Thermometers

The difference in temperature of both the bulbs is known as wet bulb depression, which can be used as input to psychrometric chart for the estimation of relative humidity. The dry bulb and wet bulb temperature lines at known values are drawn (Fig. 5.14) till it interests themselves. Relative humidity value can be obtained by measuring the value on relative humidity lines (Fig. 5.16).

5.6.5.2 Hair Hygrometers

The property of hairs to expand/contract with the relative humidity makes use of hairs in hygrometers. The variation in length of a properly treated hair is about 2.5%, with a change of relative humidity. A bundle of hairs starts shrinking/expanding with the change in humidity, which is attached to the lever for displacement of indicator on the dial to indicate relative humidity on humidity scale (Fig. 5.17). These are considered as reasonable instruments for normal ambient conditions.

5.6.5.3 Electrical Resistance Hygrometers

These instruments work on the principle of varying surface electrical resistance of some materials (e.g. aluminium oxide) with the change in relative humidity of ambient air.

5.6.5.4 Dew Point Meter

The apparatus cools down the temperature of ambient air until condensation starts. Plotting the data in psychrometric chart also provides the value of relative humidity.

5.6.5.5 Specific Volume

Specific volume indicates the volume occupied by a unit mass of dry air, in m^3/kg. It is reciprocal of air density. Specific volumes are indicated along the horizontal axis in a psychrometric chart and lines representing the constant volume appear to be slanting towards left at higher angle (Fig. 5.18).

5.6.5.6 Enthalpy

Enthalpy, h, is the amount of energy (kJ) of air per kg of dry air. It can be measured at the scale provided above the wet bulb scale at saturation, which can be measured along with wet bulb lines by crossing the curve axis till the enthalpy scales.

Q.9 The wet and dry bulb temperatures were measured as 15 and 20 °C, respectively, in a storage room. Estimate specific volume, enthalpy and relative humidity of the air.

Solution

Draw a vertical line at 20 °C and draw a line at 15 °C along the wet bulb line. The point of interaction of both the lines should be marked (Fig. 5.19).

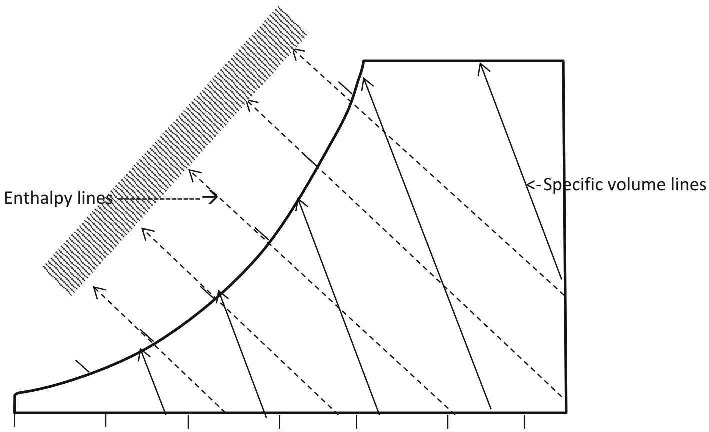


Fig. 5.18 Schematic view of psychrometric chart for enthalpy and specific volume

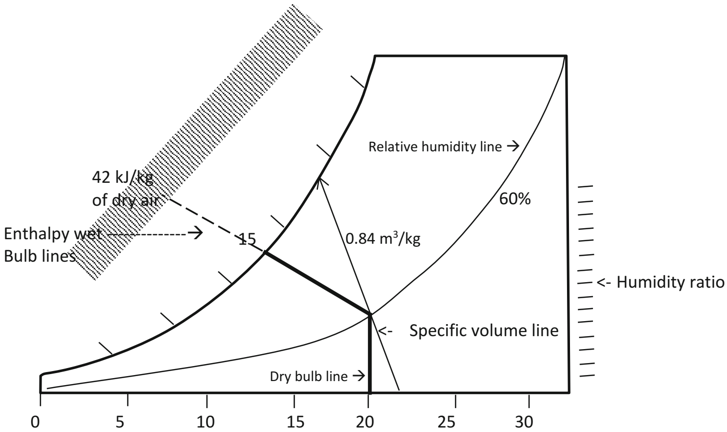


Fig. 5.19 Schematic view of psychrometric chart for Q.9

1. Relative humidity can be found at the curves = 60%
2. Enthalpy along with the constant wet bulb line = 42 kJ/kg of dry air
3. Specific volume along with sp. volume lines = 0.84 m^3/kg

Q.10 The storage room is maintained at 20 °C dry bulb and 15 °C wet bulb temperatures. The dry bulb temperature of air increased to 40 °C through heating. Estimate the heat transfer rate and humidity of air to flow 500m^3/h air.

Solution

For a drying operation, air is being heated up before sending it to drying chamber. Since the amount of water is added/removed during drying, the humidity also remains constant at the raised heated dry bulb temperature of 40 °C.

Initial condition of air:

By locating the point on psychrometric chart at WBT = 15 °C and DBT = 20 °C; following information can be extracted:

$$\text{RH} = 60\%; \text{Enthalpy} = 42\ \text{kJ/kg}, \text{Specific volume} = 0.84\ \text{m}^3/\text{kg}$$

$$\text{Now, Mass flow rate} = 500\text{m}^3/\text{h} = 500/0.84 = 595.24\ \text{kg/h}$$

Final condition of air:

By locating the point on psychrometric chart again at WBT = 21.5 °C; DBT = 40 °C; following information can be extracted:

$$\text{RH} = 18\%; \text{Enthalpy} = 62\ \text{kJ/kg}, \text{Sp.volume} = 0.899\ \text{m}^3/\text{kg}$$

$$\text{Now, rate of heating required} = (62 - 42) = 20\ \text{kJ/kg} = 20 \times 595.24\ \text{kJ/h}$$

$$= 11904.8 \text{ kJ/h} = 11904.8/3600 \text{ kJ/s} = 3.31 \text{ kW}$$

Q.11 The air is heated at 50 °C and 10% relative humidity and sent to a dryer. The exit temperature of is 35 °C. Calculate the required volume of drying air to evaporate the water at a rate of 40 kg/h.

Solution

Initial condition of air:

By locating the point on psychrometric chart at DBT = 50 °C; RH = 10%; following information can be extracted:

$$\text{WBT} = 23.77^{\circ}\text{C}; \text{Sp.volume} = 0.927 \text{ m}^3/\text{kg}; \text{Enthalpy} = 70 \text{ kJ/kg}; \text{Humidity} = 0.0077 \text{ kg/kg}$$

Final condition of air:

The drying process draws the moisture from food and humidification of air takes place, since the addition of energy of air and vapour remains the same; therefore, this process will follow constant energy lines, i.e. wet bulb lines. Therefore, following the same WBT value, 23.77 °C and exit DBT of 35 °C, the parameters for final condition is:

By locating the point on psychrometric chart again at WBT = 23.77 °C; DBT = 35 °C; following information can be extracted:

$$\text{RH} = 39\%; \text{Enthalpy} = 70 \text{ kJ/kg}; \text{Sp.volume} = 0.893 \text{ m}^3/\text{kg}; \text{Humidity} = 0.0139 \text{ kg/kg}$$

$$\text{Water loss} = 0.0139 - 0.0077 = 0.0062 \text{ kg/kg of air}$$

$$\text{The amount of moisture removed per kg of air} = 0.0062 \text{ kg/kg of air.}$$

$$\text{The requirement of drying air for removal of 40 kg water/hour} = 40/0.0062 = 6451.61 \text{ kg/h}$$

$$= 6451.61 \times 0.927 \text{ m}^3/\text{h} = 5980.64 \text{ m}^3/\text{h}$$

5.7 Heat Transfer in Drying

The drying employs heating of food material to provide energy to the food materials for the evaporation of moisture. Heat transfer may take place through any or combination of the modes of heat transfers. The rate of drying is governed by the transfer of heat to the water present in the food materials to provide necessary latent heat for vaporization. Generally, one heat transfer mode dominates in various drying processes. In case of contact drying, conduction dominates, which can be expressed by Fourier's law of heat conduction (Fig. 5.20). The temperature difference between

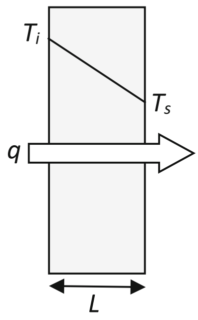


Fig. 5.20 Conduction through a solid wall

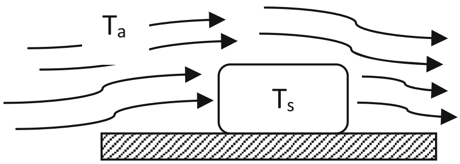


Fig. 5.21 Convective drying

the heat transferring surface (*Ti* – *Ts*) along the distance (*L*) is termed as temperature gradient (*Ti* – *Ts*)/*L*, and the rate of heat transfer (*q*) is proportional to the temperature gradient and cross-sectional area.

$$q \propto -A \times \frac{(T_i - T_s)}{L}$$

where negative sign indicates positive direction of heat flow, and the equation can be given as:

$$q = \frac{-K\,A\,(T_i - T_s)}{L} \tag{5.23}$$

where: q = rate of heat transfer, J/s; K = thermal conductivity of food material, J/m s °C; A = cross-sectional area of heat transfer, m^2; T_i = dryer temperature, °C; T_s = surface temperature of food, °C; L = length of material, *m*.

The heat transfer rate using overall heat transfer coefficient (U) in J/m^2 s °C by conduction in various surface can be modified as:

$$q = U\,A\,(T_i - T_s) \tag{5.24}$$

In case of natural or forced hot air convective drying, the Newton's law of cooling is applied (Fig. 5.21), which states that the rate of heat transfer is proportional to the temperature difference of food material and drying air and the rate of heat transfer can be given as:

$$q = h_s A \left(T_a - T_s\right) \tag{5.25}$$

where: h_s = surface heat transfer coefficient, J/m^2 s °C; T_a = drying air temperature, °C.

In case of forced hot air drying, case hardening of food surface takes place, which restricts the heat transfer rate due to poor conductivity of food materials.

5.8 Mass Transfer in Drying

Mass transfer occurs during drying due to difference in concentration/partial pressures. The mass transfer is governed by Fick's law of diffusion, which refers to the proportionality between diffusion flux or rate of mass transfer with the concentration gradient. Following equations represents the diffusion flux and mass transfer rates:

$$J = -D\frac{\Delta C}{\Delta x} \tag{5.26}$$

where J, D, ΔC and Δx are diffusion flux, mol/m^{2}s, diffusion coefficient or diffusivity, m^2/s, concentration difference, mol/m^3 and distance between the particles, m.

$$dw/_{dt} = k_g' \times A \times \Delta Y \tag{5.27}$$

where: w = mass being transferred, kg; t = duration of mass transfer, s; k'_g = mass-transfer coefficient, kg/m^{2}s; A = Area for mass transfer, m^2; ΔY = Difference in absolute humidity, kg water/kg dry matter.

The phenomenon of mass transfer remains complex due to movement pattern of moisture migration from food, which starts with the removal of moisture from the surface of the material initially. As the surface moisture diminishes, the moisture removal from deep inside the food material starts and continues till the end of drying and moisture moves along with drying air. Therefore, correlation between initial moist surface and the ambient should be established for diffusion first, wherein heat and mass transfer also take place simultaneously. The heated air remains major medium of heat transfer.

5.9 Drying Rates

The rate of drying is usually governed by the heat transfer and mass transfer simultaneously. Generally, drying of food is divided into ***constant rate*** and ***falling rate drying periods***. The former drying proceeds in high moisture foods till critical moisture content at constant rate, while later drying starts with drop in drying rate. In initial phase of drying, moisture removal occurs from whole surface, which starts

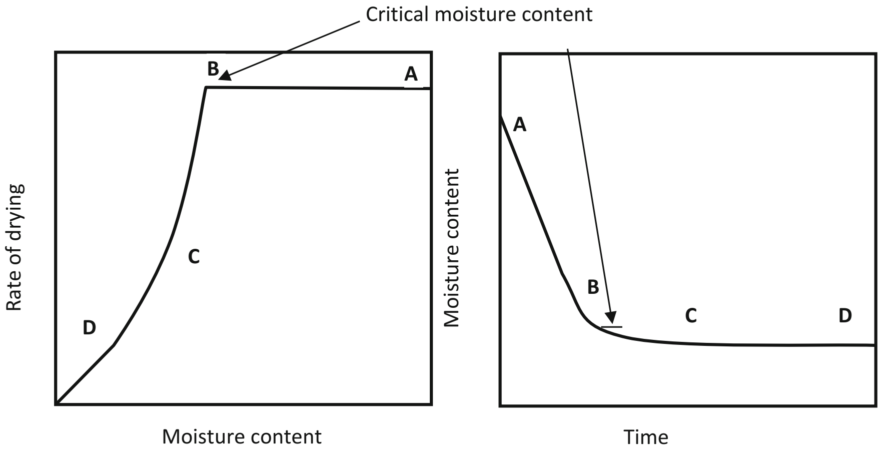


Fig. 5.22 Drying rate curves

reducing with the end of constant rate drying, and as a result rate of vaporization of water per unit time decreases.

Figure 5.22 represents a usual behaviour of food moisture content with drying time and drying rate. Constant rate drying is represented by A–B. The moisture is continuously being evaporated from food surface, which remains saturated with water, and the rate of removal of water is governed by diffusion of moisture from food surface through a stationary air film, which remains in contact with the drying air. The constant rate period also depends on the amount of moisture available on the food surface, air temperature, air humidity and speed of moisture movement from inner part of food to the surface. The water remains available at the surface for maintaining saturation through the transportation of moisture from inner side till the level of critical moisture content.

The critical moisture content demarcates constant rate period and falling rate period and can be identified as point B in the Fig. 5.22. Thereafter, the drying rate fall gradually as drying proceeds till the section (BC), which is termed as first falling rate period. The availability of drying surface for removing the moisture starts decreasing, which influences the drying rate during first falling rate drying. The movement from innermost part to surface remains at higher rates for supplying moisture for keeping surface of food saturated. The coefficients of heat and mass transfer, area available for drying and relative humidity of air remain driving factors to govern rate of drying during the period.

The drying proceeds further, and food surface is no longer remain in saturation, the temperature of food surface become more than the wet bulb temperature. The temperature of the material continues to increase till attaining the dry bulb temperature of drying air and approaches to the end of drying process. It is characterized as second falling rate period by CD section (Fig. 5.22). The moisture diffusion within food starts. The materials with higher moisture content than critical moisture content exhibit both drying periods, i.e. constant and falling rate periods. However, the material with lower moisture content than critical moisture content observes, only falling rate drying. The movement of moisture during drying is a combination of vapour diffusion, cycle of vaporization and condensation, osmotic pressure and capillary forces.

5.10 Constant Rate Drying

The moisture evaporation from food surface occurs during constant rate period. The heat supplied during this period, by the drying air, is utilized as latent heat for conversion of water to vapours and usually no increase in temperature of food is observed. The evaporation rate of moisture is influenced by heat transfer rate from the food surface as transferred heat is involved in conversion of water to vapour and no variation in temperature of food material takes place. The rate of water removal is also a mass transfer process. The difference between partial vapour pressure of material and drying air remains major thrust for drying. Drying rates can be estimated experimentally/predicted theoretically. It may be used to assess drying times for designing of a dryer. However, the rate of drying changes because of continuous decrease in moisture content of food material as drying progresses; however, change in ambience temperature and relative humidity also change, which may be assumed as constant to simplify the problem [6].

5.10.1 Estimation of Rate of Drying During Constant Rate Period

In case of constant rate of drying, mass of water removal is Δw for time 'Δt', then:

Rate of removal of moisture at constant rate,

$$\mathrm{Rc} = \frac{\Delta w}{\Delta t} = \frac{dw}{dt} = \text{constant} \tag{5.28}$$

Let Mo and Mc are initial and critical moisture contents of food material on dry basis, w is dry matter of food in kg.

The moisture lost from initial to critical moisture content in time 't' per unit mass = $Mo - Mc$

$$\text{Constant drying rate, Rc} = \frac{(M_o - M_c)}{t}$$

$$t = \frac{(M_o - M_c)}{\mathrm{Rc}}$$

$$\text{Total drying time}, t = \frac{(M_o - M_c)}{(\mathrm{d}w/\mathrm{d}t)_{\text{const.}}}$$

The removal rate of moisture from the food material, taken away by the drying air at constant rate can be represented by Eq. (5.29). Let A, $k'g$, ΔY are area for mass transfer, m^2, mass-transfer coefficient, kg/m^2s and difference in absolute humidity kg water/kg dry matter.

Constant rate of drying may be used to calculate the drying rate on the basis of A, K'_g and ΔY:

$$\boldsymbol{Rc = k'_g \times A \times \Delta Y} \tag{5.29}$$

Q.12 Calculate the rate of moisture removal and the rate of heat energy utilization from the food available food surface of 3m^2 at 30 °C with temperature and humidity of drying air 45 °C and 30%, respectively. The mass-transfer coefficient may be taken as 0.014 kg/m^2s.

Solution
Using psychrometric chart, at 45 °C and 30% relative humidity,

$$\text{Absolute humidity} = 0.0182\ \text{kg/kg}$$

Using psychrometric chart again, at 30 °C and 100% relative humidity,

$$\text{Absolute humidity} = 0.0272\ \text{kg/kg}$$

$$\text{Driving force} = 0.0272 - 0.0182 = 0.009\ \text{kg/kg}$$

$$\text{Rate of water evaporated} = k'g \times A \times (Ys - Ya)$$

$$= 0.014 \times 3 \times 0.009 = 0.000378\ \text{kg/s}$$

$$\text{Using steam table at } 30^{\circ}\text{C, latent heat} = 2429.8\ \text{kJ/kg}$$

$$\text{Heat energy required per square metre} = 0.000378 \times 2429.8$$

$$= 0.9185\ \text{kJ/s} = 0.9185\text{kW} \approx 1.0\ \text{kW}$$

Q.13 Calculate the rate of moisture removal, the rate of heat energy utilization and the heat transfer coefficient for available food surface of 3m^2 at 30 °C with temperature and humidity of drying air 45 °C and 30%, respectively. The mass-transfer coefficient may be taken as 0.014 kg/m^2s.

Solution
Using psychrometric chart, at 45 °C and 30% relative humidity,

$$\text{Absolute humidity} = 0.0182\ \text{kg/kg}$$

Using psychrometric chart again, at 30 °C and 100% relative humidity,

$$\text{Absolute humidity} == 0.0272\ \text{kg/kg}$$

$$\text{Driving force} = 0.0272 - 0.0182 = 0.009\ \text{kg/kg}$$

$$\begin{aligned}\text{Rate of water evaporated} &= k'g \times Ax\,(Ys - Ya) = 0.014 \times 3 \times 0.009\\ &= 0.000378\ \text{kg/s}\end{aligned}$$

$$\text{Using steam table at } 30^{\circ}\text{C, latent heat} = 2429.8\ \text{kJ/kg}$$

$$\text{Heat energy required per square metre} = 0.000378 \times 2429.8$$

$$= 0.9185\ \text{kJ/s} = 0.9185\ \text{kW} = 918.5\ \text{W}$$

$$\text{Temperature difference} = 45 - 30 = 15^{\circ}\text{C}$$

$$q = h\,A\Delta t$$

$$918.5 = h \times 3 \times 15$$

$$h = 918.5/(3 \times 15) = 20.41\ \text{J/m}^2\text{s}^{\circ}\text{C}$$

Q.14 The slices of potatoes were dried with drying air at 65 °C, 10% RH and with 25 kg/s rate. If the rate of evaporation from the potatoes remains 0.15 kg/s, estimate the temperature and relative humidity of the outgoing air.

Solution
Using psychrometric chart, at 65°C and 10% relative humidity,

$$\text{Absolute humidity of air} = 0.0157\ \text{kg/kg}$$

$$\text{Evaporated water added in the drying air} = 0.15/25 = 0.006\ \text{kg/kg}$$

$$\text{Humidity of leaving air} = 0.0157 + 0.006 = 0.0217\ \text{kg/kg}$$

Locate the point of drying air at 65 °C and 10% RH, follow the wet bulb line till humidity reaches to 0.0217 kg/kg and dry bulb temperature is 50 °C and 30% RH.

5.11 Falling Rate Drying

The drying rate remains the highest owing to the availability of free water at the surface of food material initially, however, drying surface decreases while falling rate period starts and expulsion of moisture from the interior of food takes place. The constituents and complexity of food describe the drying behaviour of the food material. At depleting moisture contents, drying rates remains very low.

5.11.1 Material with One Falling Rate and Drying Curve Passes through Origin

The rate of drying of these materials from initial moisture content (M_o) to the critical moisture content (Mc) depicts a constant rate (Rc), represented by A to B (Fig. 5.23). After reaching the critical moisture content (B), rate of drying then reduces in a linear relationship until almost all the moisture is removed (C), whereas equilibrium moisture content (D) of the material remains lower than the final drying rate at specific drying conditions.

The drying times needed to reach at a moisture content (M) in drying are:

During constant rate period, rate of drying:

$$\text{Constant rate}, R_c = -\frac{dm}{dt} \tag{5.30}$$

where negative sign represents the loss of moisture during drying. The total time for constant rate drying:

$$\text{Total time in constant rate}, t_c = \frac{m_{o-}m_c}{R_C} \tag{5.31}$$

Falling rate period, rate of drying:

As the rate of drying does not remain constant during the falling rate, the rate of drying will be proportional to the ratio of instantaneous moisture to the critical moisture. The rate of drying remains equal to Rc at critical moisture content, and it

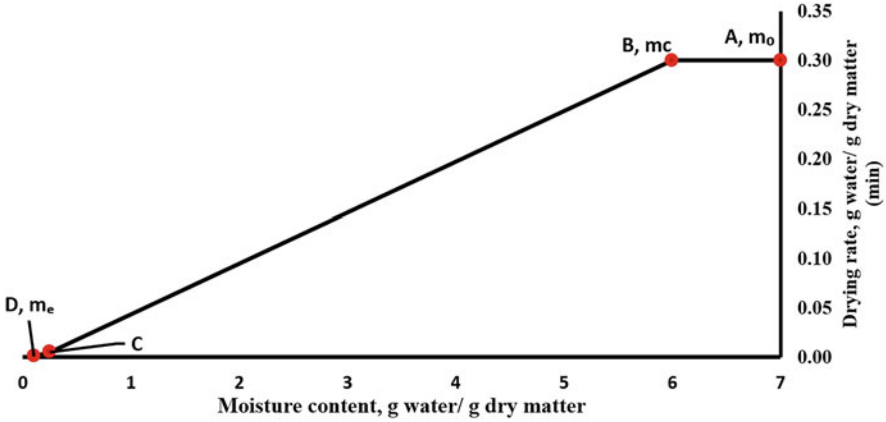


Fig. 5.23 A typical graphical representation drying rate versus moisture content having single falling rate period

reduces with the reduction of moisture below critical moisture and falling rate drying starts.

$$\text{Falling rate} = -\frac{dm}{dt} = \frac{R_c}{m_C} \times m$$

$$-\frac{dm}{m} \times \frac{m_C}{R_c} = dt$$

$$\int_{t_c}^{t} dt = -\frac{m_c}{R_C} \int_{m_c}^{m} \frac{dm}{m}$$

$$t - tc = \frac{m_c}{R_C} \times \ln \frac{m_c}{m}$$

$$t = tc + \frac{m_c}{R_C} \times \ln \frac{m_c}{m}$$

$$t = \frac{m_{o-}m_c}{R_C} + \frac{m_c}{R_C} \times \ln \frac{m_c}{m} \tag{5.32}$$

Q.15 A sample of carrot pomace with 75% moisture content (wb) has a unit water activity at moisture content higher than 1.25 kg water/kg dry matter. The pomace is being dried at a rate of 0.17 kg/kg dry matter per min. Estimate drying time required to reach at 10% moisture content on wet basis.

Solution

$$R_c = 0.17\ \text{kg/kg dry matter per min}$$

$$m_c = 1.25\ \text{kg water/kg dry matter}$$

$$\text{Initial moisture content, wb} = 85\%$$

$$\text{Moisture content (db), \%} = \frac{\text{Moisture content (wb), \%}}{100 - \text{Moisture content (wb), \%}} \times 100$$

$$\text{Initital moisture content(db), \%} = \frac{85}{100 - 85} \times 100$$

$$\text{Initital moisture content(db), \%} = \frac{85}{15} \times 100$$

$$\text{Initital moisture content (db), \%} = 567.78\% = 5.68\ \text{kg water/kg dry matter}$$

$$\text{Final moisture content, wb} = 10\%$$

$$\text{Final moisture content (db)}, \% = \frac{10}{100 - 10} \times 100$$

$$\text{Final moisture content (db)}, \% = \frac{10}{90} \times 100$$

$$\text{Final moisture content (db)}, \% = 11.11\% = 0.11 \text{ kg water/kg dry matter}$$

$$t = \frac{m_o - m_c}{R_C} + \frac{m_c}{R_C} \times \ln \frac{m_c}{m}$$

$$t = \frac{5.68 - 1.25}{0.17} + \frac{1.25}{0.17} \times \ln \frac{1.25}{0.11}$$

$$t = \frac{5.68 - 1.25}{0.17} + \frac{1.25}{0.17} \times \ln \frac{1.25}{0.11}$$

$$t = 26.06 + 17.87 = 43.93 \text{ min}$$

5.11.2 Materials with More Falling Rate Periods

Most food materials exhibit behaviours of having more than one falling rate period. In these cases, drying performed at constant rate *Rc* from the initial moisture content (*Mo*) to the critical moisture content (*Mc*) representing as A to B similar to single falling rate drying period (Fig. 5.24). In this case, the drying rate in first falling rate period deviates from the origin in a plot of drying rate and moisture content. In case of first falling rate period, the drying starts from m_{c1} with a projected residual

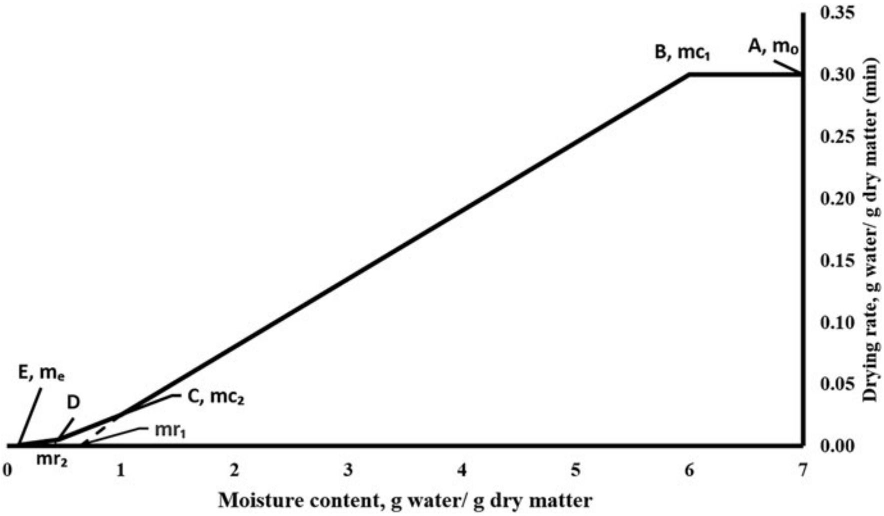


Fig. 5.24 A typical graphical representation drying rate versus moisture content having two falling rate period

moisture content of m_{r1}. However, due to the occurrence of second falling rate period, the first falling rate ceases at C with moisture content m_{c2}. Thereafter, second falling rate starts from C and continues till D until almost all the moisture content is removed with a projected residual moisture content m_{r2}, whereas equilibrium moisture content (E) of the material remains lower than the final moisture content (m_{r2}) at specific drying conditions.

During first falling rate period, the first falling rate drying starts from m_{c1} and continues till reaching at m_{c2}, and residual moisture m_{r1} remains in the material, therefore, the rate of drying:

$$\text{Falling rate} = -\frac{d(m - m_{r1})}{dt} = \frac{R_c}{m_{C1} - m_{r1}} \times (m - m_{r1})$$

Drying time during constant rate and first falling rate period, as Eq. (5.8) is modified as first falling rate drying performed between m_{c1} to m_{c2} with respective residual moisture m_{r1}, and critical moisture content may be used as $m_c = m_{c1} - m_{r1}$, instantons moisture content may be replaced as $m = m_{c2} - m_{r1}$ as the first falling rate ended at m_{c2}.

Time in constant drying and first falling rate can be estimated as

$$t_1 = \frac{m_{o-}m_{c1}}{R_C} + \frac{m_{C1} - m_{r1}}{R_C} \times \ln \frac{m_{C1} - m_{r1}}{m_{c2} - m_{r1}}$$

Similarly, drying time needed in the second falling rate period

$$t_2 = \frac{m_{C2} - m_{r2}}{R_C} \times \ln \frac{m_{C2} - m_{r2}}{m - m_{r2}}$$

Total drying time:

$$t = \frac{m_{o-}m_{c1}}{R_C} + \frac{m_{C1} - m_{r1}}{R_C} \times \ln \frac{m_{C1} - m_{r1}}{m_{c2} - m_{r1}} + \frac{m_{C2} - m_{r2}}{R_C} \times \ln \frac{m_{C2} - m_{r2}}{m - m_{r2}} \quad (5.33)$$

Q.16 The slices of apples at 5.3 g water/g dry matter are kept in forced convection dryer at 0.163 g water/g dry matter per min drying rate till critical moisture content of 2.5 g water/g dry matter and from $T_{db} = 75$ °C and $T_{wb} = 40$ °C for the first 40 min till reaching up to residual moisture content of 0.35 g water/g dry matter. The material was dried at T_{db} 70 °C and $T_{wb} = 45$ °C for the remaining drying process up to 0.15 kg water/kg dry matter with critical and residual value of 1.0 and 0.10 kg water/g dry matter, respectively.

Solution

The total drying times includes constant rate followed by the first and second falling rate periods:

$$t = \frac{5.3 - 2.5}{0.163} + \frac{2.5 - 0.35}{0.163} \times \ln \frac{2.5 - 0.35}{1 - 0.35} + \frac{1 - 0.1}{0.163} \times \ln \frac{1 - 0.1}{0.15 - 0.1}$$

$$t = 17.18 + 13.19 \times 1.20 + 5.52 \times 2.89$$

$$= 17.18 + 15.83 + 15.95 = 48.96 \text{ min}$$

5.11.3 Thin Layer Drying

Thin layer drying process may be analysed using Newton's law of cooling by replacing the temperature with moisture content, which uses a constant 'k' as suggested by Lewis [12], and can be represented as

$$\frac{dM}{dT} = -k\left(M - M_{eq}\right) \quad (5.34)$$

The moisture content depends upon time, and Eq. (5.20) can be simplified as:

$$\text{MR} = \frac{M - M_e}{M_o - M_e} = \exp\ -(k.t) \quad (5.35)$$

where MR is moisture ratio and M, M_o, and M_e are instantaneous moisture content, initial moisture content, and equilibrium moisture content, respectively.

Page [13] introduced thin layer drying equation as:

$$\text{MR} = \exp\left(-k.t^n\right) \quad (5.36)$$

where 'n' is a parameter, which depends on the material and drying temperature.

An analogous methodology to Lewis [12] model has been reported by Henderson and Pebis [14]

$$\text{MR} = a.\exp\left(-k.t\right) \quad (5.37)$$

and the logarithmic model [15]

$$\text{MR} = a.\exp\left(-k.\ t\right) + c \quad (5.38)$$

where a and c are model constants.

Henderson [16] considered liquid diffusion and presented classical solution for thin layer drying by two-term exponential model:

$$\text{MR} = a.\exp\left(-k_0.t\right) + b.\exp\left(-k_1.t\right) \quad (5.39)$$

Wang and Singh [17] employed following model for drying of rough rice:

$$\mathrm{MR} = 1 + a.t + b.t^2 \tag{5.40}$$

Following simplified/modified equation was used by Diamante and Munro [18] on hot air thin layer drying of sweet potato slices:

$$\mathrm{MR} = a.\exp\left(-c\left({}^{t}\!/\!{}_{L^2}\right)\right) \tag{5.41}$$

$$\mathrm{MR} = a.\exp\left(-c\left({}^{t}\!/\!{}_{L^2}\right)^n\right) \tag{5.42}$$

where L is half thickness of the sample.

Approximation model based on diffusion applied for grapes drying by Yaldiz et al. [19]:

$$\mathrm{MR} = a.\exp(-k.t) + (1-a)\exp(-k.a.t) \tag{5.43}$$

Verma et al. [20] applied and recommended the following model for thin layer drying of rice:

$$\mathrm{MR} = a.\exp(-k.t) + (1-a).\exp(-g.t) \tag{5.44}$$

Midilli et al. [21] applied the following model for thin layer drying of pistachio nuts:

$$\mathrm{MR} = a.\exp(-k.t^n) + b.t \tag{5.45}$$

Hii et al. [22] also suggested a model for thin layer drying of cocoa:

$$\mathrm{MR} = a.\exp(-k.t^n) + c.\exp(-g.t^n) \tag{5.46}$$

where a, c, k, g are model constants.

The moisture ratio, $\mathrm{MR} = (M - M_e)/(M_0 - M_e)$ may be modified to M/M_0 by neglecting equilibrium moisture content due to longer time elapsed in drying. The appropriateness of mathematical models can be tested using reduced chi-square, correlation coefficient and root mean square error. The experimental and predicted moisture contents are also used for the validation of the models.

5.11.4 Calculation of Effective Diffusivities

The falling rate period also used Fick's diffusion equation for characterizing the food product. The Crank [23] model is used for the estimation of diffusivity assuming uniform initial moisture distribution.

Case I: For Slab or Plane Sheet

Considering effective diffusivity (D_{eff}) and half-thickness of slab (m), moisture ratio can be represented as:

$$\mathrm{MR}_i = \frac{8}{\pi^2}\sum\nolimits_{n=0}^{\infty}\frac{1}{(2n+1)^2}\exp\left(-\frac{(2n+1)^2\pi^2 D_{\mathrm{eff}}t}{4{L_0}^2}\right) \tag{5.47}$$

In case of considering the first term of the series, the equation can be shortened and expressed as:

$$\ln \mathrm{MR} = \ln\frac{8}{\pi^2} - \frac{\pi^2 D_{\mathrm{eff}}t}{4{L_0}^2} \tag{5.48}$$

Diffusivities are estimated through plotting the logarithm of moisture ratio (ln MR) with drying time (t) and slope and effective diffusivity can be calculated as:

$$\mathrm{Slope} = -\frac{\pi^2 D_{\mathrm{eff}}}{4\,{L_0}^2} \tag{5.49}$$

$$D_{\mathrm{eff}} = -\left(\frac{4\,{L_0}^2}{\pi^2}\right)\times \mathrm{Slope} \tag{5.50}$$

where Slope = $(\ln \mathrm{MR}_2 - \ln \mathrm{MR}_1)/(t_2 - t_1)$.

Case II: For Spherical-Shaped Material

$$\mathrm{MR}_i = \sum_{n=1}^{\infty}\frac{6}{n^2\pi^2}\exp\left(-D_{\mathrm{eff}}n^2\pi^2 t/R^2\right) \tag{5.51}$$

where R = radius of the sphere/kernel

Considering the first term of the series, the equation can be shortened and expressed as:

$$\ln \mathrm{MR} = \ln\frac{6}{\pi^2} - \frac{\pi^2 D_{\mathrm{eff}}t}{R^2} \tag{5.52}$$

$$\mathrm{Slope} = -\frac{\pi^2 D_{\mathrm{eff}}}{R^2} \tag{5.53}$$

Case III: For Cylindrical-Shaped Material

$$\mathrm{MR}_i = \sum_{n=1}^{\infty}\frac{4}{R^2{\propto_n}^2}\exp\left(-D_{\mathrm{eff}}{\propto_n}^2 t\right) \tag{5.54}$$

Considering the first term of the series, the equation can be shortened and expressed as:

$$\ln \mathrm{MR} = \ln \frac{4}{R^2 \propto_n{}^2} - \propto_n{}^2 D_{\mathrm{eff}}\, t \tag{5.55}$$

$$\mathrm{Slope} = -\propto_n{}^2 D_{\mathrm{eff}} \tag{5.56}$$

where α_n is the positive root of zero-order Bessel function [24].

5.11.5 Calculation of Activation Energy

Arrhenius-type relationship can also be used for determining the effective diffusivity:

$$D_{eff} = D_0 \exp\left(-\frac{E_a}{RT}\right) \tag{5.57}$$

where $D_{0,}$ $E_{a,}$ R and T are pre-exponential factor (m^2/s), activation energy (kJ/mol), universal gas constant (kJ/mol K) and absolute temperature (K), respectively.

The effective diffusivity in logarithm $\ln(D_{\mathrm{eff}})$ form can be plotted with reciprocal of absolute temperature (T)

$$\ln\ (D_{\mathrm{eff}}) = \ln\ (D_o) - \left(\frac{E_a}{R}\right) \times \frac{1}{T} \tag{5.58}$$

The activation of energy can be estimated by determining the slope of the above-mentioned equation [25].

5.12 Types of Dryers

In food processing industries, different foods are processed using different ingredients. It is expected to have a number of dryers, which are selected on the type of product for drying and other quality-related parameters. A number of dryers, which are popular in industry, are described as follows:

5.12.1 Tray Dryers

These types of dryers have an insulated chamber, which has an opening for incoming fresh air along with a separate heating arrangement and a plate to exhaust the moist air through holes provided at the upper side of the dryer. Several steel trays are fitted in the cavities marked in the inner body of the dryers (Figs. 5.25 and 5.26). Insulation in the walls is being provided to minimize heat loss to the ambience. The product is being spread on trays in thin layers for faster drying rate. A circulation fan is generally provided to maintain same temperature throughout the dryer. These dryers are appropriate for drying fruits, vegetables and several other food products. The

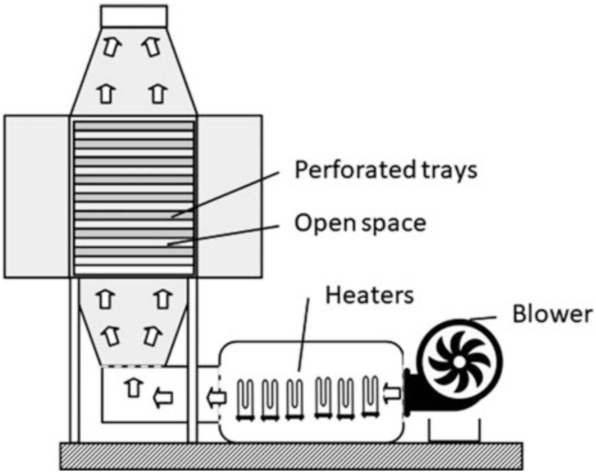


Fig. 5.25 Tray dryer with perforated trays

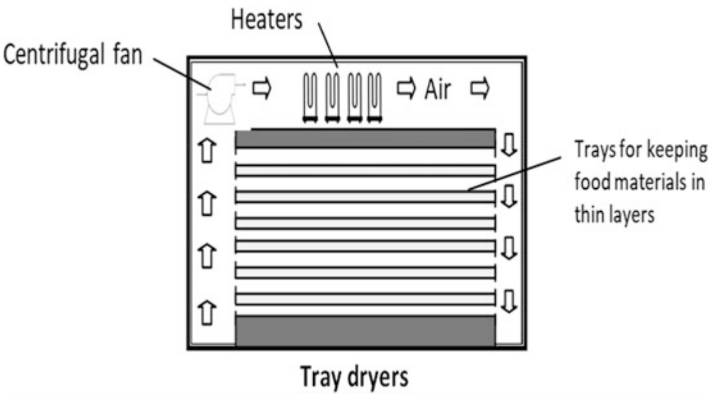


Fig. 5.26 Tray dryer with regular trays

perforated trays are used in case of drying of fruits and vegetables in whole or in pieces, while flat regular trays are used for drying of fruit pulp in crushed form and the drying air pass over the material.

5.12.2 Tunnel Dryers

These types of dryers are similar to tray dryers, having larger capacity, making it suitable for industrial purposes. Several moving trolleys or belt conveyers are provided (Fig. 5.27). Several heaters are generally arranged on air inlet to heat the air. Sometimes, heaters are being provided along with the tunnels for heating the air passing through the tunnels. It may have co-current and counter current

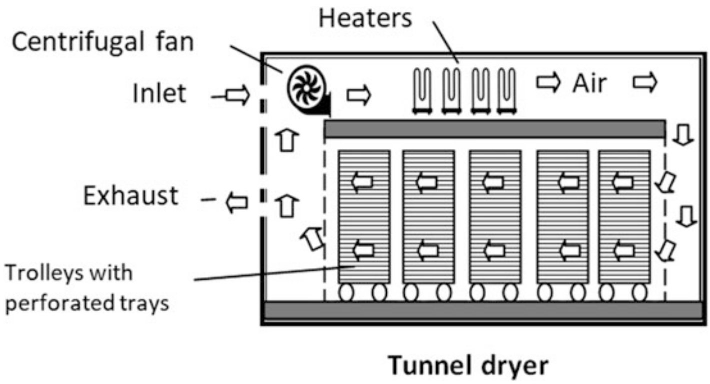
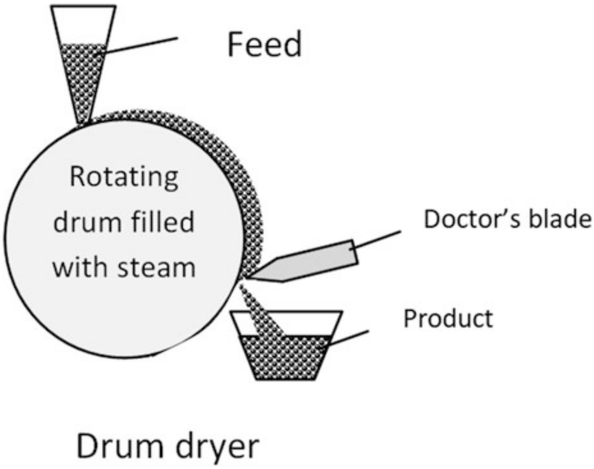


Fig. 5.27 Tunnel dryer with perforated trays

Fig. 5.28 Drum dryer



arrangements for drying air and product flow. In some cases, cross flow may also be used by making several compartments.

5.12.3 Drum/Rotary Dryers

These dryers have hollow drum of larger diameter. In case of drum dryer, the feed in the form of pulp is placed over the outer surface of drum by spreading in thin layers. The inner side of the drum is being heated with high-temperature steam, and the heat is being transferred through conduction from metal sheet forming the drum (Fig. 5.28).

The food material remains on the surface while rotation of drum and drying takes place by absorbing the heat from the surface of drum. A scraper is provided to detach the material from the drum after completion of drying. The drying uses the energy

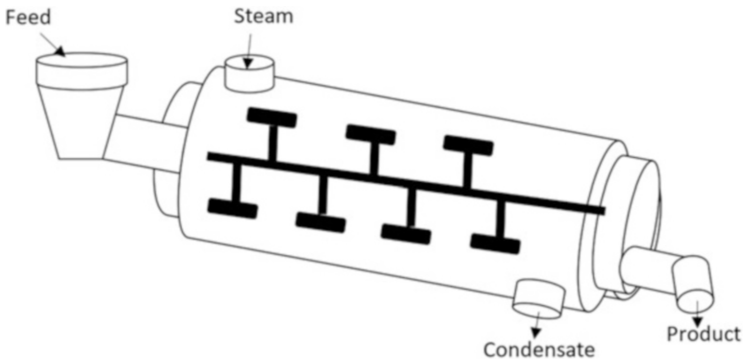


Fig. 5.29 Rotary dryer

transferred through conduction; therefore, thermal conductivity of drum surface and heat transfer coefficient play a vital role in drying. These dryers are useful for drying pulp or pomace. Thermal efficiency of these dryers is high due to contact heat transfer.

The food material is fed in the drying chamber in case of rotary dryer, which is inclined towards the output and heated through steam. The dryer is of cylindrical shape and remains stationary (Fig. 5.29). Several paddles are provided to agitate the food material throughout the travel from the feed inlet to the product outlet. The food material meets heated surface and temperature of food material increases, which facilitate the removal of water. The material is fed inside the drum into the cylindrical space provided in rotary dryer, while the material is being placed over the circular surface of rotating drum in drum dryer.

5.12.4 Fluidized Bed Dryers

Fluidized bed dryer uses an air stream flowing in upward direction to maintain the material in suspended state by countering the effect of gravity. The rate of drying is very high, and moisture removal is fast and uniform as all the sides of the material get equal opportunity to face the drying air directly. These dryers are used for materials having small size for carrying out the fluidization (Fig. 5.30). The airflow also directs the flow to convey the material through feed trough. The convective heat transfer remains the major mode of heat transfer for drying air to the food material.

5.12.5 Pneumatic Dryers

Food material is conveyed by higher velocity heated air stream in pneumatic dryers. Higher velocity creates turbulence in stream, which conveys material and maintain the material in suspension. Heaters are provided for heating of drying air, and classifiers are needed to sperate the materials from the air (Fig. 5.31). In case of higher residual moisture in the dried product, it can be again circulated in the dryer.

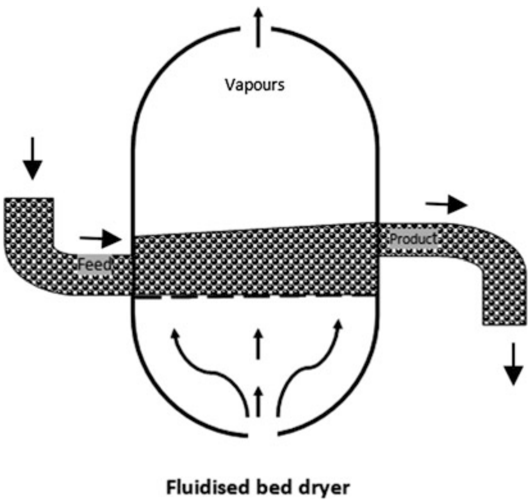


Fig. 5.30 Fluidized bed dryer

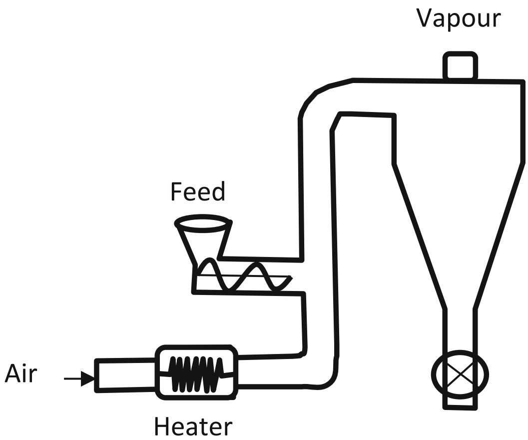


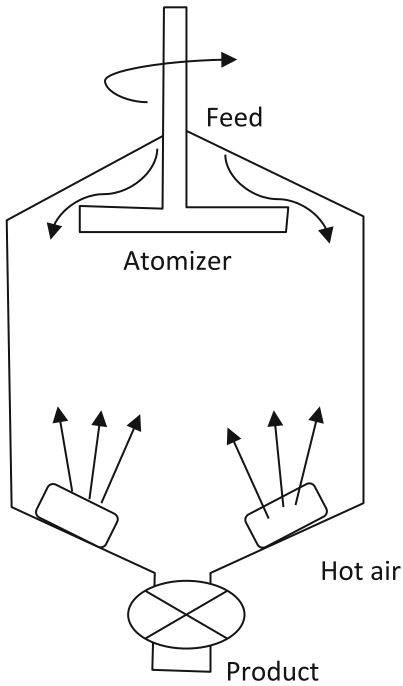
Fig. 5.31 Pneumatic dryer

The velocity of drying air is low to maintain the suspension of material in fluidized bed dryer. The food material that is being conveyed with drying air is separated in cyclone separator attached to the pneumatic dryer.

5.12.6 Spray Dryers

Spray dryers work on the principal of drying liquid or pumpable pulp in the form of fine droplets, which dry rapidly with heated air stream. The drying remains very rapid due to the availability of increased surface area by forming the fine droplets (Fig. 5.32). The dried material is fed to cyclone separator for continuously withdrawn of dried material and cooled to retain the quality attributes. The temperature of drying air, heat transfer coefficient and diameter of droplets are important parameters

Fig. 5.32 Spray dryer



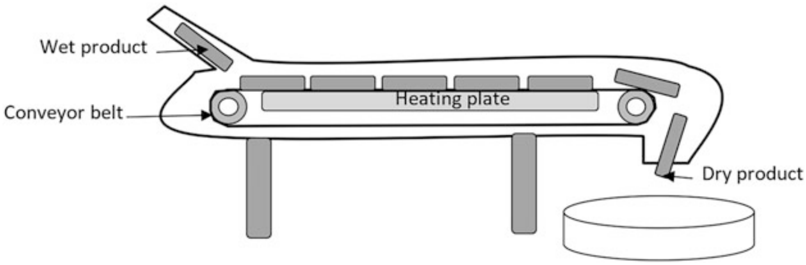


Fig. 5.33 Belt dryer

to govern the rate of drying and drying time. The dryer body is large enough to allow particle for settling with minimum sticking on the walls. The size can be as large up to 6 m of diameter and about 20 m of height. The spray dried products contain hollow spaces, which provide excellent rehydration properties of dried products.

5.12.7 Belt/Trough Dryers

The food material is placed on a horizontal belt in thin layers, and air is being passed through heating place, which heats the air for passing through the material (Fig. 5.33). Sometimes, scrappers are placed to transport the material in place of moving the material form feed inlet to product outlet. These can be placed in several numbers to obtain desired moisture content in a single pass for matching with continuous processing operations. The trough-shaped perforated belts are also used to convey the material. The air is heated and passed from the bottom side of the belt to pass through the food material. The speed of the belt is controlled according to the level of drying and exposure time. The trough dryer is preferred in handling of smaller dices of fruits and vegetables, peas, etc., while the belt dryers are suitable to dry apples, grapes, tomato, garlic, potato slices, etc.

5.12.8 Bin Dryers

The grains like wheat, corn, rice, etc. are stored in bins. The grains are moistened during high relative humidity weather conditions. The bin dryers are useful for drying grains. They are made of cylindrical bins having perforated bottoms to allow heated air to pass through material for drying (Fig. 5.34). As drying progresses, the grains placed at the bottom dried first, and the zone of drying moves upward till the completion of drying.

5.12.9 Vacuum Dryers

These dryers are similar to the tray dryers; however, the operating pressure makes these dryers distinct (Fig. 5.35). These are operated under vacuum, which facilitate the removal of water from the food material easily. The heat is usually transferred

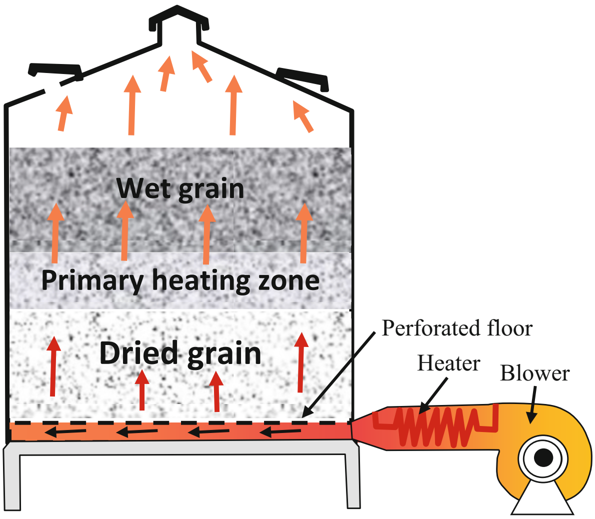


Fig. 5.34 Bin dryer

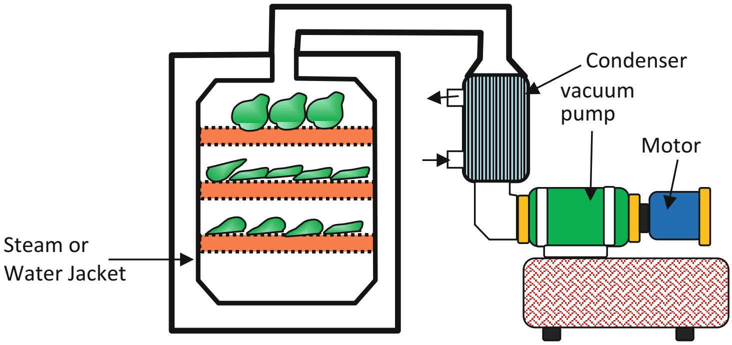


Fig. 5.35 Vacuum dryer

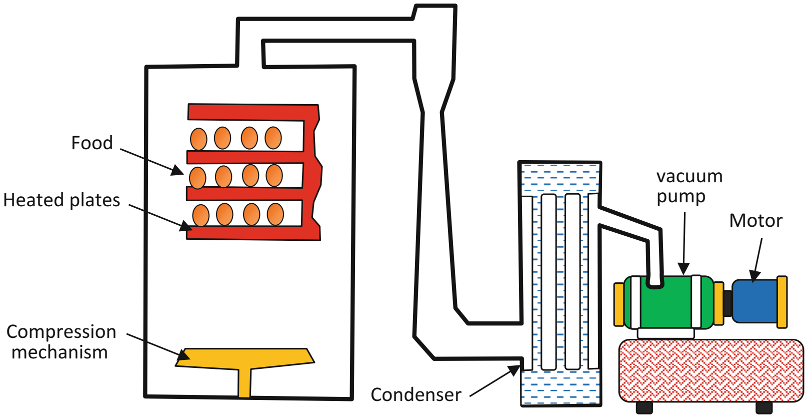


Fig. 5.36 Freeze dryer

through radiation or conduction. The vapours as a result of drying are condensed in condenser.

5.12.10 Freeze Dryers/Lyophilizer

The food material is kept on the shelves in a compartment under high vacuum condition. The material is mostly frozen before loading on the shelf (Fig. 5.36). The conduction and radiation modes are being used to transfer the heat. The vapours generated are recovered through vacuum pump. A sheet of expanded metal is also used to enhance heat transfer rate to food material through conduction and accelerate the freeze-drying process. It also facilitates uniform removal of water from the food material. The food should be placed on metal plate in such way, so that maximum surface area should remain in contact with metal plate to receive maximum heat. The condensation of vapour can be obtained using refrigerated condenser.

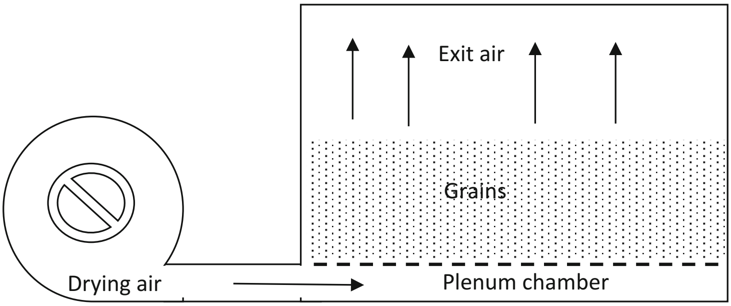


Fig. 5.37 Flat bed dryer

5.12.11 Flat Bed Dryers

These dryers have a perforated bottom chamber to place the food materials, and air is blown from the perforation provided at the bottom of chamber (Fig. 5.37). Since the depth of food material remains less, the drying time is also shorter. The capacity of such dryers is limited to 1–2 tonnes. These can be efficiently used on the farms. The height of bed over the bed is limited to 1.2 m. Quicker drying, less over drying and lower pressure requirement are the advantages of using these dryers. The depth of the material remains less as compared to deep bin dryer.

5.12.12 Continuous Flow Dryer

These are made in vertical shape, the grains are poured from the top, and the dried grain is being collected at the bottom. The conveyors are used to regulate the flow of grains (Fig. 5.38). The grains are diverted in mix type version of dryer using baffles, which accelerate the drying rate through mixing during movement in zig zag flow. The flow rate of air is kept about 50–95 m^3/min per ton and drying air temperature is usually limited to 65 °C. Whereas, in case of non-mixing type version, the grain move downwards, which gets heated through the plenum chamber provided at the centre of dryer, while drying air temperature is limited to 54 °C and flow rate is increased up to 125–250 m^3/min per ton for drying the grains appropriately.

5.12.13 LSU Dryer

It is a continuous-type heated air dryer, which was developed by Louisiana State University during the year 1950. The dryer was designed to ensure the good mixing of grain and air for greater contact and gentle heat treatment. Several inverted-V-shaped channels are used and placed in a vertical column (Fig. 5.39). These channels are placed in such way that every alternate row is kept open towards the heated air blower side to blow the air inside the dryer, which provides air to get ample chances to mix with grain directly while moving upward and make an exit from remaining

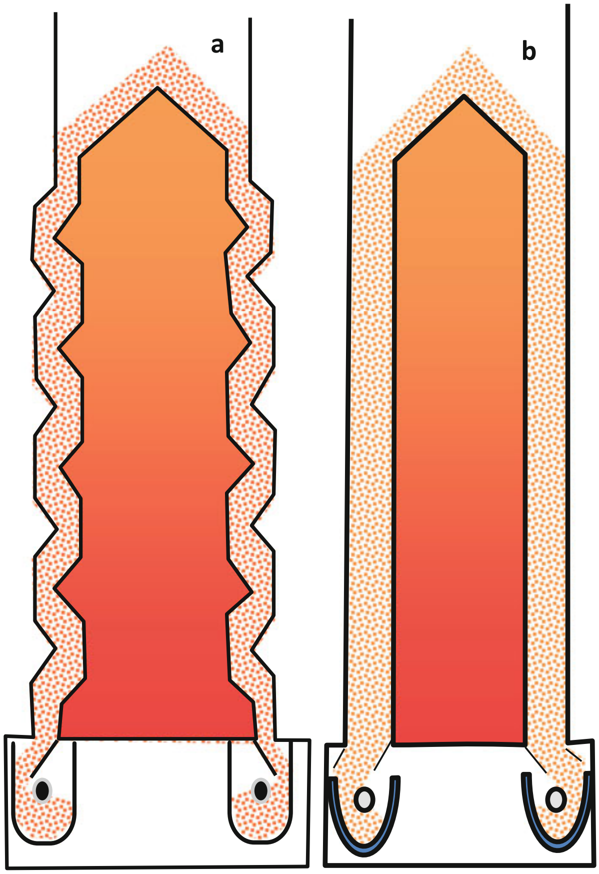


Fig. 5.38 Continuous flow dryers. (**a**) Mixing dryer. (**b**) Non-mixing dryer

alternate channels, which are kept open to the ambient to exit the air. The dryer is manufactured in large capacities and are installed in commercial rice mills (Fig. 5.39).

5.12.14 Solar Dryers

Solar dryers are gaining popularity in developing world as a better alternative to sun drying practices in open floor (Fig. 5.40). Sometimes, these provide a very good option for supplementation and replacement of artificial mechanical dryers to save the cost of fuel/energy. The drying temperatures in solar drying are comparatively higher than the sun drying, which enhances the drying rate and lower the final moisture content of the dried food material. Based on exposure to sun light, the dryers may be divided into three categories, viz. direct, indirect and mixed type. The exposure to direct sunlight can be avoided in indirect-type solar dryer, which

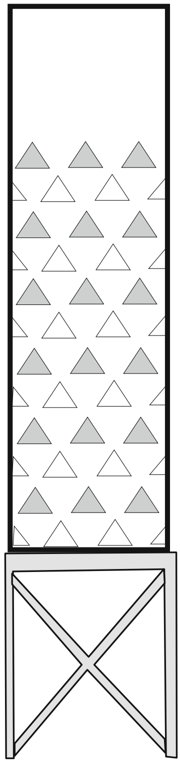


Fig. 5.39 LSU dryer

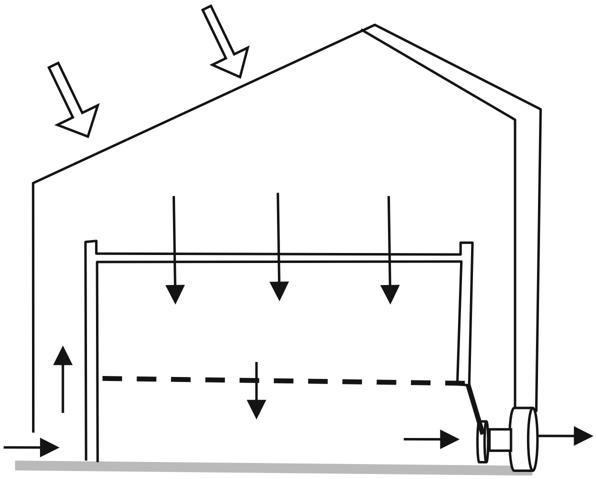


Fig. 5.40 Solar dryer

improves the product characteristics. However, higher drying temperatures are attained in direct-type solar dryers.

5.13 Advanced Drying Technologies

A list of various drying technologies, applications and their advantages are summarized in Table 5.1.

5.14 Dryer Performance and Efficiency

The dryer performance depends on several factors including design, maintenance and operational methods. The dryer performance is also adjudged by the impact of drying on food quality, uniformity of drying, faster drying rates and efficient energy utilization. The energy efficiency remains useful for assessing performance of dryer, making comparisons with other dryers, making improvements in a dryer or using any alternative drying technique.

The minimum quantity of heat required is latent heat to remove water through evaporation, so dryer efficiency can be represented by the ratio of minimum amount of heat required to the actual amount of heat provided in a dryer. The efficiency of drying system affects energy consumption and may increase drying cost. It can be defined in terms of energy needed for drying process from the amount of energy consumed. Overall thermal efficiency can be expressed as:

$$\text{Overall thermal efficiency} = \frac{\text{Amount of energy needed}}{\text{Amount of energy consumed}} \times 100 \tag{5.59}$$

However, because of complex phenomena of food, water and drying mechanism, other efficiency measures are also used. Another approach uses energy balance of the air, assuming the drying operation in adiabatic condition, where heat is not exchanged from the dryer to the surrounding. The heat transfer for the drying corresponds to the drop in drying air temperature and rise in temperature in ambience air (Fig. 5.41).

The air dryer efficiency, η, can be represented as:

$$\eta = \frac{T_1 - T_2}{T_1 - T_a} \times 100 \tag{5.60}$$

where T_1, T_2 and T_a are the heated (inlet) air temperature (°C), outlet air temperature (°C) and ambient air temperature (°C), respectively.

Generally, the difference in numerator part remains a major factor for determining the efficiency. The thermal efficiency of drum dryers, spray dryers and radiant dryers varies between 35–80%, 20–50% and 30–40%, respectively [6].

Table 5.1 List of newer drying techniques and their applications [26]

S. No.	Name of drying	Details	Application	Advantages
1.	Microwave drying	For home and industrial applications due to penetration of microwaves directly into the food material, which causes rapid internal heating through ionic conductance and dipole rotation	Coriander leaves, potato slices, corn, yam, etc.	Shortens the drying time, reduces energy consumption and provides good quality food product
(i)	Microwave-assisted convective drying	First, microwave energy heat the interior part of food rapidly which accelerate movement of moisture from interior to surface for evaporation through convection	Leafy vegetables, etc.	Product with lower bulk density, higher rehydration ratio, lower change in colour
(ii)	Microwave-assisted vacuum drying	Food dehydration due to rapid volumetric heating and low pressure, which accelerate evaporation due to decrease in boiling point at lower pressure	Carrot, tomato slices, banana, grapes, etc.	Shortens drying time and maintain the quality of food products
(iii)	Microwave-assisted spouted bed drying	Solves the issue of nonuniformity in case of microwave heating applications	Parboiled wheat, bulgur, sweet potato dices, etc.	Accelerated drying rates and improved quality of food products
(iv)	Microwave-assisted fluidized bed drying	Increases drying rate with improvement in product quality	Soybean, cooked dice, unfrozen cooked rice etc.	Drying time and specific energy consumption can be saved
(v)	Microwave-assisted freeze drying	Better quality of food products as compared to other drying processes	Cucumbers, banana cubes, etc.	High porosity, low colour, flavour and nutrient degradations and also good rehydration properties
2.	Infrared radiation (IR)-assisted dryings	IR is a part of the electromagnetic spectrum and falls in a wavelength ranging from 0.75 to 1000 μm Near-IR (NIR) (0.75–1.4 μm),	Dried foodstuffs such as fruits, vegetables, grains, etc.	Compact equipment, energy saving, environmental friendly and simple operation as well as contactless heating

		mid-IR (MIR) (1.4–3.0 μm) and far-IR (FIR) (3.0–1000 μm)		
(i)	IR-assisted hot air drying (HAD)	The penetration of IR provide rapid heating of material at inner layers, which accelerate the movement of moisture towards the surface	Sweet potatoes, potatoes, pineapples, mulberry leaf tea, longan, tomatoes, red pepper, onions, carrots, apples, berries, etc.	It takes 2–2.5 lesser times to dry the material as compared to convection drying alone, while keeping good surface quality and high efficiency lower shrinkage, improved rehydration, lower hardness and lower toughness
(ii)	IR-assisted microwave drying	MW drying has the specific advantage of rapid heating due to the penetration of MWs into the volume of the product. Infrared heating can intensively heat the sample surface; therefore, it is usually used to assist MW drying (IR-MW) to accelerate the evaporation from the surface water and to prevent sogginess of the dried product	Egg plants, bread crumbs, carrots, banana, kiwifruit, peach, green pepper, black tea, raspberry, red chilli, etc.	Increases the drying rate of agricultural products and preserves the quality attributes of products
(iii)	IR-assisted vacuum drying	Drying food products under vacuum provides high drying rate, low drying temperature and oxygen-deficient processing environment, thereby improves the quality and nutritive values of the dried products	Welsh onion, potato, banana, lemon, red pepper and pumpkin	High drying rate, low drying temperature and oxygen-deficient processing environment, which improves the quality and nutritive values of the dried products
(iv)	IR-assisted freeze drying	Freeze drying (FD) dehydrates frozen materials by a process of sublimation under high vacuum, which uses IR for providing energy for evaporation	Sweet potato, mushroom, pear, yam slices, apple cubes, banana slices, banana strawberry, etc.	Improves the drying rate and reduces the energy consumption

(continued)

Table 5.1 (continued)

S. No.	Name of drying	Details	Application	Advantages
3.	Radio frequency drying	Radio frequency (RF) is a novel technique, with a frequency range of 3 kHz to 300 MHz, which is much lower than that of microwave (MW) (300 MHz to 300 GHz)	Blanching, thawing, cooking, drying, disinfection and extraction	Produces heat volumetrically, rapid drying with considerable reduced drying time and high energy efficiency
(i)	RF-assisted convective drying—Combined RF and hot air (CRFHA)	Faster than that of hot air drying alone	Crush, tear, curl method (CTC tea), alfalfa leaves, broad bean seeds, lettuces, corn seeds, etc.	Moisture transfer and temperature increase is rapid due to volumetric heating, which shortens the drying time
(ii)	RF-assisted vacuum drying (RFVD)	Moisture removal is rapid due to vacuum	Heat-sensitive agricultural foods	Accelerate the drying process
(iii)	RF-assisted spouted and fluidized bed drying	Fluidized/spouted bed drying with radio frequency provides accelerated drying rates due to fluidization of food material	Grains, corn	More uniform exposure of particulates to electromagnetic energy due to excellent mixing of the solid and the gas
4.	Foam mat drying	Liquid, pulp, or semisolid material is converted into stable foam by incorporating a substantial volume of air or an inert gas in the presence of a foaming agent. Bubbling/ whipping is done for foam formation. Foaming agents are egg white/albumin, soy protein, lecithin and milk protein concentrate, whereas the common stabilizing agents are methyl cellulose, agar, gum Arabic, starch and egg white	Custard apple, tomato pump, fruit juices, etc.	Simple, lesser expensive and time consuming

5.	Spray freeze drying	It involves three stages: Atomization of liquid into droplets, freezing (solidifying) them using a cold fluid, followed by sublimation of these frozen droplets at low temperature and pressure	High-value products, which include coffee powder, whey protein, egg albumin, etc.	Better retention of volatiles and nutritional components and improved physical properties
6.	Heat pump drying	The energy from the dryer exhaust gas is utilized using refrigeration cycle	Suitable for apple, ginger, guava, papaya, lecithin, grated carrot, etc.	The humidity and temperature of drying air can be changed according to the food sensitivity, which facilitates drying at lower temperature
7.	Electrohydrodynamic drying	Electrohydrodynamic (EHD) drying refers to the removal of water from the wet material, that is exposed to strong electric field due to aerodynamic action of the so-called corona wind, ionic wind or electric wind. This wind originates from a sharp end of the electrically conducting pin (needle) or fine horizontal wire as a result of ions leaving this pin/wire and impinging the surface of the material being dried	Suitable for heat-sensitive biomaterials (vegetables, mushrooms, fruits, tofu, etc.)	Faster drying rates in comparison to hot air drying, lower shrinkage, higher rehydration ratio and better retention of nutrients
8.	Direct and instant controlled pressure drop swell (DIC) drying [15]	DIC is a high-temperature/short-time (HTST) treatment, leading to a low final temperature which may cross the glass transition Tg of many partially dried fruits and vegetables. The SD (swell drying)–DIC method results in a well-controlled macro- and microstructure. The high expansion ratio induces significant crispness	It can specifically be used for expanded granules or aiming at obtaining starch-free, crispy, tasty and highly nutritional snacks, can be applied for decontamination and elimination of insects and larvae	It maintains the nutritional value through enhancing the availability of the bioactive compounds in fruits and vegetables and reduces both drying time and energy consumption

(continued)

Table 5.1 (continued)

S. No.	Name of drying	Details	Application	Advantages
9.	Impinging stream drying	Two streams with high-velocity impinge/collide together. One of the streams carries the material for drying, while drying air is used in another stream. A zone of intense heat and mass transfer is created due to collision of streams, which accelerate the rate of drying	Paddy, parboiled paddy, etc.	Increases head rice yield

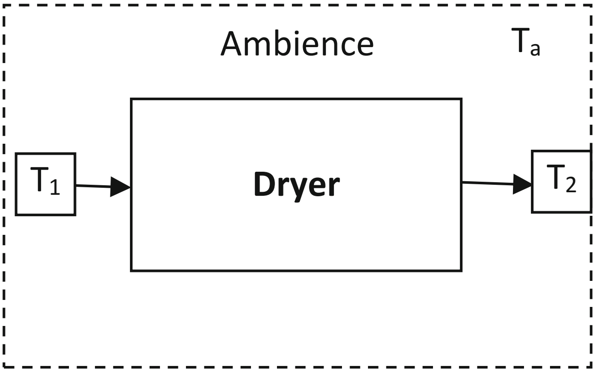


Fig. 5.41 Schematic diagram of dryer

Q.17 The 500 kg of ripe tomato pulp is dried from 90% to 8% moisture content by heated air at 75 °C at flow rate of 15,000 m^3/h from ambient temperature of 30 °C, which was reduced to 60 °C after passing through the dryer and exit at the same temperature. The drying completes within 8 h of working and specific heat of tomato pulp is 3.67 kJ/kg °C. The latent heat, specific heat and density of air can be taken as 2331 kJ/kg, 1.0 kJ/kg °C and 1.02 kg/m^3, respectively. Estimate overall thermal efficiency and air-drying efficiency.

Solution

$$\text{Initial mass of tomato pulp} = 500\,\text{kg}$$

$$\text{Initial moisture content} = 90\%$$

$$\text{Final moisture content} = 8\%$$

$$\text{Initial mass of water in tomato pulp} = 500 \times 90/100 = 450\,\text{kg}$$

$$\text{Mass of solid in tomato pulp} = 500 - 450 = 50\,\text{kg}$$

$$\text{Final mass of water in tomato pulp} = 8 \times 50/(100 - 8) = 4.3\,\text{kg}$$

$$\text{Final mass of tomato pulp} = 50 + 4.3 = 54.3\,\text{kg}$$

$$\text{Mass of water removed in drying} = 500 - 54.3 = 445.7\,\text{kg}$$

Energy needed:

$$\text{Now sensible heat required to increase the temperature of tomato pulp from 30 to } 60^{\circ}\text{C} = m \times \text{cp} \times \Delta\text{t}$$

$$= 500 \times 3.67 \times (60 - 30) = 55050\,\text{kJ}$$

$$\text{Latent heat required to evaporate the water from the tomato pulp} = m \times L$$

$$= 445.7 \times 2331 = 1038927\ \text{kJ}$$

$$\text{Total energy required to evaporate the water} = m \times c_P \times \Delta \text{t} + m \times L$$

$$= 55050 + 1038927 = 1093977\ \text{kJ}$$

Energy consumed:

$$\text{Flow rate of air} = 15000\ \text{m}^3/\text{h}$$

$$\text{Total time of drying} = 8\ \text{h}$$

$$\text{Total volume of air required} = 15000 \times 8 = 120000\ \text{m}^3$$

$$\text{Density of air} = 1.02\ \text{kg}/\text{m}^3$$

$$\text{Total mass of air required} = 120000 \times 1.02 = 122400\ \text{kg}$$

$$\text{Total amount of energy provided by air} = m \times \text{cp} \times \Delta t$$

$$= 122400 \times 1 \times (75 - 60) = 1836000\ \text{kJ}$$

Estimation of Efficiencies

$$\text{Overall thermal efficiency} = \frac{\text{Amount of energy needed}}{\text{Amount of energy consumed}} \times 100$$

$$\text{Overall thermal efficiency} = \frac{1093977}{1836000} \times 100 = 59.54\%$$

$$\text{Air dryer efficiency}, \eta = \frac{T_1 - T_2}{T_1 - T_a} \times 100 = \frac{75 - 60}{75 - 30} \times 100 = \mathbf{33.33}\%$$

5.15 Effect of Drying on Foods

The drying of food products affects the product quality. The retention of quality attributes and drying efficiency remain necessary for optimization of processing parameters [27]. Some of the important characteristics, to be taken into account are given as follows:

5.15.1 Texture

The solid food materials are characterized by their texture and play a vital role on the quality attributes. The texture of food material is also affected with the cleaning, pre-treatments and size reduction along with drying of fruits and vegetables. More changes in the texture of dried food at higher temperature are evident due to movement of water from interior to the surface of the food. The movement of water from the food remains specific to the type of food and drying conditions. Some of the mechanisms for change of texture are:

- *Gelatinization of starch:* The gelatinization of starch in the presence of moisture and heat creates variation in moisture, structure and internal stresses.
- *Development of cracks:* Numerous methods of drying of food ruptures, cracks, compresses and distorts the comparatively hard cells, which leads to development of a shrunken shrivelled appearance, and the material does not regain completely and has a significant amount of difference in fresh and rehydrated foods.
- *Denaturation of protein*: The aggregate formation during drying leads to denaturation of proteins, which reduces the water-holding capacity and toughening of tissues.
- *Case hardening:* The chemical and physical alteration in solutes available at surface takes place due to the removal of water. The capillaries presented on the surface ruptures and blocks the openings to create a hard and impermeable layer at the surface, which can reduce the drying rate.

5.15.2 Flavour

- The volatile component, which generates the flavour, is lost from the food during drying.
- The structure of the dried material becomes more porous, which increases the effect of oxygen and remains susceptible for oxidation.
- The flavour of dried foods can be improved by restricting oxidative or hydrolytic enzymes using different aids such as ascorbic acid, citric acid, sulphur dioxide, etc.

5.15.3 Colour

- *Enzymatic browning:* The loss in colour of dried foods has numerous reasons as drying alters surface characteristics, which causes different reflectivity and as a result different colour values. Chlorophyll, carotenoids and other heat-sensitive pigments present in fruits and vegetables alters due to application of heat and oxidation.
- *Non-enzymatic browning:* The temperature and water activity of food are important factors for Maillard reactions. The rate of darkening increases markedly at high drying temperatures.

5.15.4 Nutritional Value

The nutritional value of food material is largely affected by drying, which can be optimized by using appropriate procedures, drying temperature, time and storage conditions.

- The preparation of fruits and vegetables generally deteriorate more in comparison to drying operation. Therefore, preparation of fruits and vegetables must be appropriately selected.
- Lower temperatures, shorter drying exposure and low oxygen level reduce the loss of vitamin C, which remain sensitive to oxidation and heat treatment. Thiamine also remains sensitive to heat treatment.
- The digestibility and biological value of proteins do not deteriorate considerably during drying in most of the foods.

5.16 Exercise

1. How drying affects the storability of the food product? Explain in brief.
2. What is the difference between drying and dehydration? Discuss the advantages and limitations of the drying of food material too.
3. Draw the phase diagram of water and explain its significance in lyophilization of perishable foods.
4. Whether boiling point of water can be increased or decreased? Explain the reason in brief.
5. State the mechanism of drying and draw a mass balance diagram depicting drying process along with various equation used.
6. About 450 kg of bottle gourd with 92% moisture content is dried to 8% using tray dryer, estimate the amount of drying material produced.
   [Ans. 39.1 kg]
7. The water chestnut contains 62.5% moisture content, which needs to be dried to 9% for producing flour. Estimate the amount of water to be evaporated from an initial mass of 20 kg chestnut and the amount of energy required, neglecting sensible heat required. (Assume latent heat of water = 2260 kJ/kg).
   [Ans. 11.8 kg, 26,573.6 kJ]
8. A banana was dried to 5% in the form of slices. If the initial mass and moisture of banana are 10 kg and 77%, estimate the amount of dried banana slices prepared.
   [Ans. 2.4 kg]
9. List various methods used for moisture content determination and explain any one of the methods and application in details.
10. Represent a drying process on a psychrometrics chart. Also explain about energy required for moisture removal and temperature gain during drying of food materials.

11. What is the difference between equilibrium moisture content (EMC) and critical moisture content (CMC)? Explain the importance of EMC in drying processes.
12. Explain the process for drying of fruits and vegetables through sublimation.
13. A bin holds 2000 kg of wet grain containing 75% dry matter. This grain is to be dried to a final moisture content of 14% (wb). (a) Determine the initial and final moisture content of grain on dry basis. (b) Determine the weight of water removed during drying.
    [Ans. (a) 33.3%, 16.3% (b) 255.8 kg]
14. Define the term equilibrium moisture content and state its importance.
15. Determine the values of constant *c* and *n* from the Henderson's equation for the following data obtained under two different conditions of EMC studies of sunflower seed.

Condition	RH (%)	Temperature (°C)	EMC (% d.b.)
1	60	35	11
2	70	45	14

[Ans. $n = 0.9985$, $c = 0.00271$]

16. Discuss the application of heat and mass transfer in drying processes. Also, state the governing equation of heat and mass transfer in drying processes.
17. In an experimentation, the total pressure and humidity of wet air are 110 kPa and 0.035 kg/kg, respectively. (i) Calculate the partial pressure exerted by vapours. (ii) If the saturation pressure remains 10.0 kPa, estimate relative humidity. (iii) If the temperature of air is 40 °C, estimate relative humidity. (iv) What should be the partial pressure and relative humidity at 65 °C and at dew point.
    [Ans. (i) 5.9 kPa, (ii) 59%, (iii) 79.95%, (iv) 5.9 kPa and 100%]
18. The humidity of air is 0.027 kg/kg at total pressure of 123 kPa, estimate the partial vapour pressure and relative humidity in case of saturation vapour pressure at 61 °C is 21.89 kPa.
    [Ans. 5.1 kPa, 23.3%]
19. The humidity of air is 0.107 kg/kg at a total pressure of 90 kPa, estimate the partial vapour pressure and relative humidity in case of saturation vapour pressure of 19.03 kPa.
    [Ans. 13.2 kPa, 69.3%]
20. If the total pressure of 77 kPa is exerted by an air with 0.072 kg/kg and the saturation vapour pressure is 10.5 kPa, calculate partial vapour pressure and relative humidity.
    [Ans. 8.0 kPa, 79.2%]
21. State the mechanism of heat transfer rates using suitable curves of drying rates with respect to moisture content and time. Explain various rate periods of drying along with their physical significance.
22. What is the difference between equilibrium moisture content (EMC) and critical moisture content (CMC)? Explain their importance in drying processes.
23. Explain the reason of reduction in the rate of drying. How these can be explained in fruits and vegetables.

24. Following observations were recorded during thin layer drying of custard apple pulp. Apply Lewis model and estimate the value of coefficient and coefficient of determination using any spreadsheet program.

Drying time (min)	0	60	120	180	240	300	360	420	480	540	600
Moisture ratio	1	0.71	0.44	0.24	0.07	0.06	0.05	0.03	0.03	0.02	0.02

[Ans. $k = -0.008$, $R^2 = 0.9799$]

25. Which drying removes water through sublimation? Explain the process in detail.
26. Explain the working of LSU with the help of neat sketches.
27. State the difference between various tray dryers used in drying of material.
28. What is the difference in application of air in fluidized bed dryer and pneumatic dryers.
29. A food material has 5.5 m^2 surface area with a temperature of 40 °C, estimate the rate of moisture removal, rate of heat energy utilization and heat transfer coefficient, when temperature and humidity of the drying air are 55 °C and 30%, respectively. The mass-transfer coefficient may be taken as 0.017 kg/m^{2}s. *(Note: Use psychrometric chart and steam table).*
    [Ans. 0.00173 kg/s, 4.16 kW, 50.45 J/m^{2}s °C]
30. A tray consisting of mango leather has 15.4 m^2 surface area with a temperature of 37 °C, estimate the rate of moisture removal, rate of heat energy utilization and heat transfer coefficient, when temperature and humidity of the drying air are 70 °C and 10%, respectively. The mass-transfer coefficient may be taken as 0.016 kg/m^{2}s. *(Note: Use psychrometric chart and steam table).*
    [Ans. 0.005248 kg/s, 12.67 kW, 24.92 J/m^{2}s °C]
31. List various advanced drying technologies. Explain any one of the technologies for drying of fruit pulp in brief.

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Size Reduction

6

Yogesh Kumar, Vijay Singh Sharanagat, and Kshitiz Kumar

Abstract

In this chapter, the mechanism and factors affecting size reduction process and the laws governing these operations are discussed. Size reduction is a process in which particles with smaller size and large surface areas are formed, which ultimately eases the processing. The chapter explains the size reduction mechanism during compression, impact, cutting, shearing, and attrition. The stress-strain behavior of materials during mechanical failure also plays an important role during size reduction. To evaluate the effectiveness of size reduction operation, analysis of newly formed surfaces and energy involved becomes important. A better understanding of equipment and operation parameters can minimize the overall input energy. The popular size reduction equipments for agricultural produce, viz., hammer mill, ball mill, burr mill, jaw crusher, gyratory crusher, crushing roll, cutter mill, Reitz mill, and colloid mills, are explained using schematic diagrams. The heat generated during size reduction is always a big concern in processing spices and herbs. Hence, advanced size reduction operations like hammer mill with water jackets and cryogenic grinding are used to protect the aromatic and volatile components. In liquid food, homogenization

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is frequently used to break particulate matter into smaller and uniform particle sizes to form dispersion. The chapter also deals with different size reduction laws.

Keywords

Size reduction mechanism · Stress-strain behaviour · Grinding · Laws of size reduction · Size reduction equipments · Low temperature grinding · Size reduction in liquids

6.1 Introduction

Size reduction is a mechanical process and an important unit operation, in which large particles are changed to smaller size. The mechanical breakdown of solids does not change the chemical composition and only alters the state of aggregation of solids. The large size of solid material limits their applications and processing. Hence, large size solid requires to be brought down into smaller size before their use, especially in food processing. Fine particles have a large surface area and more absorption capacity, are easy to mix, and have low crystallinity which ultimately ease the processing as well as enzymatic digestibility of food. Most of the process operations related to size reduction are applied to solid foods; however, size reduction is also desired in liquid food like homogenization of milk.

Size reduction is a very inefficient operation, and only 1 to 2% of input energy is utilized for size reduction, and the remaining energy is lost in the form of either heat or sound. Most of the energy applied for size reduction is absorbed by the equipment itself; therefore, the size reduction process is considered as inefficient. Due to this, the actual available energy for size reduction is limited to a small fraction of the total energy. Moreover, the energy consumption also depends on the type of materials, for example, a plastic material will consume more energy because the material requires energy in changing the shape before creating new surfaces. On the other hand, brittle materials are more likely to directly fail and create new surfaces without changing shape. Most of the theories postulated for size reduction consider that the material is brittle and will fracture before elongation or contraction in feed particles [1].

6.2 Size Reduction Mechanism

6.2.1 Compression/Crushing

When a material is pressed by an external compressive force above its compressive strength, it gets squeezed and compacted and finally fails. The slow application of compressive force causes rupturing in many directions. Due to this, crushing produces irregularly shaped and sized particles. However, the features of particles and new surfaces also depend on the type of material being compressed and how compression is applied. The compression is preferred when the feed is crystalline, very hard, and friable having abrasive and/or non-sticky surfaces and coarse product is desired. Crushers are used for flour, grits, meal from grains, and size reduction of sugars, salt, and mineral stones. Crushing of oilseeds increases the surface area and is an important step in the expression and solvent-based extraction of oil.

6.2.2 Impact

If a large sudden force is applied over the material beyond its strength, it fails. Unlike crushing or compression, the fracture propagates through the weak regions of the material and creates new surfaces of failed regions. Moreover, the shock given to the material limits the time of deformation and vibration, and majority of energy is utilized in material fracturing. The impact is used to create very fine powder from a wide range of feed. The example of application of impact force includes cracking of nut with hammer. Combined with shearing force, impact force is used for the size reduction of fibrous food [2].

6.2.3 Cutting

Cutting involves a hard, sharp, and thin knife which is forced through the material at high speed. Cutting is used to create smaller pieces from the large ones making them suitable for further processing. The forces acting on the various faces of cutting devices are compression force, frictional force, deformation force, and separation force. Cutting of food products can be divided into four phases: (1) First is the start-up phase during which contact between the cutting edge and the material being cut is achieved. (2) Second is the deformation phase just before the penetration of cutting devices during which cutting force increases linearly. (3) Third is the separation phase in which the actual separation of product occurs. During this, the resistance of the product along with the friction force between the product and cutting device determines the cutting force. (4) Fourth is the detaching phase in which the separation is completed. The dominating force during cutting depends upon the nature of food material. In homogenous compact solid food material, the frictional force is dominant, while in porous solids and vegetable tissues, the separation force acting on the cutting edge is the dominant. In cheese and bacon, the frictional force may comprise up to 40% of the total cutting force [3].

6.2.4 Shearing

The shearing force combines the action of cutting and crushing. The equipment used to cause shearing contains both a knife and a bar.

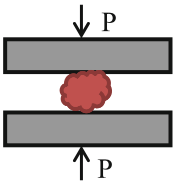
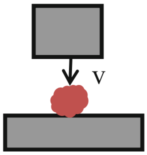
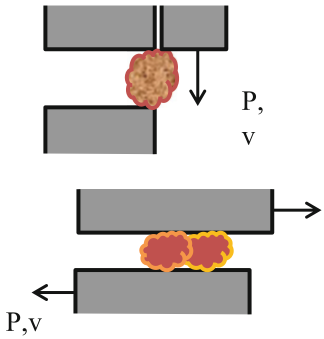
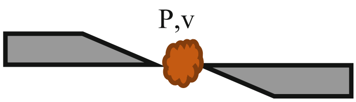
The thickness of edges of knife decides material will fail to cutting or crushing. Cutting dominates if a sharp and thin edged knife is used for the size reduction, whereas crushing occurs if a thick and dull edged knife is used. However, the thickness of the knife should be such that it is able to bear the shock resulting from the material being hit. An ideal shearing unit consists of sharp and thin edged knife with a very small clearance between the bar and the knife. Shearing is preferred if feed material has soft to medium hardness and the end product desired has relatively coarse particles.

6.2.5 Attrition

Attrition involves shear and compression which cause rubbing or wearing action due to friction. The material to be reduced is kept between two metal disks which rotate in opposite direction.

To increase the shear and rubbing, the speed of disks is kept different from each other. It is used to create very fine particles from friable and non-abrasive feed. Table 6.1 illustrates the different forces applied for reducing the agricultural products.

Table 6.1 Forces used in size reduction of agricultural products

Forces	Schematic diagram	Example
Compression		Jaw crusher, crushing rolls
Impact		Hammer mill, ball mill
Attrition (compressive + shearing force)		Disk attrition mill
Cutting (compression + friction)		Rotary knife cutter

6.3 Stress-Strain Behavior during Size Reduction

Studying the stress-strain behavior of solid materials helps in understanding the behavior of that solid under applied stress and how its deformation and failure take place. The stress-strain relation during size reduction can be understood through the curve 2 in Fig. 6.1. If the applied stress remains below point E, the deformation is elastic in nature. Elastic deformation represents the ability of the material to revert to its original dimension on the removal of applied stress, which indicates that the material is obeying Hooke's law (stress and strain are proportional to each other for small deformations) till point E on the curve. If the applied stress is increased a little bit beyond proportional limit E up to point Y, the strain developed is not proportional to stress; however, the material still returns to its original dimension on the removal of stress. The point Y on the curve is called *elastic limit or yield point* [4].

Yield point represents the departure of linearity of stress-strain curve beyond which permanent deformation in the material creeps in, i.e., the material exhibits plastic behavior. If the applied stress is continued beyond yield point Y, the strain increases rapidly even for a small change in stress. In general, the elastic limit is ill-defined stress, but for some material, the onset of plastic deformation is denoted by sudden drop in stress indicated by concave portion of the curve after yield point. The stress of the concave region in such material is defined as the lower yield point. The curve in the plastic region will always show nonlinear relation between shear stress and strain. If the applied stress is continued further, the material is finally ruptured at fracture point (point F). Depending on the mechanical properties, the biological materials may exhibit different types of stress-strain curve, as shown in Fig. 6.1. The longitudinal portion of the stress-strain curve is closer to the stress axis for hard (stiff) materials, while in soft (flexible) materials, it is away from the stress axis. Hence, materials represented by curves 1, 2, and 3 in Fig. 6.1 are hard, while materials represented by curves 4 and 5 are soft. The longitudinal portion of the stress-strain curve is long in the case of strong material, while in weak material, it is

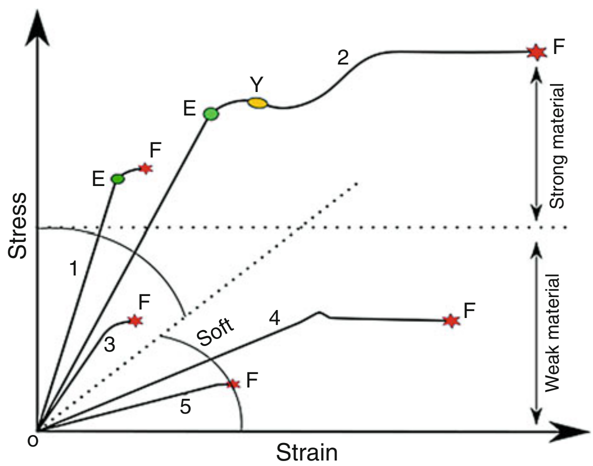


Fig. 6.1 Behavior of a material under applied stress

Table 6.2 The nature of materials exhibited by different stress-strain curves in Fig. 6.1

Stress-strain curve	Nature of material
Curve 1	Hard, strong, and brittle
Curve 2	Hard, strong, and ductile
Curve 3	Hard, weak, and brittle
Curve 4	Soft, weak, and ductile
Curve 5	Soft, weak, and brittle

short. Hence, materials represented by curves 1 and 2 in Fig. 6.1 are strong, while materials represented by curves 3, 4, and 5 are weak. The fracture point (point F) in the case of ductile material is after a long concave portion, while in brittle material, the fracture point is after a minimal elastic portion without any concave part of stress-strain curve. Hence, materials represented by curves 2 and 4 in Fig. 6.1 are ductile, while materials represented by curves 1, 3, and 5 are brittle.

The nature of materials represented by different stress-strain curves in Fig. 6.1 is summarized in Table 6.2.

6.4 Factors Affecting Size Reduction Process

There are various factors, which affect the size reduction process. These factors include nature, physical and chemical properties of rawmaterials, type of size reduction mechanism, time and external factors [5]. The nature of materials affecting size reduction is summarized in Table 6.3, whereas other factors that can affect size reduction are concluded in Table 6.4.

6.5 Grinding

Grinding involves the conversion of materials into fine powder by fracturing. The fracture occurs due to stress generated by mechanical components of grinder. Major portion of the mechanical stress is internally absorbed by feed as strain energy in the beginning of grinding. However, failure does not appear until strain energy exceeds a critical level. When strain energy is enough, fracture starts to occur in the weaker region of materials, and the energy stored inside the material is liberated. Time is also an important factor in the fracturing process [6].

6.5.1 New Surface Formed by Grinding

In the initial stage of the grinding, the particles are of courser size, but as the grinding is continued, the coarser particles are converted to finer particles. In the end of grinding process, the product consists of a mixture of various particle sizes with a higher fraction of a particular size. Fine particles have large surface area. Specific surface area is defined as the surface area per unit mass.

Table 6.3 The nature of materials affecting the size reduction process

	Factors	Remarks
1	Hardness	Soft material fails easily to shear as compared to hard
2	Elasticity/ stickiness	Elastic/sticky materials become soft due to stress applied during milling. Materials often adhere to the mill surfaces and may block screen due to sticky nature. Hence, materials like waxes, resins, and gums should be chilled prior to milling
3	Friability	Friable materials have the tendency to fail along well-defined planes. Brittle materials have the tendency to convert into fine particles easily
4	Toughness	Some substance is tough in nature due to their fibrous structure. It is difficult to mill tough materials as compared to hard or brittle. Cutting should be preferred during milling of tough materials
5	Melting point	Materials with low melting point components (wax, fats/oil, and lipid) are soften due to heat generation during size reduction. Thus, they should be cooled along with mill
6	Hygroscopic	If a material is hygroscopic, it absorbs the atmospheric moisture rapidly. To avoid this, milling should be performed in dried and less humid conditions
7	Thermolability	If a substance contains components prone to oxidation and hydrolysis due to ambient oxygen and moisture, the heat generated during milling enhances these chemical reactions. Hence, to avoid degradation, milling should be performed in inert close system of CO_2 or N_2
8	Volatility	Substances containing volatile components (mainly aromatic compounds) are more likely to degrade during size reduction due to heat. Cryogenic milling is recommended mainly in the case of spices and aromatic plants

Table 6.4 Other factors affecting size reduction

	Factors	Remarks
1	Moisture content	It affects the mechanical properties like hardness, toughness, and stickiness. Generally, moisture below 5% is sufficient for dry milling and more than 50% for wet milling
2	Particle size	A feed of proper size distribution results in better milling output. If the feed has non-uniform size distribution, then the reducing efficiency of equipment reduces, and the equipment may not handle the oversized feed. Thus, the feed should be pretreated as per the requirement of milling equipment to maintain uniform flow
3	Purity required	The output of size reduction might get contaminated due to abrasive wear of milling parts. This can be avoided by choosing a mill with minimal or no wear and cleaning the mill parts prior to milling

6.5.2 Calculation of Specific Surface Area

For the calculation of specific surface area, two parameters are required: one is the particle size distribution, and the other is the shape factor. The particle size distribution obtained through sieve analysis is used to calculate the typical dimension or average diameter, D_p, of a particle. The typical dimension D_p of the particle can arbitrarily be correlated to the volume (V_p) and the surface area (A_p) of the particle as:

$$V_P = p \times D_P^3 \tag{6.1}$$

$$A_P = 6q \times D_P^2 \tag{6.2}$$

where V_p is the volume of the particle, A_p area of the particle surface, and D_p typical dimension of the particle and p and q are the volume shape factor and surface shape factor, respectively, which connect the particle geometries.

For cube-shaped particle, the typical dimension, D_p, will be equal to the side of the cube in the above equation. The volume and surface area of cube are $D_p{}^3$ and $6D_p{}^2$, respectively. Hence, the volume shape factor (p) as well as surface shape factor (q) is equal to 1 for cube-shaped particle. The ratio of surface area to volume would be $6/D_p$.

For spherical particle, the typical dimension, D_p, will be equal to the diameter of the sphere. For a sphere of diameter D_p, the volume and surface area are $(\pi/6)\ D_p{}^3$ and $\pi D_p{}^2$, respectively. Hence, for sphere, the volume shape factor (p) as well as surface shape factor (q) is π/6. For sphere, also the ratio of surface area to volume would be $6/D_p$.

A shape factor is now defined as $q/p = \lambda$; therefore, for a cube or a sphere, $\lambda = 1$. Thus, shape factor is the ratio of the particle property to the property of a sphere having a diameter equal to the measured particle dimension.

Now, the ratio of surface area to volume can be obtained by dividing Eq. (6.2) by Eq. (6.1):

$$\frac{A_P}{V_P} = \frac{6q}{p \times D_P} = \frac{6\lambda}{D_P} \tag{6.3}$$

The above equation can be rearranged as:

$$A_P = \frac{6q \times V_P}{p \times D_P} = 6\lambda \left(\frac{V_P}{D_P} \right) \tag{6.4}$$

If there is a mass m of particles of density ρ_p, the number of particles is $(m/\rho_p \times V_P)$ each of area A_p.

$$\text{So total area}, A_t = \left(\frac{m}{\rho_p \times V_P} \right) * \left(\frac{6q \times V_P}{p \times D_P} \right) = \frac{6q \times m}{\rho_p \times p \times D_P} \tag{6.6}$$

$$\therefore A_t = \frac{6\lambda m}{\rho_p \times D_P} \tag{6.7}$$

6.5.3 Degree of Grinding

This is defined as the ratio of the overall surface area of the final product to the overall surface area of the feed. It can be expressed as:

$$d_g = \frac{S_P}{S_f} \tag{6.8}$$

where d_g is the degree of grinding, S_p overall surface area of the final product, and S_f overall surface area of the feed.

6.5.4 Fineness Modulus

Fineness modulus (FM) is equal to the sum of cumulative percentage mass retained over different sieves divided by 100. It can be used to find the average particle size using the empirical equation:

$$D_P = 0.135(1.366)^{FM} \tag{6.9}$$

where D_P is the average particle size (mm) and FM fineness modulus.

Example 6.1 Find the fineness modulus from the given data and calculate the average particle size.

IS sieve no.	100	50	40	30	20	15	pan
Weight of material retained (g)	0	1.5	30	40.6	50.4	9.9	8

Solution:

IS sieve no.	Weight retained (g)	Cumulative weight retained (g)	Cumulative % of weight retained (%)	Fineness modulus	Average particle size (mm)
100	0.0	0.00	0.00	$\frac{256.41}{100} = 2.5641$	$D_P = 0.135 (1.366)^{FM}$ Or, $D_P = 0.135 (1.366)^{2.5641}$ =0.300 mm
50	1.5	1.50	1.07		
40	30	31.50	22.44		
30	40.6	72.10	51.35		
20	50.4	122.50	87.25		
15	9.9	132.40	94.30		
Pan	8.0	140.4			
Total	140.4		256.41		

6.6 Laws of Size Reduction and Energy Calculation

The theories for the calculation for energy required in size reduction consider that the energy required to create a small change in the particle size is proportional to the original size of the particle [7].

$$-\left(\frac{dE}{dD}\right) = k \times D^n \tag{6.10}$$

where, dE is the differential energy required, dD is the change in a typical dimension, D is the magnitude of a typical length dimension, k, n are constants, $(-)$ sign indicates reduction in size of D.

6.6.1 Rittinger's Law

This is the oldest law for the calculation of energy required for the size reduction operation. This law was developed by Peter von Rittinger in 1867. Rittinger considered the material to be brittle. He postulated that the energy required for size reduction is directly proportional to the change in the surface area and n is assumed as -2.

$$-\left(\frac{dE}{dD}\right) = K_R \times D^{-2} \tag{6.11}$$

The total energy (E) required to reduce the size of particles can be calculated by rearranging and integrating the above equation within the limit $E = 0$ at D_f (initial feed size) and $E = E$ at D_p (final product size).

$$-\int_0^E dE = K_R \int_{D_f}^{D_p} D^{-2} dD \tag{6.12}$$

$$[-E]_0^E = K_R\left[-\frac{1}{D}\right]_{D_f}^{D_p} \text{ or}, E = -K_R\left[\left(-\frac{1}{D_p}\right) - \left(-\frac{1}{D_f}\right)\right]$$

$$E = K_R\left(\frac{1}{D_p} - \frac{1}{D_f}\right) \tag{6.13}$$

$$\frac{P}{\dot{m}} = E = K_R\left(\frac{1}{D_p} - \frac{1}{D_f}\right) \tag{6.14}$$

where D_f is the particle size of the feed (m), D_p particle size of the product (m), E total energy (kJ), P power required (kW), $\dot{m}$ mass flow rate (kg/s), and K_R Rittinger's constant.

Also, $E \propto \frac{1}{\text{particlesize}}$.

Rittinger's law is more suitable where there is a large increase in surface area such as in fine grinding.

6.6.2 Kick's Law

Kick (1885) assumed that the energy required for size reduction is directly proportional to the change in dimension and n is assumed as −1.

$$-\left(\frac{dE}{dD}\right) = K_K D^{-1} \tag{6.15}$$

The total energy (E) required to reduce the size of particles can be calculated by rearranging and integrating the above equation within the limit E = 0 at D_f (initial feed size) and E = E at D_p (final product size).

$$-\int_0^E dE = K_K \int_{D_f}^{D_P} D^{-1} dD \tag{6.16}$$

$$[-E]_0^E = K_K [\ln D]_{D_f}^{D_p}$$

or,$E = -K_K[(\ln D_p) - (\ln D_f)]$

$$E = \frac{P}{\dot{m}} = K_K \, ln\left(\frac{D_f}{D_p}\right) \tag{6.17}$$

where D_f is the particle size of the feed (m), D_p particle size of the product (m), E total energy (kJ), P power required (kW), $\dot{m}$ mass flow rate (kg/s), and K_K Kick's constant.

Also, $E \propto \frac{D_f}{D_p}$.

Hence, by Kick's law, the energy required to grind particles for the same reduction ratio $\left(\frac{D_f}{D_p}\right)$ is the same and does not depend on feed size.

Kick's law is more suitable where coarser grinding takes place. This particular equation is valid for bigger particle size, for example, size reduction from 12 cm to 6 cm or from 6 cm to 3 cm.

6.6.3 Bond's Law

This law was developed by the Fred Chester Bond, an American mining engineer in 1952. He stated that the energy required for size reduction is proportional to the square root of the surface area-volume ratio of the product. Since, grinding will not yield particles of same size, Bond assumed the final particles size as size of mess in which 80% of materials is passed. He assumed $n = -\frac{3}{2}$, which is in between −2 and − 1.

$$-\left(\frac{dE}{dD}\right) = KD^{-\frac{3}{2}} \tag{6.18}$$

The total energy (E) required to reduce the size of particles can be calculated by rearranging and integrating the above equation within the limit E = 0 at D_f (initial feed size) and E = E at D_p (final product size).

$$-\int_0^E dE = K\int_{D_f}^{D_p} D^{-\frac{3}{2}}dD \tag{6.19}$$

$$[-E]_0^E = K\left[-2\times\frac{1}{\sqrt{D}}\right]_{D_f}^{D_p} \text{ or, } E = 2\times K\left[\left(\frac{1}{\sqrt{D_p}}\right)-\left(\frac{1}{\sqrt{D_f}}\right)\right]$$

$$E = K_B\left(\frac{1}{\sqrt{D_p}}-\frac{1}{\sqrt{D_f}}\right) \tag{6.20}$$

where $K_B = 2\ K$.

Another empirical form of Bond's equation is written in terms of constant work index (W_i). Work index has been defined as the energy required to reduce the unit mass of material from infinite size to a size where 80% of materials is below 100 μm.

$$E = \frac{P}{\dot{m}} = 10W_i\left(\frac{1}{\sqrt{D_p}}-\frac{1}{\sqrt{D_f}}\right) \tag{6.21}$$

where D_f is the particle size of the feed (m), D_p particle size of the product (m), E total energy (kWh/tonne), P power required (kW), $\dot{m}$ mass flow rate (tonne/h), W_i work index (kWh/tonne), and K_K Bond's constant.

If we take the size of the feed and the final product in mm, then

$$E = \frac{P}{\dot{m}} = 0.3162W_i\left(\frac{1}{\sqrt{D_p}}-\frac{1}{\sqrt{D_f}}\right) \tag{6.22}$$

Equations (6.21) and (6.22) are empirical in nature, and the constants 10 and 0.3162 used in them, respectively, are on the basis of experimental results obtained in different units.

Bond's law is applicable for both coarse and fine grinding (Figs. 6.2 and 6.3) and (Table 6.5).

6.6.4 Summary of Laws of Size Reduction

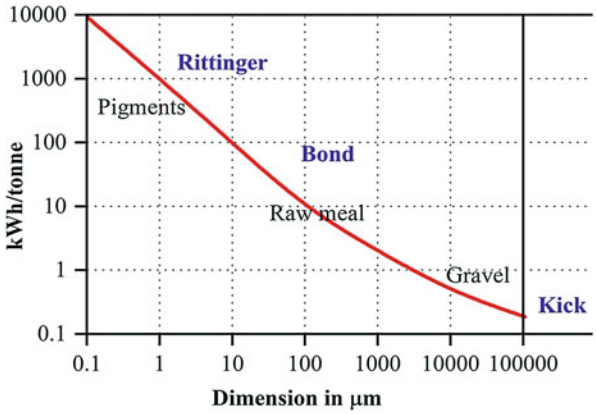


Fig. 6.2 Application of size reduction laws based on materials

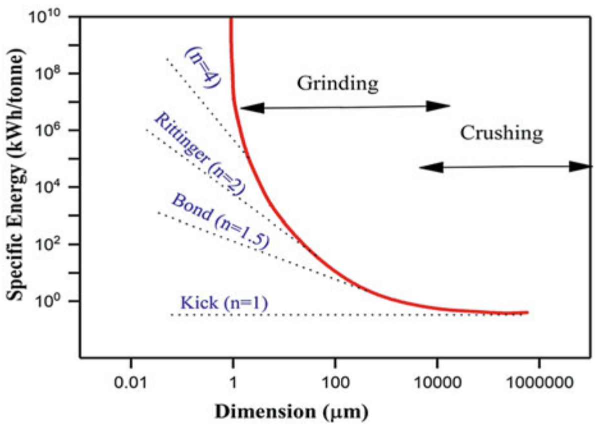


Fig. 6.3 Application of size reduction laws based on methods

Table 6.5 Summarizing laws of size reduction

Salient features	Rittinger's law	Kick's law	Bond's law
Assumption	Energy required is directly proportional to the change in surface area	Energy required is directly proportional to the change in dimension (size reduction ratio)	Energy required for size reduction is proportional to the square root of the surface area-volume ratio of the product
Equation	$E = K_R\left(\frac{1}{D_p} - \frac{1}{D_f}\right)$	$E = K_K \times \ ln\left(\frac{D_f}{D_p}\right)$	$E = K_B\left(\frac{1}{\sqrt{D_p}} - \frac{1}{\sqrt{D_f}}\right)$
Value of n	−2	−1	−3/2
Application	Suitable where there is a large increase in the surface area, for example, fine grinding	Suitable where there is a small increase in the surface area, for example, course crushing	Suitable for a variety of materials undergoing coarse, medium, and fine size reduction

6.7 Size Reduction Equipments

6.7.1 Hammer Mill

A standard hammer mill operates primarily on the principle of impact, although attrition also takes place. A hammer mill consists of a feeding unit, a number of hinged or fixed hammers connected to a rotating shaft inside milling casing, and a sieve to control the size of the product. The impact takes place when the hammer hits the feed material when they are passing through the little gap between the hammer and breaker plate as shown in Fig. 6.4. The brittle and hard materials are more suitable for hammer mill grinding. They have been found useful in the grinding of dried fruits and vegetables, sugars, milk solid, spices, and sometimes fibrous food materials [7, 8].

6.7.2 Ball Mill

Impact and attrition are the main forces involved during size reduction through ball mill. A ball mill consists of a cylinder, which is filled with 30–35% of its volume by small steel balls and is rotated through motor. When the cylinder starts to rotate, the balls start to lift under centrifugal and frictional forces and fall back into the cylinder and onto the feed as gravitational pull exceeds those forces (Fig. 6.5). The impact force is provided as the ball falls from the top of the cylinder. The rotation of cylinder is usually between 4 and 20 rpm and primarily depends upon the diameter of both

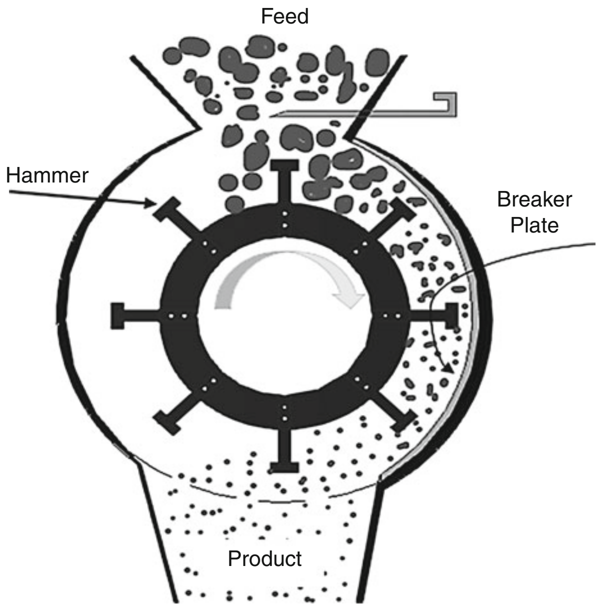


Fig. 6.4 Schematic of hammer mill

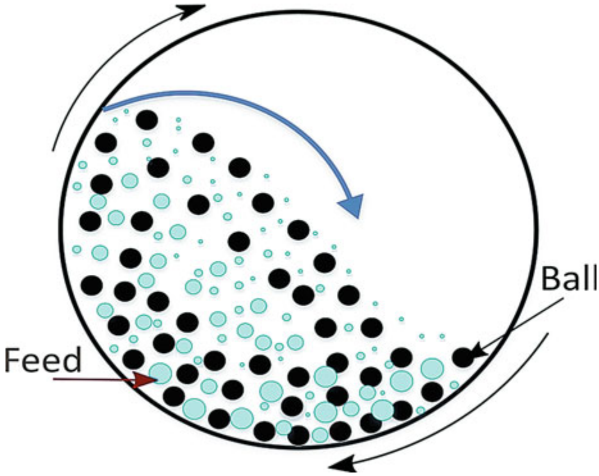


Fig. 6.5 Working of ball mill

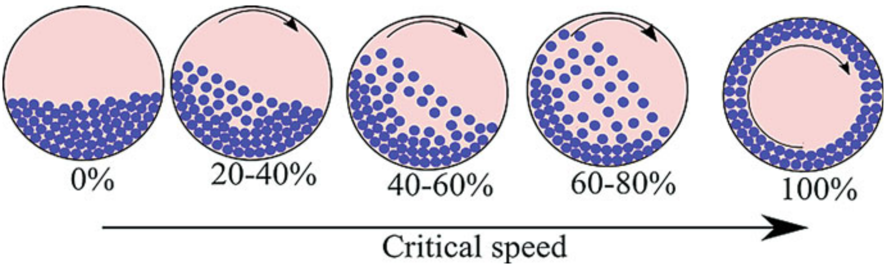


Fig. 6.6 Ball position at different percentages of critical speed

cylinder and ball. If the peripheral speed of the cylinder exceeds a certain speed called critical speed, the mill starts to act like a centrifuge [9].

The balls in mill having speed more than critical speed never fall back and stay on the perimeter of the cylinder due to higher centrifugal force on them. The point where the centrifugal force becomes greater than the gravitational force is called the "critical speed" (Fig. 6.6).

Ball mills are suitable for single-stage grinding, where fine materials are desired. In two-stage grinding, it can be used as the second-stage regrinding process. In the first stage, very coarse materials are ground by other grinding method. The shape of the final products is circular after grinding in the ball mill. The degree of fineness of the final product can be controlled by changing the diameter of the ball.

6.7.2.1 Calculation of Critical Speed

When the ball is at the highest position on the cylinder, the centrifugal force is equal to the gravitational force, i.e.,

$$m\omega^2(R - r) = m\,g \tag{6.23}$$

$$(2\pi n_c)^2 = \frac{g}{(R - r)} \qquad (6.\ (24))$$

$$n_c = \frac{1}{2\pi}\sqrt{\frac{g}{R - r}} \tag{6.25}$$

where g is 9.8 m/s^2, R radius of the cylinder (m), r radius of the ball (m), and n_c critical speed (rps).

The operating speed of the ball mill is kept at 65–80% of the critical speed. The lower values are kept for the wet grinding in viscous solution, while a higher value is kept for dry grinding.

6.7.3 Burr Mill or Plate Mill

A burr mill or plate mill consists of two horizontal/vertical circular abrasive plates, either one or both revolving and separated by a small clearance (Fig. 6.7). The clearance between plates is adjusted by the operator depending on the feed and product size. A small clearance results in finer and smaller products, whereas a large gap produces coarser output. The feed is provided near the axis of rotation and is sheared and crushed as it moves to the edges of plates. Often, the device includes a revolving screw that pushes the food through. Burr mill is generally used for the grinding of hard and small food product like grains, beans, spices, and seeds. Hence, burr mills are usually manufactured for a single purpose, for example, burr mill for coffee beans, wheat, spices, etc.

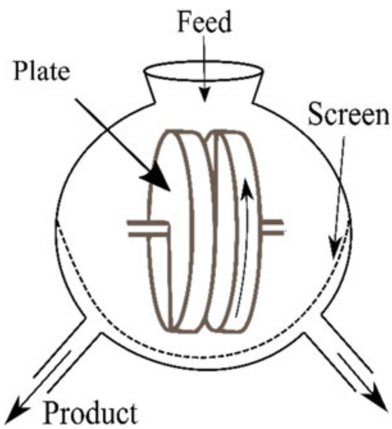


Fig. 6.7 Schematic of burr mill

6.7.4 Jaw Crusher

A jaw crusher mainly uses compression for breaking the large solid particle into relatively coarser output. It consists of several important mechanical components as shown in Fig. 6.9. The crushing force is generated by the two jaws, one of which is fixed, while the other reciprocates. The stationary vertical jaw is called fixed jaw, while the reciprocating jaw is known as swing jaw. The swing jaw moves back and forth relative to it, by a cam or pitman mechanism, acting like a class II lever as shown in Fig. 6.8. The gap between the two jaws at vertical position is known as sizing gap and can be adjusted using adjusting wedges.

The actual size reduction takes place in the cavity between the two jaws (Fig. 6.9). The inertia for size reduction is created by a heavy flywheel. The swing jaw is connected to the flywheel by a shaft which creates an eccentric motion for the reciprocation jaw. The feed cannot leave the crushing chamber until its size reduces to less than the sizing gap. Therefore, the final product consists of particle size lesser than the sizing gap of jaw crusher. However, the application of jaw crusher is very limited in food industries.

Fig. 6.8 Class II lever mechanism

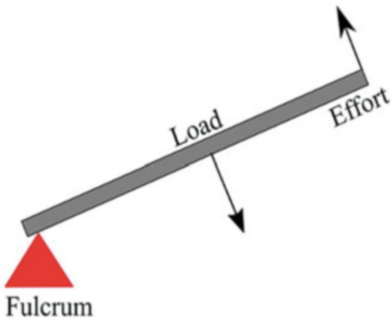
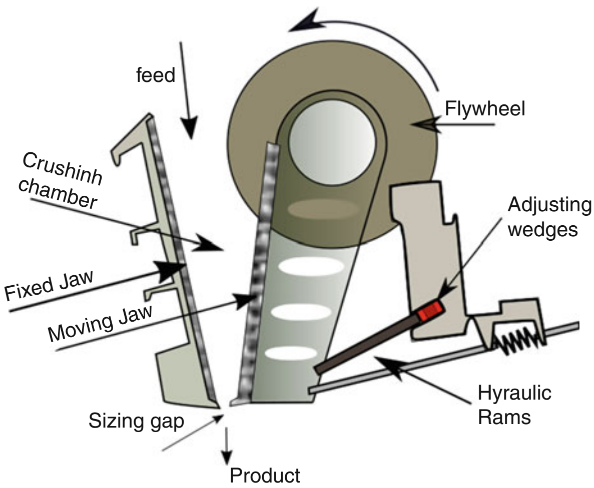


Fig. 6.9 Schematic diagram of Jaw crusher



6.7.5 Gyratory Crusher

The working of gyratory crusher is very much similar to a jaw crusher. It consists of a solid cone set on a revolving shaft within a conical or vertical sloped hollow casing as shown in Fig. 6.10. The solid cone revolves in a circular path without rotating, and when it approaches the casing surface, crushing takes place. The crushed material moves downward and is continually crushed till it becomes small enough to fall through the gap between the two surfaces. This kind of crusher is used in size reduction of hard and dry solids having size comparatively smaller as in the case of jaw crushers. They can reduce the size of feed by a maximum of about one-tenth its size. However, moist or sticky feed should be avoided as gyratory crusher is prone to jamming [10].

6.7.6 Crushing Roll

A crushing roll consists of two or more steel rollers rotating in opposite direction and pulls the feed in the clearance between them (Fig. 6.11). The size reduction takes place mainly due to compression if both rolls rotate at the same speed. However, shearing may take place if rolls rotate at different speed. Sometimes, fluted rollers are used to increase the shearing force. Theoretically, roll crushers can reduce the size of feed by one-fourth. However, it cannot crush particles of feed having minimum size 10 Mesh (2 mm). The clearance between the rolls is kept according to the final product size desired, with consideration that the largest feed particle can only be four times the gap between the first two rollers. The other factors which affect the

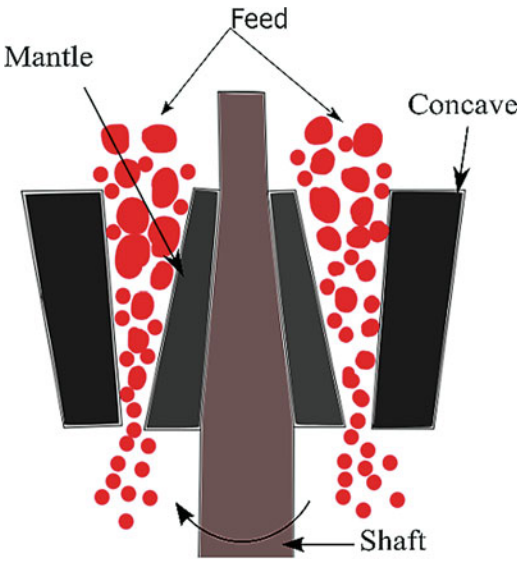


Fig. 6.10 Schematic of gyratory

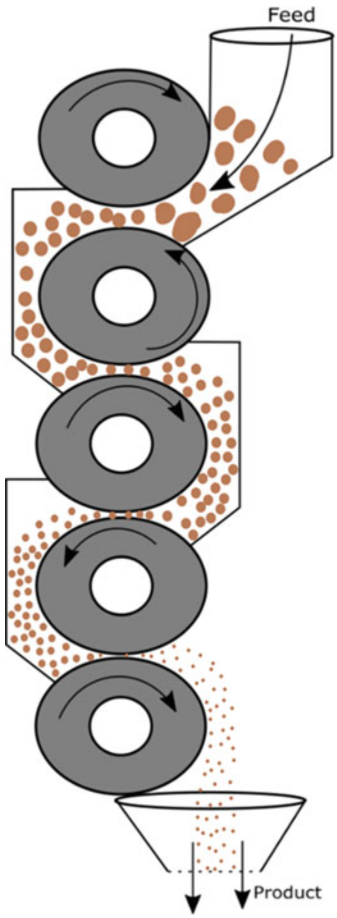


Fig. 6.11 Schematic of crushing roll

operation of roll crusher are rotational speed, diameter of rolls, capacity, and particle size of both feed and product. The roll crushers are generally used for size reduction of soft, dry, and non-sticky feed.

The crushing rolls are mainly of two types:

(a) Smooth roll crusher.
(b) Serrated or toothed-roll crusher.

6.7.6.1 Smooth Roll Crusher

Smooth roll crusher operates best when the final size is three to four times less than the feed size (Fig. 6.12). They are used as secondary crushers. Feed materials used for smooth rollers have diameters 13–102 mm. The diameter of the rolls varies with the clearance between them, the feed size, and the coefficient of internal friction of

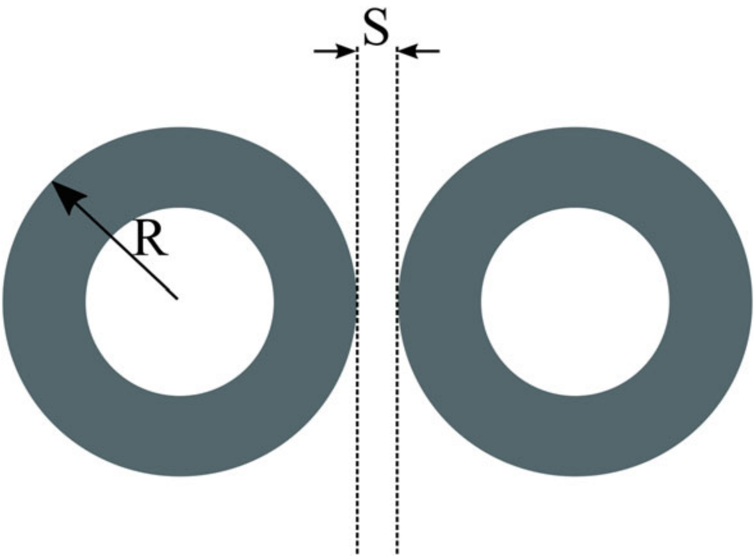


Fig. 6.12 Smooth roll crusher

material to be crushed. The size of the material that can be caught by the rolls depends upon the coefficient of friction between the material and the roll surface and can be calculated by the following equation.

$$d_f = 0.04\,R + \frac{S}{2} \tag{6.26}$$

where d_f is the maximum size of feed caught by rolls, R rolls' radius, and S gap between the rolls.

The smooth roll crusher is used for the extraction of juice from sugarcane, to make grits or meals from food grains, and in making food grain flakes.

6.7.6.2 Serrated or Toothed-Roll Crusher

Compression, impact, and shear are the main forces acting in serrated crusher (Fig. 6.13). These types of crushers contain one or two serrated or toothed roll as per the need. They can reduce the much larger particles than smooth roll crusher.

6.7.7 Cutter Mill

Cutting mills are generally used in size reduction of soft to medium-hard, brittle, fibrous, tough, plastic, or temperature-sensitive materials (Fig. 6.14). The comminution in cutter mill takes place mainly due to cutting and shearing. In addition, the

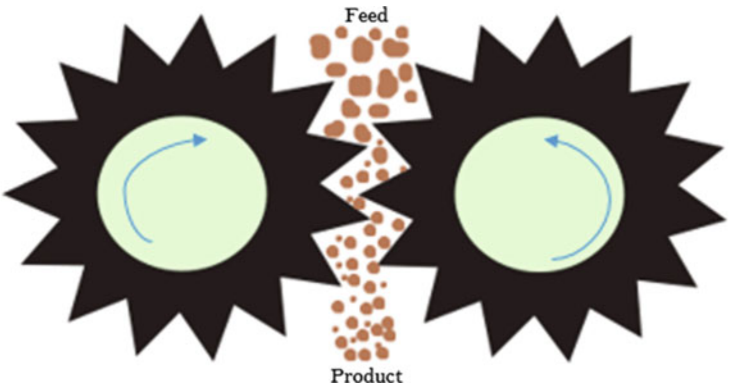
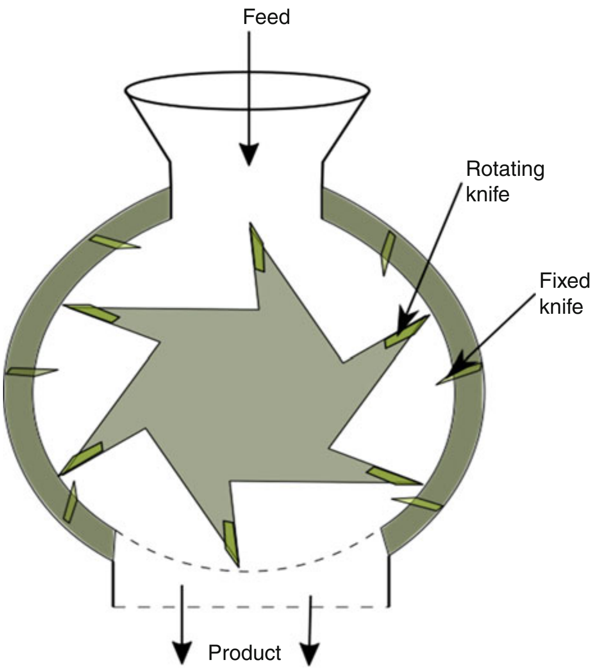


Fig. 6.13 Serrated or toothed-roll crusher

Fig. 6.14 Schematic of cutter mill



fineness of the product is controlled by selecting a desired sieve cassette. Cutter mill consists of a rotor inside a casing to which a number of knives are attached. A screen having pore size equal to the desired product diameter is placed at the bottom.

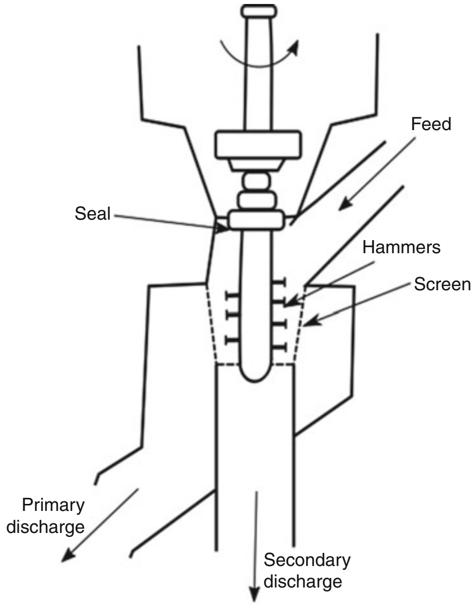


Fig. 6.15 Schematic of Ritz mill

6.7.8 Reitz Mill

Rietz mill is used to grind such materials which are otherwise hard to grind, for example, materials high in oil or moisture content (Fig. 6.15). This mill usually consists of a vertical rotor inside a circular screen enclosure. The rotor includes a number of hammers running at a fairly close clearance. The hammers are generally fixed to the rotor, but swing hammers are also used in some cases.

6.7.9 Colloid Mills

A colloid mill is used in the size reduction of solids and droplet present in suspension or emulsion (Fig. 6.16). A colloid mill consists of a rotating cone (rotor), a static cone (stator), and a feeding unit. The size reduction mainly takes place due to the shearing action in the narrow gap between the rotor and stator. The wear is reduced by using hardened steel made rotor and stator.

Colloid mills have been found effective in the size reduction of solids and for the preparation of suspensions. They are used for grinding, dispersing, and homogenizing of high viscous fluids like cream, gels, etc. In food processing, it is used to process purees, food paste, pulps, and other similar products.

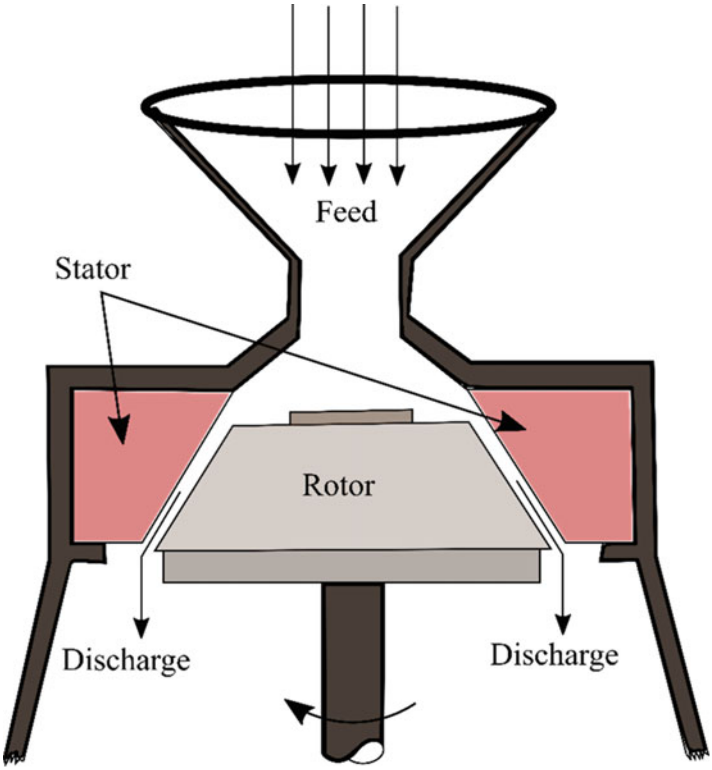


Fig. 6.16 Schematic of a colloid mill

6.7.10 Concentric Cylinder Abrasive Mills

Concentric cylinder abrasive mills are mostly used for dehusking and splitting of pulses or cereals. These mills work on the principle of frictional properties. These machines consist of two concentric cylinders; the outside is a large drum of metal, and the inside is a rotating abrasive roller. Generally, the outer cylinder is made as the bottom half portion is perforated to act like a screen and the upper half portion is made from plane metal sheet. Clearance between the outer and inner cylinder may be constant to give even abrasion or kept more at feeding end and continuously decreasing toward the discharge end. Size reduction takes place in the annular space between both cylinders.

6.8 Low-Temperature Grinding

As discussed earlier, grinding is an energy-consuming unit operation, and only a small percentage of the total energy is used for the creation of new surfaces. The rest of input mechanical energy is lost in the form of either heat or sound during size

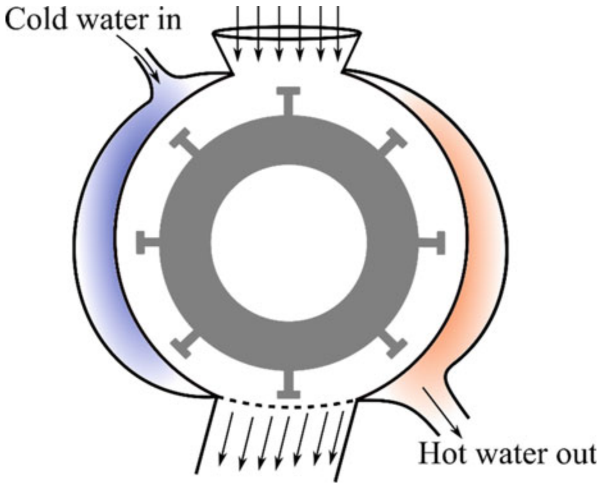


Fig. 6.17 Hammer mill with water jacket for low-temperature grinding

reduction. The rise in temperature is not an issue for grinding of wheat, rice, pulses, or other similar grains, as they have very less heat-sensitive compounds. However, the rise in temperature significantly affects the flavor and aroma of spices and medicinal qualities of herbs, which contain a wide range of heat labile aromatic compounds. In the conventional grinding of spices, friction during grinding results in rise of temperature (42–95 °C) inside the grinding chamber. The temperature continuously rises as grinding progresses. The temperature may further increase, if significant oil content is present in the spices. The oils have lower heat capacity than water and hence result in higher temperature rise for a given amount of frictional heat generated. The rise in temperature can be avoided by using a cooling jacket or a heat exchanger around the grinding chamber. By using simple cooling methods, if the temperature inside chamber is maintained around 7.9–21.2 °C, the losses in the volatile compounds can be reduced up to 15% as compared to normal grinding [11, 12]. Generally, hammer mill is used to grind spices and with water jacket (Fig. 6.17), to limit the losses of heat-sensitive compounds.

6.9 Cryogenic Grinding

Cryogenic grinding is a step further and superior to the low-temperature grinding method. It is used when very high levels of retention of aromatic compounds are required. In this grinding method, size reduction is possible at sub-zero temperature ranging from 0 to −195.6 °C. The whole cryogenic grinding process can be divided into three stages: (1) coarse grinding, (2) precooling, and (3) fine grinding.

The cryogenic grinding starts with coarse grinding of dried herbs or spices in normal- or low-temperature condition. Coarse grinding due to very less friction does not generate much heat, and hence the temperature of grinding chamber does not increase to the extent that it can damage the volatile compounds. Once coarse grinding is complete, the ground powders are taken to precooling unit whose main

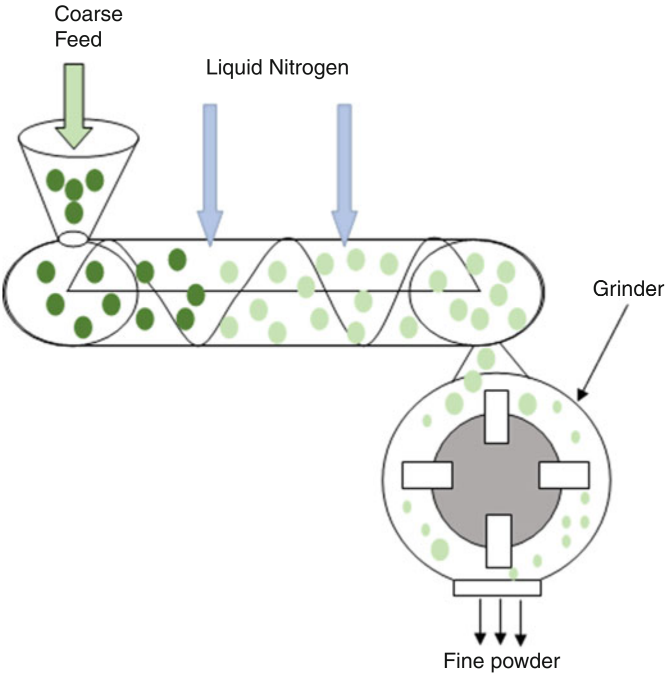


Fig. 6.18 Schematic diagram of cryogenic grinding

component is screw conveyor assembly (Fig. 6.18). Here the coarse ground material is exposed to cryogen such as liquid nitrogen. Cryogen removes the heat from the coarse material and reduces the temperature below the freezing point. The fat present in the spices and herbs also gets solidified. Now the cooled coarse material is fed to the grinder where fine grinding takes place. As the particle temperature is very low, the material goes through ductile-to-brittle transition and gets fractured easily when subjected to impact and shear force during grinding. The low temperature of powders prevents the rise in temperature by absorbing the heat generated in the grinding chamber [12].

Cryogenic grinding has been found to be superior for the retention of volatile oil in spices and herbs. The other advantages include formation of finer and uniform particle size distribution. It also provides an inert atmosphere, thus eliminating the possibility of oxidation. However, maintaining such a low temperature incurs extra cost and may not be necessary for many of the spices.

6.10 Size Reduction of Liquid

6.10.1 Emulsification

According to IUPAC, emulsion is a fluid colloid system in which an immiscible liquid is suspended in the other liquid. An emulsion consists of disperse phase, which disperses in other liquid called continuous phase. The diameters of droplets usually range from approximately 1 μm to 100 μm. If droplet size is less than 0.1 μm, dispersion is known as colloidal. Stability of emulsion is a kinetic concept means resisting the changes in its properties over time (Fig. 6.19). Stable emulsion can persist without change for a long period of time, and disperse phase droplets have no tendency to stick with each other, rising or falling in continuous phase [13].

6.10.2 Factors Affecting the Stability of Emulsion

- Diameter of dispersed droplets.
- Density difference between the disperse phase and continuous phase.
- Viscosity of continuous phase.
- Temperature.
- Interfacial surface tension between the two phases.
- Change in pH and ionic strength.
- Emulsion composition.

6.10.3 Mechanism of Emulsion Breakdown

- *Sedimentation*: When the density of the dispersed phase is more than the continuous phase, droplets fall downward to settle at the bottom.
- *Creaming*: When the density of the dispersed phase is lesser the than continuous phase, droplets move upward toward the surface under the influence of buoyancy.

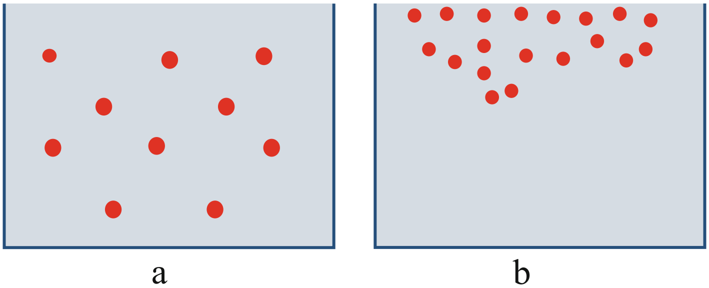


Fig. 6.19 Stable and unstable emulsion

- *Flocculation*: When there is an attractive force between the droplets, droplets stick together to form aggregate like bunches of grapes, but are able to retain their integrity.
- *Coalescence:* When two or more droplets merge into each other and form a larger droplet, the average droplet size increases over time.
- *Oswald ripening:* When smaller droplets move towards larger droplets of disperse phase through continuous phase, larger droplets to grow in size while smaller droplets become diminished or may disappear. This phenomenon is based on the fact that when the droplet size decreases, the solubility of the material within the droplet increases.

6.10.4 Stokes' Law and Emulsion Stability

Qualitative indication of physical factor influencing the stability of an emulsion can be given by Stokes' law. Sedimentation under gravity may break the emulsion and can cause instability with time due to the relative flow of droplets downward. Hence, a small velocity downward can enhance the instability of emulsion. Droplet size, density differences, and viscosity are related to settling velocity, as given in the following equation:

$$V_s = \frac{{D_p}^2 \cdot g \cdot (\rho_p - \rho_f)}{18\mu} \tag{6.27}$$

where V_s is the settling velocity (m/s), D_p and ρ_p are the diameter (m) and density of droplets (kg/m^3), ρ_f is the density of continuous phase (kg/m^3), μ is the viscosity of continuous phase (Pa.s), and g is the acceleration due to gravity (m/s^2).

The above equation indicates that settling velocity is directly proportional to the square of droplet size, that's why droplet size is critically important in maintaining the emulsion stability. Also, lower density differences and higher viscosity enhance the stability of emulsion.

6.10.5 Emulsifier

Emulsifiers (emulgents) are those substances which stabilize emulsion by enhancing kinetic stability. An emulsifier consists of both polar which is water soluble (hydrophilic) and nonpolar part (hydrophobic). Due to dual parts of emulsifier, droplets of oil are surrounded by the emulsifier molecule, and therefore the oil core is hidden from the water-friendly tails of the emulsifier. Emulsifier having more solubility in water generally forms oil-in-water emulsion, whereas emulsifier having more solubility in oil forms water-in-oil emulsion. Foods that contain emulsifier include butter, margarine, cakes, soft drinks, ice cream, etc. Some common food emulsifiers used are egg yolk, honey, polyglycerol ester, sorbitan ester, monoglyceride, mustard, soy lecithin, etc. [14].

6.10.6 Size Reduction and Preparation of Emulsion

The basic requirement for an emulsion is the small droplet size of disperse phase, which can be achieved by imposing high shear stress, agitation, or disturbance to the liquid of disperse phase. High shear forces break the liquid to be dispersed into fine droplets to form emulsion. The equipment used for this purpose is popularly known as homogenizer, and the process is called homogenization.

Homogenization is an important size reduction operation where particulate matter in liquid is broken down to smaller and uniform particle size. Homogenization results in the formation of dispersion. The size reduction in a homogenizer takes place due to shearing, cavitation, and turbulence when a fluid is forced through a narrow space of valve as shown in Fig. 6.20. Shearing takes place in the narrow gap when the high-velocity fluid passes through the valve. The cavitation occurs due to sudden and high pressure drop, in which formation and subsequent collapse of the vapor bubbles take place. The high pressure drop also results in the release of fluid energy which generates intense turbulent eddies of size the same as the droplet diameter. The high energy generated together with the pressure difference breaks down the droplets into smaller size.

Based on the pressure applied, homogenization is of two types: high-pressure homogenization (HPH) and ultra-high-pressure homogenization (UHPH). A HPH uses the pressure in range 150–200 MPa, whereas UHPH works between 350 and 400 MPa. In general, positive displacement pumps are used in the pumping of unhomogenized fluid.

Homogenization is used as an important unit operation in food, pharmaceutical, and cosmetic industries. The most common example is the homogenization of milk

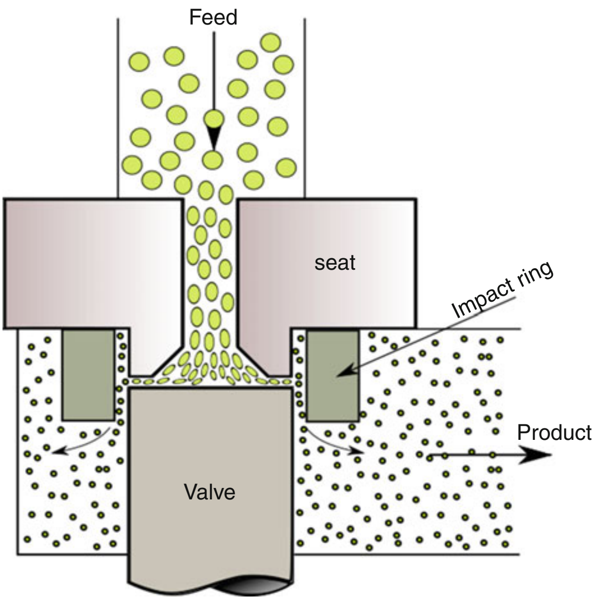


Fig. 6.20 Schematic of high-pressure valve homogenizer

to create homogenous mixture by breaking up the fat globules into uniform particles so that they remain suspended in the milk.

6.11 Solved Examples

Example 6.2 During a milling operation using a 10 H.P. motor, the size of the food was reduced from 7 mm to 0.0011 mm. Find out if this motor would be adequate if the size of the food material is reduced to 0.0005 mm. Use Rittinger's equation for the calculation and take 1 H.P. = 754.7 W.

Solution:

According to Rittinger's law:

$$\frac{P}{\dot{m}} = k\left(\frac{1}{D_p} - \frac{1}{D_{f.}}\right)$$

$$\frac{10 \times 745.7}{\dot{m}} = k\left(\frac{1}{0.0011} - \frac{1}{7}\right)$$

$$\dot{m} \times k = 8.203$$

By putting the value of k for the second condition where D_p is 0.0005,

$$P = m \dot{\times} k\left(\frac{1}{0.0005} - \frac{1}{7}\right)$$

$$P = 8.203\left(\frac{1}{0.0005} - \frac{1}{7}\right)$$

Or, $P = 16404.83$ and W = 21.99 H.P.

Therefore, the motor is not suitable for reduction to size 0.0005 from the initial size of 7 mm, and an increase in power of more than 100% is required.

Example 6.3 In a wheat milling experiment, it was found that to grind 4-mm-sized grains to IS sieve 35 (0.351 mm opening), the power requirement was 10 kW. Calculate the power requirement for milling wheat by the same mill to IS sieve 15 (0.157 mm opening) using (1) Rittinger's law and (2) Kick's law. The feed rate of milling is 180 kg/h.

Solution:

Given that P = 10 kW and $\dot{m}$ = 180 kg/h = 0.18 tonne/h.,

1. Using Rittinger's law:

$$\frac{P}{\dot{m}} = k\left(\frac{1}{D_p} - \frac{1}{D_f}\right)$$

$$\frac{10}{0.18} = k\left(\frac{1}{0.351} - \frac{1}{4}\right)$$

$$k = 21.37$$

By putting the value of k in the second condition where D_p is 0.157 mm,

$$\frac{P}{0.18} = 21.37\left(\frac{1}{0.157} - \frac{1}{4}\right)$$

$$P = 23.53\ kW$$

2. Using Kick's law:

$$\frac{P}{\dot{m}} = k * \ ln\left(\frac{D_f}{D_p}\right)$$

$$\frac{10}{0.18} = k * \ ln\left(\frac{4}{0.351}\right)$$

$$k = 22.83$$

By putting the value of k in the second condition where D_p is 0.157 mm,

$$\frac{P}{0.18} = 22.83 * \ ln\left(\frac{4}{0.157}\right)$$

$P = 13.30\ kW$

Example 6.4 A crusher requires 8 kWh for grinding a material at a rate of 150 kg/h from 1 cm size to 5 mm size. How much power will be required if the reduction is 1.2 mm?

Solution: Given that 8 = 10 kWh and $\dot{m}$ = 100 kg/h = 0.1 tonne/h,

1. Using Rittinger's law:

$$\frac{P}{\dot{m}} = k\left(\frac{1}{D_p} - \frac{1}{D_f}\right)$$

$$\frac{8}{0.1} = k\left(\frac{1}{5} - \frac{1}{10}\right)$$

$$k = 800$$

By putting the value of k in the second condition where D_p is 1.2 mm,

$$\frac{P}{0.1} = 800\left(\frac{1}{1.2} - \frac{1}{10}\right)$$

$$P = 58.66\ kWh$$

2. Using Kick's law:

$$\frac{P}{\dot{m}} = k * \ ln\left(\frac{D_f}{D_p}\right)$$

$$\frac{8}{0.1} = k * \ ln\left(\frac{10}{5}\right)$$

$$k = 115.44$$

By putting the value of k in the second condition where D_p is 0.157 mm,

$$\frac{P}{0.1} = 115.44 * \ ln\left(\frac{10}{1.2}\right)$$

$$P = 24.47\ kW \tag{6.h}$$

Example 6.5 How much power is required to crush 2.5 tonnes/h of a material if 80% of the feed passes through IS sieve no. 480 (4.75 mm opening) and 80% of the product passes through IS sieve no. 50 (0.5 mm opening)? Take the work index of the material as 6.5.

Solution:

According to Bond's law:

$$\frac{P}{\dot{m}} = 0.3162W_i\left(\frac{1}{\surd \mathrm{D_p}} - \frac{1}{\surd \mathrm{D_f}}\right)$$

$$\frac{P}{2.5} = 0.3162 * 6.5\left(\frac{1}{\surd 0.5} - \frac{1}{\surd 4.75}\right)$$

or P=4.91 kW

Example 6.6 Calculate the power required for the size reduction of material having initial size such that 80% passes through a 76.2 mm screen and 80% of the final product passes a 3.17 mm screen. Take feed rate as 12 tonnes/h and work index of the material as 15.

Solution:

According to Bond's law:

$$\frac{P}{\dot{m}} = 0.3162 W_i \left(\frac{1}{\surd \mathrm{D_p}} - \frac{1}{\surd \mathrm{D_f}} \right)$$

$$\frac{P}{12} = 0.3162 * 15 \left(\frac{1}{\surd 3.17} - \frac{1}{\surd 76.2} \right)$$

$or\ P = 25.45\ kW$

Example 6.7 Calculate the power required for the size reduction of material having initial size such that 80% passes through a 101.6 mm screen and 80% of the final product passes a 3.175 mm screen. Take feed rate as 300 tonnes/h and work index of the material as 18.12. Also calculate the power required to crush the product further where 80% is less than 1 mm.

Solution:

(a) Given that feed = 300 t/h, work index = 18.12, feed size = 101.6 mm, and product size = 3.175 mm,

$$\frac{P}{\dot{m}} = 0.3162 W_i \left(\frac{1}{\surd \mathrm{D_p}} - \frac{1}{\surd \mathrm{D_f}} \right)$$

$$\frac{P}{300} = 0.3162 * 18.12 \left(\frac{1}{\surd 3.175} - \frac{1}{\surd 101.6} \right)$$

$$P = 767.74\ kW$$

(b) When the product size is 1 mm,

$$\frac{P}{300} = 0.3162 * 18.12 \left(\frac{1}{\surd 1} - \frac{1}{\surd 101.6} \right)$$

$P = 1548.33\ kW$

Example 6.8 Ground salt was analyzed using IS sieve where it was found that 40% of the total salt passed through sieve number 200 (2.032 mm opening) and retained on sieve number 170 (1.676 mm opening). Calculate the surface area of the salt if 4 Kg of the sample having a density of 1030 Kgm^{-3} and a shape factor of 1.70 is used for grinding.

Solution:

The mean aperture of IS sieve no. 200 and sieve no. 170 = 1.854 mm = 1.854×10^{-3} m.

The total area is given by:

$$A_t = \frac{6\lambda m}{\rho_P D_P}$$

Hence,

$$A_t = \frac{6\,x\,1.7\,x\,0.4\,x\,4}{1030 \text{ x } 1.854 \text{ x } 10^{-3}}$$

$$or, A_t = 8.55\ m^2$$

Example 6.9 A ball mill used for grinding dry solid having 2500 mm diameter is charged with 100 mm balls. Calculate the operating speed in revolution per minute.

Solution:

The critical speed of ball mill is

$$n_c = \frac{1}{2\pi}\sqrt{\frac{g}{R-r}}$$

Or, $n_c = \frac{1}{2x3.1416}\sqrt{\frac{9.8}{2.5-0.1}}$

$$n_c = 0.314\ rps$$

$$n_c \approx 19\ rpm$$

The operating speed for the dry grinding is $= n_c\ x\ 0.8$
$\approx$ 15 rpm

Example 6.10 A ball mill is found that it is not working properly. What should be the modification needed if the mill diameter is 1 m and run at 0.8 Hz? Assume necessary data if required.

Solution:

Given the actual speed of ball mill, (ω_a) = 2π*f = 2π * 0.8 = 5.02 rad/s.

Assuming the diameter of ball to be very small compared to the mill diameter, (R-r) = 0.5 m.

The critical angular speed of ball mill (ω_c) $= \sqrt{\frac{g}{R-r}} = \sqrt{\frac{9.8}{0.5}}$ = 4.43 rad/s.

We can see that the actual speed of mill is higher than critical speed. For proper operation of a ball mill, the operating speed should be in between (0.5 and 0.75) ω_c.

Choosing an operating speed say (0.7) ω_c, i.e., 0.7 * 4.43 = 3.1 rad/s

Hence, the operating speed should be 3.1 rad/s, i.e., 3.1/2π = 0.49 Hz.

Exercise

1. Describe the mechanism of size reduction in food particles.
2. What are the forces involved in the size reduction of agricultural products?
3. Discuss the stress-strain behavior of solid food particle during size reduction.

4. What are the factors affecting the size reduction process in food materials?
5. Define the following terms:

   (a) Degree of grinding.
   (b) Fineness modulus.
   (c) Work index.
   (d) Critical speed of ball mill.
   (e) Oswald ripening.

6. Write short notes on:
   (a) New surface formed by grinding.
   (b) Gyratory crusher.
7. Describe the laws for energy calculation during the size reduction of food materials.
8. Discuss the size reduction process in solid food material.
9. Describe the mechanism of size reduction in liquid food material.
10. Describe a method for the calculation of average particle size for ground food material.
11. What is the significance of fineness modulus?
12. Describe the construction and working of:
    (a) Hammer mill.
    (b) Ball mill.
    (c) Burr mill.
    (d) Crushing roll.
13. What is emulsification? What are the factors affecting the stability of emulsion?
14. Discuss the various mechanisms of emulsion breakdown.
15. What is the significance of terminal velocity in emulsion stability?
16. What is homogenization? Describe the size reduction of liquid in a homogenizer.
17. A solid feed consisting of 20 mm particles is crushed to an average size of 5 mm and requires 18 kJ/kg energy for this size reduction. If other conditions are similar, calculate the energy required (kJ/kg) to crush the feed from 25 mm to 3 mm. (Use Rittinger's law.) (Ans: 35.2 kJ/kg).
18. A food material having an initial mean diameter of 12 mm was ground to 4 mm. The energy required for this grinding operation is 12 kJ/kg. The same food material having an initial mean diameter of 2 mm is ground to a final size of x, and the energy required for the process is 252 kJ/kg. Find the value of x using Rittinger's law. (Ans: 0.25 mm).
19. Find the fineness modulus from the given data and calculate the average particle size.

IS sieve no.	100	50	40	30	20	15	pan
Weight of material retained (g)	0	4	40	50	10	8	4

(Ans: 0.35 mm)

20. Find the fineness modulus of 200 g of the ground material if the masses retained are 20%, 50%, 20%, and 10% of ground material on the three successive sieves and a pan, respectively. (Ans: 3.6).
21. A ball mill of 1.8 m diameter is discharged with each ball having a diameter of 40 mm for grinding solid materials. The rotational speed of the balls is 80% of the critical speed. What will be the operating speed in rpm? (Ans: 25.5 rpm).
22. The power requirement for grinding food material having an initial size of 50 mm and final size of 25 mm keeping feed rate of 20 tonnes/h is 400 kW. Out of this, the power required for running the empty mill is 5 kW. Calculate the power required using Rittinger's law if the feed rate is changed to 12 tonnes/h and final size of the product is 10 mm. (Ans: 63 kW).
23. Calculate the terminal falling velocity of 80-μm-diameter starch granules having a density of 1600 kg/m^3 in water at room temperature. The density and viscosity of water at 25 °C are 1000 kg/m^3 and 1.002×10^{-3} Pa.s, respectively. (Ans: 0.002 m/s or 0.12 m/min).
24. How much power is required to crush 4 tonnes/h of a material if 80% of the feed passes through IS sieve no. 480 (4.75 mm opening) and 80% of the product passes through IS sieve no. 50 (0.5 mm opening)? Take the work index of the material as 5.4. (Ans: 6.5 kW).
25. Ground spice was analyzed using IS sieve where it was found that 50% of the total salt passed through sieve number 200 (2.032 mm opening) and retained on sieve number 170 (1.676 mm opening). Calculate the surface area of the salt if 3 kg of the sample having a density of 1040 kgm^{-3} and a shape factor of 1.60 is used for grinding. (Ans: 14.9m^2).
26. Wheat is milled at a rate of 5 tonnes/h, and the power required for this operation is 40 kW. Assuming Bond's law, determine the work index, and find the total power requirement to mill down wheat to a distribution where 80% passes through a 100 μm sieve. The distribution of feed and product is given in the following table. (Ans: $W_i = 18.3$).

Initial distribution		Final distribution	
Sieve size (μm)	Retained mass fraction	Sieve size (μm)	Retained mass fraction
6730	0.00	605	0.00
4760	0.10	425	0.10
3360	0.10	300	0.12
2380	0.75	212	0.66
1680	0.05	150	0.10
		100	0.02

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Mixing and Forming

7

Monica Premi and Vishal Sharma

Abstract

In this chapter, the fundamentals of the mixing process and its application in the food industry are described. The convection and diffusive mixing mechanisms are explained. The types of mixing equipment used for the different food processing operations are also explained in detail. Mixing is one of the most commonly used unit operations where a homogeneous mixture is obtained by dispersing two or more ingredients together. Depending on the state of mixing, the process can be classified as solid/solid, solid/liquid, liquid/liquid, and liquid/gas mixing, respectively. There is a complex relationship between the product quality characteristics and the mixing pattern. The selection of mixers plays a significant role in mixing performance (in terms of mixing time, product yield, and overall cost) as it affects the product's overall quality. The different mixers can be effectively used to perform various functions such as dough formation, aeration in batter, dough texture development, homogenization of particulates in suspension, etc. The flow pattern, mixing rate, and power consumption are elaborated with worked examples. Forming is a size enlargement process that also aids in food processing unlike mixing and is carried out immediately after the mixing process, where high viscous or dough-like textures are molded into different sizes and shapes. Forming equipment are specifically designed for the processing of specific products such as biscuit former and bread and pie molder for bakery and confectionery molder for confectionary. Several worked examples

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are also included in the chapter for better understanding of the concepts of mixing and forming operation.

Keywords

Mixing mechanism · Mixing operations · Different types of mixing operations · Selection and classification of mixing equipments · Forming (bread, biscuit and confectionery moulders) · Recent advancement in mixing

7.1 Introduction

Mixing is the fundamental unit operation where uniform mixture is produced by dispersing one or more components within the other. The particulate component in a minor amount is known as dispersed phase, and the larger component is known as continuous phase.

Mixing is a process of combining all ingredients (solid, liquid, gas, or a combination of the three) to obtain a homogenous mixture, which aids in food processing. The quality of the final products and its attributes usually depends on mixing performance. Mixing efficiency depends upon the impeller design (including its diameter). The different mixing operations are used for paste, batter, and dough formation, aeration in batter and chocolate products, flavor dispersion in solids or solutions, gas dissolution in aqueous solution, texture development in ice creams and dough, and homogenization of particulate suspension. Extrusion and size reduction process also possess mixing action.

Forming (molding) is a size enlargement process carried out immediately just after the mixing process. It also aids in processing, where foods with higher viscosity or foods with dough-like texture are formed (molded) in different sizes and shapes in order to increase the handling convenience and to have varieties of bakery, confectionery, and snack products. Alike mixing, forming also has an indirect effect on the shelf life or nutritional quality of food products. Critical points that need consideration during the forming process are the size and weight of pieces formed, uniformity in smaller foods, and uniform heat transfer rate at the center of baked food. Examples include bread molder, biscuit former, and confectionary molder. Extrusion process also has forming function.

7.2 Mixing

7.2.1 Features of Mixing

- It involves the whole spectrum of materials from free-flowing powders to a viscous paste-like dough.
- It involves many components, which exist in different physical states and have different properties.

- Energy consumption rate varies widely for each dispersing component. For example, shear-sensitive liquids consume low energy in comparison to emulsification, where it consumes high energy.
- Particularly, in particulate mixing, both mixing and segregation occur simultaneously, but segregation takes place during discharge from the mixer. Therefore, the mixer discharge design is critical.
- It involves the dispersion of gas bubbles or air into pastes and liquid products such as ice cream, bubbly chocolates, and meringues.
- In many viscous products, bubble incorporation is unacceptable as it can lead to spoilage (oxidation) and inconsistent package fillings. Sometimes, the process such as bubble exclusion or de-aeration exclusion can also be categorized into mixing operation as end product, which results in a higher level of homogeneity.
- The state of any mixture is the result of complex mixing mechanisms that are involved in it. Therefore, process control and online monitoring play an important role.

7.2.2 Objective

There are a number of aspects for which mixing operation is carried out in food products, which include:

- To obtain a uniform distribution of components.
- For reduction of non-uniformities.
- For reduction of stagnation zone.
- For efficient heat transfer.
- To aid in processing.
- To alter the eating quality of food.
- To obtain desired product characteristics.

7.2.3 Characteristics of Mixture

Mixture consists of two or more components that are combined in such a way that every substance retains its own identity. The characteristics of the mixture are:

- It is an impure substance.
- It doesn't have a specific formula—Constituents of the mixture are not present in a fixed ratio.
- Constituents of a mixture retain their original properties.
- Properties of the mixture are the properties of components.
- Mixture components can be separated by physical methods such as heating, distillation, crystallization, etc.
- It can be either homogenous or heterogeneous.

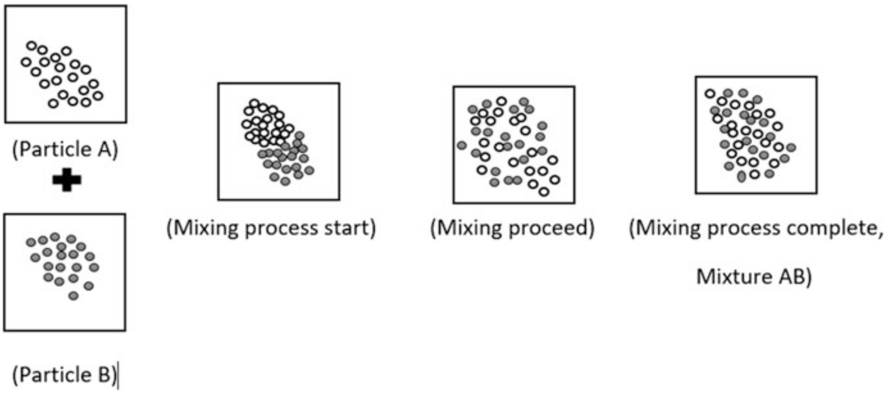


Fig. 7.1 Stages in mixing to obtain a random complete mixture

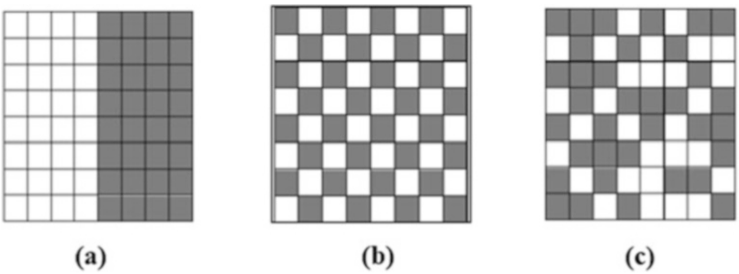


Fig. 7.2 States of mixing

During initial mixing, components are grouped together in a vessel, but components are still separated as pure components. The frequency of component occurrence in whole vessel is proportional to the fraction of these components. As mixing proceeds, each component starts dispersing within the other, and the components' proportions increase in the whole vessel approximately to the overall proportions of the components. Complete mixing is achieved at the point where all the samples contain the same proportion of components as in whole mixture (Fig. 7.1). This state of mixing represents the ordered mixing or ideal mixing of each component (Fig. 7.2b), and practically, this is an improbable result from the mixing process. Alternative state of acceptable mixing is random mixing in which the chance of occurrence of components in samples is the same as that of statistical random dispersion (Fig. 7.2c).

7.2.4 Mixing Mechanism

There are three mechanisms by which mixing behavior can be described:

- *Convective mixing (macro-mixing)*: It involves the displacement of a large mass of particles together from one zone to another in the mixture by using mechanical agitation such as blades or screw or paddle elements. Due to the rotational motion of agitating impellers, a circulatory flow is induced. This circulatory flow is mainly responsible for the macroscopic mixing of bulk powder mixtures and contributes to convective mixing. A large portion of the mixture moves relatively at higher rates, but no changes are expected at the microscopic level. Thus, the pure convective mixing is found to be less effective on a fine level as it contributes to poor mixing characteristics. For batch operations, convective mixing is effective, whereas it is not considered very effective for continuous operations. Shearing occurs in this type of mixing. Therefore, sometimes, shear mixing is considered as part of this mixing.
- *Shear mixing*: It involves momentum exchange of particles having different velocities. This velocity distribution takes place around the vessel walls and the agitating impeller due to extension and compression of bulk powders. Shearing force occurs in this type of mixing, where a group of particles are mixed thoroughly by the formation of slipping of planes. This type of mixing enhances semi-microscopic mixing and is effective in both the batch and continuous operations. In rotary vessel mixers, shear mixing takes place. In free-flowing powders, both shear and diffusive mixing lead to de-mixing (segregation) of particles; thus, for such powder, mixing mainly takes place due to convection.
- *Diffusive mixing (micro-mixing)*: It involves the random movement of particles that changes its position relative to one another; hence, it is referred to as random walk phenomenon. Diffusive mixing is suitable for fragile agglomerates that require gentle and slow mixing, but is not preferable for cohesive powders. The diffusive mixing is best suited for axial-type mixing. Pure diffusive mixing is highly effective in the production of intimate mixtures at individual particle level, but it takes place at a very slow rate.

Usually, in simple barrel-type mixers, pure diffusive mixing occurs, whereas in spiral ribbon-type trough mixer, mostly pure convective mixing takes place. Hence, by combining the features of both convective (speed) and diffusive (effectiveness) mixing, an effective operation can be achieved.

During the mixing operation, either all the mechanisms exist, or only one or two may predominate. This usually depends on the type of mixer used and physical properties of particles. Selection of mixer plays a significant role in mixing performance. For example, for uniform mixing in cohesive powders, it requires shear and convection mechanism. Therefore, ploughs and blades are more appropriate for mixing rather than using tumbling mixers.

7.2.5 Types of Mixing Operation

In food industries, it can be distinguished on the basis of the following.

7.2.5.1 State of Mixing

- *Solid/solid mixing*: It is applicable for mixing tea, coffee, dried soups, and cake mixes.
- *Solid/liquid mixing*: It is applicable for mixing dairy products and paste and preparation of the dough.
- *Liquid/liquid mixing*: It is applicable for mixing emulsions for margarines and spreads.
- *Liquid/gas mixing*: It is applicable for mixing whipped cream and ice creams.

7.2.5.2 Mixing and Segregation Properties

- *Positive mixture*: It is prepared from the materials such as gases and miscible liquids, which get mixed immediately and irreversibly by the process of diffusion and tend to approach as an ideal mixture. These mixtures require no energy for mixing.
- *Negative mixture*: It is the mixture with components that separate out. These mixtures require higher energy and external force to keep the components adequately dispersed.
- *Neutral mixture*: It is static in behavior. These mixtures such as paste and powders do not mix or segregate spontaneously.

7.2.5.3 State of Mixing May Include the Following

Dispersing and Dissolution into Liquids

Mixing is a process of combining all the components together to ultimately form either a uniform dispersion or a homogenous phase. Turbulent mixing of two miscible liquids with low viscosity is easy to process, whereas dissolution of gums and extenders is more complex, as the solution becomes more viscous during mixing. Particularly, for such cases, mixers, which induce both turbulent and laminar mixing, are more effective.

The emulsification process involves the dispersion of either partially miscible or immiscible liquid into the other to form droplet dispersion in a continuous phase. Dispersed liquid volume fraction may be 80%, but if the volume fraction exceeds 50%, then the dispersion is quite difficult. Typical examples of oil-in-water emulsion (o/w) are mayonnaise, ice cream, and salad creams, where fat is dispersed in the aqueous medium, whereas margarine is an example of water-in-oil emulsion (w/o), where water is dispersed in the fat medium.

Particularly, in some cases, it is often required to disperse solids into the liquid. If the solid material is to be dispersed in a liquid, which is in small quantity, then the mixer used must be able to circulate the entire bulk.

Some mixers are also used to disperse air into liquids, emulsions, and slurries. On the other hand, mixers are also used to de-aerate highly viscous liquid, where air can lead to unavoidable reactions. The de-aeration process facilitates packaging and also ensures keeping the quality of foods (visual appearance) that are susceptible to oxidation.

Mixing of Particulate Materials

Mixing of particulate materials is quite difficult as particles vary widely in size, shape, surface characteristics, and density. These variations in particle characteristics led free-flowing mixture to segregation or un-mixing of mixture. Cohesive powders, on the other hand, do not move freely when agitated, but the behavior of bulk material may vary, and that also depends upon the moisture and oil content, which may further complicate the mixing process. Muesli is the example of a free-flowing mixture that tends to segregate during mixing, whereas soup mix is an example of a cohesive mixture that agglomerates during mixing.

Mixing of Batter and Dough

Mixing of batter and dough is performed by utilizing a series of agitation, which induce interaction among all the components such as flour, salt, enzyme, yeast, sweeteners, air, reducing and oxidizing agent, and water. Mixers used for mixing batter and dough must induce shear in order to homogenize the ingredients and also to aerate the mixture.

By using different mixing operations, dough, batter, and paste can be produced [1]. Often, batter for cake is produced by dissolving soluble solids and mixing along with a high concentration of insoluble solids. Paste is usually formed by physical and chemical reaction during mixing such as comminution or precipitation. Kneading of dough involves physical process such as extensive mixing and stretching of the material, which promotes biochemical reaction and leads to gluten development.

7.2.6 Measurement

7.2.6.1 Sampling

Sampling can be very simple or complex. The sampling process is only acceptable if the sample represents the whole mixture. But, there is a difference between the mixture and the sample. Therefore, all the mixing process usually consists of sampling location and procedure, number of samples, and sample size.

7.2.6.2 Methods of Sampling

The choice of technique used for sampling mixture depends upon the mixer and mixture characteristics. Most commonly used methods for sampling mixture are as follows:

- *Sampling by probe*: This device is used for sampling, which contains a solid rod with radial holes. When sampling is done, the rod is rotated to uncover all the holes. Recent advancement in sampling is the application of photoelectric probe, which is connected to the computer for faster processing data. Recently, pneumatic and Probe-A-Vac probes are used where air is used in combination with the probe. This consists of a small cylinder inside a larger cylinder, where the air is forced down between the cylinders by using negative pressure. The negative pressure drags the particles in a smaller cylinder and also helps in pushing the probe into the mixture.

- *Sampling by complete subdivision of mixture*: Tray is used in this method where it is subdivided into many cells to hold the mixture. Although this process of sampling is accurate, it is a very time-consuming process.
- *Sampling by freezing the mixture*: In this process, the mixture is frozen, and then a small section is utilized out of it.
- *Sampling by mechanical belt cup type*: These samplers consist of cups, which regularly take the sample from the mixture by dipping into the material on a moving belt or from the material that drops at the terminal of the belt.
- *Sampling by outlet stream*: In this, a sample is collected at a fixed time period from the mixer outlet.
- *Sampling by manual cup type*: It is particularly used for the sampling of grains. In this sampling type, samplers consist of containers that are in the form of pelican pouches and are known as "pelican sampler," which is passed through the stream of free-falling substance [2].

The different locations used for sampling are orderly or randomly distributed throughout the bulk. In ordered sampling, samples are collected at a regular interval of time, whereas, in random sampling, tables of random numbers are used to track or locate the random position in the mixture. Nowadays, computer-aided selection is commonly preferred. The different methods used to analyze the samples are numeric counting, chemical analysis, X-ray fluorescence, flame spectroscopy, magnetic separation, and radioactive counting [3].

7.2.6.3 Sample Size

For accurate mixing information, the sample size should not be too small or too large taken from the bulk; otherwise, it will provide incorrect information. No systematic methodology in common has been proposed to obtain an accurate sample size. Sometimes, both process conditions and product requirements suggest the sample size. As a thumb rule, not more than 5% of the sample is to be considered from the bulk.

Some researchers have correlated the impact of sample size on the mixing index. For the completely random mixture, totally segregated mixture is independent of the sample size, whereas the sample composition variance decreases inversely with sample size [4].

7.2.6.4 Scale of Scrutiny

The prime concern for any processor is to ensure that the product should maintain homogeneity, when examined on the consumer's scale of scrutiny. Mixing is done to obtain a uniform distribution of components among the mixture. The concentration of each component measured should be expressed in terms of relative concentration.

As each assessment depends upon the sample size, therefore, it is important to achieve homogeneity in a predetermined scale of scrutiny in any practical process.

7.2.7 Mixing Operations in the Food Industry

There is a complex link between the product characteristics and mixing pattern. The criteria for successful mixing depend on the desirable quality of product (in terms of functionality, homogeneity, particulate integrity, and sensory characteristics), energy and process efficiency, flexibility (to changes in processing), safety, hygiene, and legal issues (standard for some food composition).

7.2.7.1 Solid Mixing

Mechanism

Solid mixing involves convective, shear, and diffusive mixing. As mixing proceeds, all the three mechanisms proceed simultaneously in a mixer. The characteristic curve of the mixing process is the graph between the mixing time (t) and degree of mixedness (M, logarithmic scale) as shown in Fig. 7.3. The curve plays a predominate role in evaluating the mixer performance. Generally, during the initial mixing (I), convective mixing predominates, and in the intermediate stage of mixing (II), less convective and more shear mixing occurs. In the final stage of mixing (III), diffusive mixing becomes more effective [5].

Theory

It is a complex process, where the mixing efficiency is significantly influenced by the solid characteristics and mixers and its operating conditions. Unlike the mixing of liquid and viscous paste, complete uniform distributions of components are not possible in particulate solids or dry powders.

In solid, the degree of mixing depends upon the following parameters:

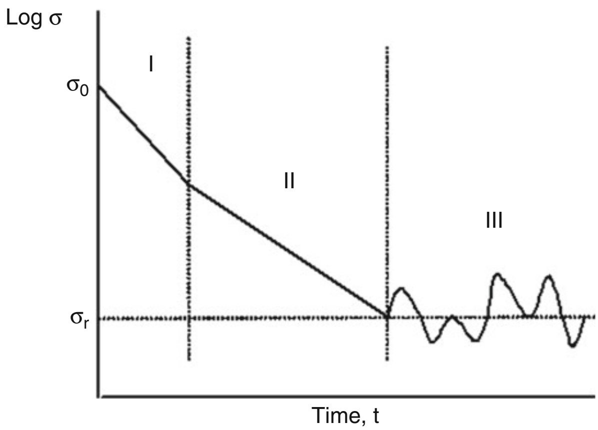


Fig. 7.3 Characteristic curve of mixing process: (I) convective mixing, (II) convective and shear mixing, and (III) diffusive mixing

- Component's characteristics: particle shape, size, density, moisture content, flow and surface characteristics, a tendency to agglomerate
- Mixer characteristics: dimension and geometry, construction material, agitator used, surface finish, efficiency
- Operating conditions: the amount of each constituent, the proportion of mixture volume to the mixer, mixer speed, sequence, method and rate of adding material, and rate and degree of mixing

Mixing and Segregation

Generally, materials of similar shape, size, and density form a uniform mixture rather than dissimilar materials. Dissimilarities in these properties lead to segregation of components during mixing. The consistency of the end product relies on the components of food and type of mixer and its operating conditions, which directly relates to the equilibrium between mixing and segregation (Fig. 7.4).

Granular convection is a phenomenon in which the granular material is exposed to either vibration or shaking. It exhibits a circular pattern which is very much similar to that of fluid convection [6] and led to the accumulation of particles preferentially one over another. This is the reason why small particles usually slip beneath the large particles in a food packet [7]. This phenomenon is also known as Brazilian nut effect or muesli effect [8]. It is commonly observed in mixed nuts and muesli breakfast mix, which contain particles of different sizes but are of the same density. Particle mixing can never be homogenous as that of fluid mixing as particles contribute to segregation, whereas fluid molecules always tend to mix.

Mixing of solid plays a critically important role in the formulation of several products such as baby food, ready-to-eat soup, spice blends, coffee (3-in-1), etc.

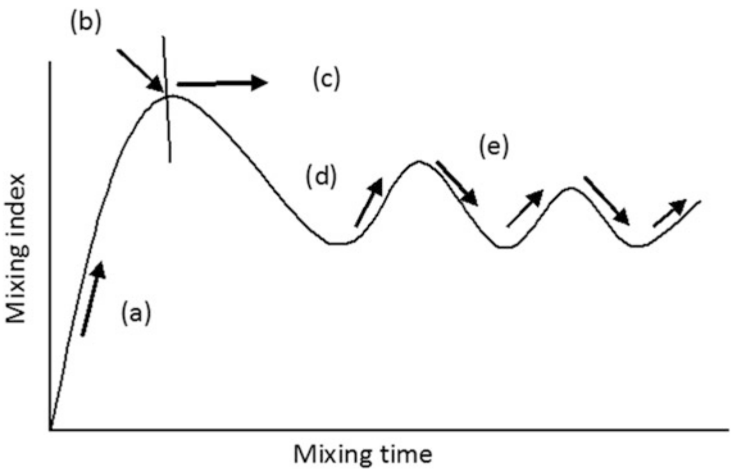


Fig. 7.4 Profile of mixing process: (**a**) mixing, (**b**) optimum mixing, (**c**) over-mixing, (**d**) re-mixing, and (**e**) re-segregation

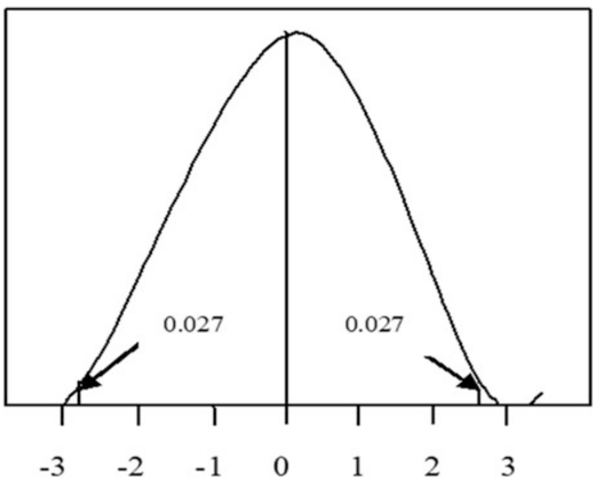
Particularly in few mixtures, after a fixed period of time, uniformity is achieved, and then gradually segregation (or un-mixing) starts. Therefore, it is crucial in such case to maintain mixing time precisely. Hence, long mixing period does not guarantee perfect mixing. Practically, if optimum mixing time passes, the mixture tends to segregate. For a process, mixing duration is usually determined either by testing or by the operator's knowledge. The quality (homogeneity) of the final blended output can also be described as composition variance that gets decreased over a period of time as mixing continues (Fig. 7.4). Commonly used method for determining the homogeneity of blended product is an analysis of "grab sample." It is a sampling technique where a single sample is taken at a specific time. Grab sample is also known as an individual sample or catch sample, for example, collecting a beaker of emulsion and testing for its pH. Usually, material with particle size greater than 75 mm tends to segregate very easily during mechanical zigzag, but material with particle size below 10 mm will not segregate substantially.

Different methods adopted to reduce product segregation during the mixing process include improvement in material properties (i.e., by reducing absolute size, narrowing size distribution, and avoiding irregularly shaped particles), continuous mixing in a controlled manner (i.e., by maintaining humidity and reducing vibration), and proper selection of operational parameters and handling equipment [9].

Mixing Quality (Mixedness)

As mixing proceeds, the samples become more homogenous or uniform in terms of its composition, and it represents the mean composition of the total mixture. The simplest method used for calculating the deviation in composition is to apply the statistical means known as standard deviation. It provides an adequate technique of estimating the level to which fractional concentration of a component scatters around its mean value in different samples (Fig. 7.5).

Fig. 7.5 Normal probability distribution



Standard deviation is estimated by using the equation:

$$\sigma_{\mathrm{m}} = \sqrt{\left[\frac{1}{n-1}\sum (x-\acute{x})^2\right]} \tag{7.1}$$

where σ is the standard deviation, x is the component's concentration in all sample, $\acute{x}$ is the mean concentration of samples, and n is the number of samples.

Equation (7.1) can be applied for a maximum of 30 samples ($N<30$). For a larger sample size, the equation is modified as ($1/N$). Standard deviation is calculated by using Eq. (7.1) for the measured sample composition. Usually, it is convenient to apply σ^2 (known as the variance of the mixture) instead of σ, which is the variance of the fractional sample composition from the mean sample composition. For perfect mixing, the standard deviation ($\sigma_\infty=0$) should be zero. But, ideally, $\sigma_\infty=0$ cannot be attained. But, by using effective mixer, this value can be reduced. Standard deviation gets lowered with increase in mixture homogeneity.

Mixing Index

Mixing index (M) measures the level of mixing, which proceeds toward homogeneity. The mixing quality of true mixture lies between the perfectly mixed mixture (random) and that of totally un-mixed mixture (segregated). The extent of mixing can be assessed by using the number of mixing indices [10].

$$M_1 = \frac{\sigma_{\mathrm{m}} - \sigma_\infty}{\sigma_0 - \sigma_\infty} \tag{7.2}$$

$$M_2 = \frac{\log \sigma_{\mathrm{m}} - \sigma_\infty}{\log \sigma_0 - \sigma_\infty} \tag{7.3}$$

$$M_3 = \frac{\sigma_{\mathrm{m}}^2 - \sigma_\infty^2}{\sigma_0^2 - \sigma_\infty^2} \tag{7.4}$$

where σ_0, σ_{m}, and σ_∞ are the standard deviation in the beginning of mixing, while mixing, and of a perfectly mixed sample, respectively. σ_0 can be calculated using the equation:

$$\sigma_0 = \sqrt{[V_1(1-V_1)]} \tag{7.5}$$

where V is the component's average fractional mass of the mixture.

Mixing index M_1 is used for low mixing rates or when components are mixed in approximately equal masses, M_2 is used for high mixing rate or when a small quantity of one sample is mixed in bulk material, and M_3 is used for solid/liquid mixing in a similar condition to M_1. M_3 is also used for the mixing of heavy paste. Practically, all the three mixing indices are assessed, and the one best-suited mixer for particular ingredients can be selected.

Mixing index (M) for a true mixture ranges from 0 (completely segregated) to 1 (completely randomized). As mixing continues, $M = 1$ approaches asymptotically, but in reality, this assumption is not always affirmed as in the case of free-flowing powders, the phenomenon of de-mixing is not considered.

Mixing Rate and Mixing Efficiency

Mixing time is directly correlated to the mixing index and can be expressed as:

$$\ln M = -Kt_{\mathrm{m}} \quad (7.6)$$

where K is the mixing rate constant that depends on the nature of components and type of mixer used and t_{m} is the mixing time.

Ideally, when mixing is completed, all the samples must have the similar concentration of each component that was added at the start of mixing.

Mixing/blending efficiency of the blender can also be expressed as:

$$\eta_{\mathrm{M}} = \left(\frac{\sigma}{\sigma_0}\right) \quad (7.7)$$

Mixing Energy Input

A significant amount of energy is consumed for mixing. As such, there is no relation between the mixing progress and energy consumption. But, in extreme cases preferentially in the mixing of high viscous liquids, there may be shearing action along one plane in a sticky material, which is then recombined to restore the original pattern and then repeating this same action again may consume sufficient energy but perform no mixing action. In well-designed mixers, energy consumption depends on the duration of mixing. For example, during the mixing of flour for dough preparation using high-speed mixers, the power input (energy utilized) at any specific time can be used to estimate the required mixing time. Power input has a direct relation with chemical reactions that are involved during mixing as flour components oxidized during mixing, which increases the resistance to shear and thus increases the power requirement for operating the mixer.

Problem 7.1 During dough preparation, 450 g of powdered sugar is blended with 50 kg of wheat flour. After 1, 10, and 20 min, five samples of 50 g were collected and analyzed for the powdered sugar percentage. The outputs obtained are as follows:

Powdered sugar % after	1 min	0.13	0.20	0.29	0.11	0.57
	10 min	0.54	0.51	0.40	0.50	0.48
	20 min	0.46	0.44	0.43	0.43	0.44

For each mixing time, calculate the mixing index.

Solution:

In the mix, the average fractional mass of powdered sugar

$$= \frac{450}{50 * 10^3}$$

$$= 8 * 10^{-3}$$

By using the equation

$$\sigma_o = \sqrt{[8 * 10^{-3}(1 - 8 * 10^{-3})]}$$

$$= 8.888$$

Mixing after 20 min
Mean concentration of samples ($\acute{x} = 0.448$)
After 1 min, using equation

$$\sigma_m = \sqrt{\left[\frac{1}{5-1}\sum (x - 0.448)^2\right]}$$

(Subtract the $\acute{x}$ (=0.448) from x for each five samples, square the output, and sum the squares.)

$$\sigma_m = \sqrt{\frac{1}{5-1} * 0.315}$$

$$\sigma_m = \sqrt{0.25 * 0.315}$$

$$\sigma_m = \sqrt{0.078}$$

$$\sigma_m = 0.279$$

After 10 min

$$\sigma_m = 0.067$$

After 20 min

$$\sigma_m = 0.015$$

Mixing index M_2 after 1 min

$$M_2 = \frac{\log 0.279 - \log 0.01}{\log 8.888 - \log 0.01}$$

$$M_2 = 0.493$$

After 10 min

$$M_2 = 0.282$$

After 20 min

$$M_2 = 0.016$$

Using equation after 20 min

$$\ln 0.016 = -k * 1200$$

$$k = 0.0034$$

Time required for $\sigma_m = \sigma_\infty = 0.01$ is found then:

$$\ln 0.01 = -0.0034 * t_m$$

$$t_m = 1355\,\text{s}$$

Remaining mixing time = 1355 – 1200

$$= 155\,\text{s}$$

$$= 2.58\ \text{min}\,.$$

Problem 7.2 A confectionery industry prepares powder mixer for toffee manufacturing. Sugar of 22 kg and other material of 78 kg are blended for 7 min at a steady speed. The sugar content of the ten samples of the mixture, each weighing 20 g, was examined. The outputs, in weight %, are 21.8, 22.0, 21.8, 21.7, 23.0, 22.7, 21.4, 22.3, 22.0, and 20.9.

(a) Calculate the root-mean-square deviation (RMSD) and variance.
(b) Calculate the mixing index; assume the particles are small and of equal size.

Solution:

(a) The sugar concentration of the sugar in the mixture is 22%.
Let p be the individual result found for a sample. For this sample, the deviation $(p - 22)$ was calculated. Then $(p - 22)^2$ for each sample deviation was calculated. The results were summed, and then the sum was divided by the 10 (number of samples). The resultant output is the variance. Taking the square root of the variance and this will be RMS:

Sample no.	P	$(p - 0.22)^2$
1	0.218	0.00000400
2	0.220	0.00000000
3	0.218	0.00000400
4	0.217	0.00000900
5	0.230	0.00010000
6	0.227	0.00004900
7	0.214	0.00003600
8	0.223	0.00000900
9	0.220	0.00000000
10	0.209	0.00012100
Σ		0.00033200
$\Sigma/n = S^2$		0.0000332
RMS $= S$		0.0057619

(b) Due to the large number of particles in the sample, the mixing index M is given by the following equation:

$$M = 1 - \frac{S^2}{S_0^2}$$

$$S_0^2 = q(1 - q)$$

$$= 0.22 * 0.78$$

$$= 0.1716$$

$$M = 1 - \frac{0.0000332}{0.1716} = 0.9998$$

The quality of mixing is very good.

7.2.7.2 Liquid Mixing

Flow Pattern

The movement induced in low viscosity liquids by mixers is shown in Fig. 7.6 and can be characterized by:

- A longitudinal velocity (axial velocity, V_a), acting parallel to the mixer shaft.
- A rotational velocity (tangential velocity, V_t), acting tangentially to the mixer shaft. It simply rotates the fluid and leads to vortex formation. It has no significant effect on mixing.
- A radial velocity (V_r), acting perpendicular to the mixer shaft.

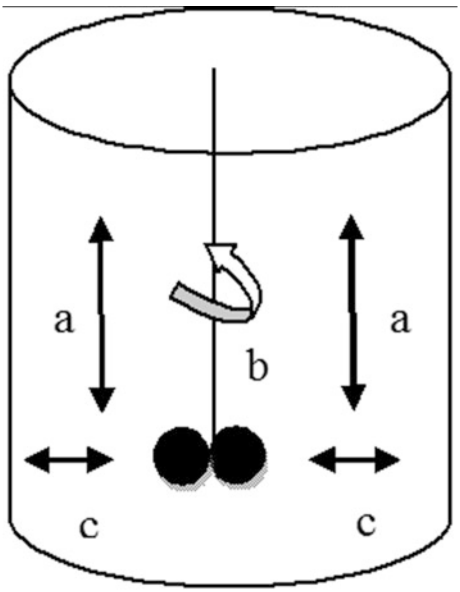


Fig. 7.6 Component velocities induced during mixing: (**a**) longitudinal velocity, (**b**) rotational velocity, and (**c**) radial velocity

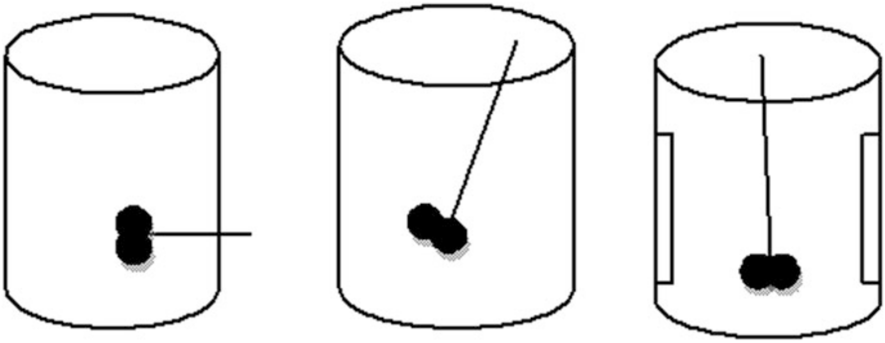


Fig. 7.7 Different positions of mixer shafts for effective mixing of liquids

For successful mixing, the following actions are implemented to induce both longitudinal and radial velocities during liquid mixing:

- Attaching baffles on the mixer wall
- Positioning of mixer shaft or blades (either angled or off-center) (Fig. 7.7)
- Installing impellers set that rotate in opposite directions

For mixing low viscosity fluids effectively, throughout the liquid bulk, turbulence is created to entrain the slow-moving portion within the faster one. During mixing, vortex formation should be avoided as it provides hindrance by circulating the

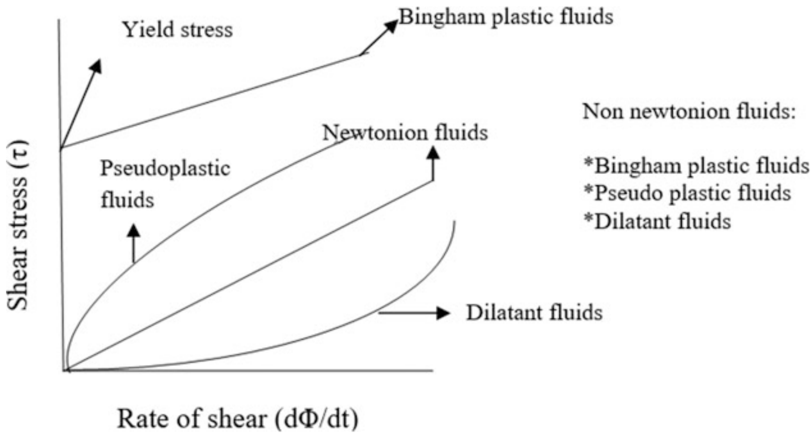


Fig. 7.8 Types of non-Newtonian fluids

adjoining layers of the liquid at a same speed, whereas, in highly viscous fluids, such as dough/paste, mixing is done by different actions such as:

- By kneading the material into the other material or adjacent the vessel wall
- By folding the un-mixed portion within the mixed one
- By shearing for stretching the material

These actions help to create and recombine new surfaces in the food that lead to efficient mixing. As the material does not flow readily, therefore, it is required to either move the food into the mixer or move the blade through the vessel.

Mostly, liquid foods are non-Newtonian, and their types (Fig. 7.8) are:

- *Viscoelastic foods*—which exhibit viscous and elastic properties both like dough and require stretching and folding action for shearing the material. Planetary and twin shaft mixers with intermeshing blades are suitable for viscoelastic foods.
- *Pseudoplastic foods*—also known as shear-thinning fluids, where increasing the shear rate results in a decrease in viscosity. These fluids exhibit yield stress that must be overcome for flow to occur. Foods like sauces form a thinned material zone around the agitator during mixing, and the bulk of food doesn't move. This zone becomes apparent more quickly by increasing the agitator speed. Roller mills or gate or planetary mixers are suitable for this type of food.
- Dilatant foods—are also known as shear-thickening fluids where viscosity increases as the shear rate increases. Foods like chocolate require great care while mixing. Paddle or planetary mixers are suitable for mixing dilatant foods. These foods require adequate power for proper mixing; otherwise, increase in viscosity would damage the shafts and drive mechanism.

Mixing Rate

The mixing rate is usually described in terms of mixing index. The mixing rate constant (K) depends on the features of mixing equipment and on the characteristics of the type of liquid food.

The effect of mixing characteristics of the mixer on mixing rate constant is calculated as:

$$K \propto \frac{D^3 N}{D_t^2 z} \tag{7.8}$$

where D is the agitator diameter (m), N is the agitator speed (rev s^{-1}), z is the liquid height (m), and D_t is the vessel diameter (m).

Power Consumption

The power consumption of mixing equipment depends upon:

- Quantity and type of food (nature and viscosity)
- Impeller characteristics (type, position, size, and speed)

The mixing quality depends upon the energy utilized by unit mass or unit volume fluid. Liquid flow can be explained by using three dimensionless numbers:

- *Reynolds number (Re): Re* is the ratio between inertial and viscous forces. It is used to determine the type of flow discharge whether laminar or turbulent (elevated *Re*—turbulent regime).

$$Re = \frac{D^2 N \rho_m}{\mu_m} \tag{7.9}$$

- *Froude number (Fr): Fr* is the ratio between gravitational and inertial forces. It is used to indicate the effect of gravity on fluid motion and also predicts the vortex formation in the mixer (elevated *Fr*—vortex formed). It is only important if $Re > 300$ and unbaffled vessel is used for mixing.

$$Fr = \frac{DN^2}{g} \tag{7.10}$$

- *Power number (Po): Po* relates power (torque) with agitator diameter, speed of the shaft, and liquid density.

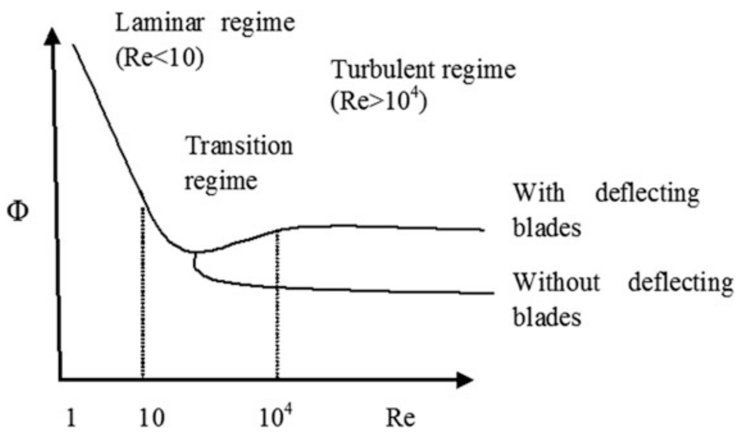


Fig. 7.9 Plots of power function versus Reynolds number

$$Po = \frac{P}{\rho_m N^3 D^5} \tag{7.11}$$

where P is the power transmitted by agitator (W), ρ_m is the mixture density (kg m^{-3}), N is the speed of rotation (s^{-1}), D is the impeller diameter (m), μ_m is the viscosity of mixture (Nsm^{-2}), and g is the acceleration due to gravity (m s^{-1}).

These three dimensionless numbers (Re, Fr, and Po) are important power correlations in the mixing field. These numbers help to understand all the forces induced during each mixing operation and also relate to operating conditions and mixer dimension used. These three dimensionless numbers are related to each other and can be expressed as:

$$Po = K(Re)^n(Fr)^m \tag{7.12}$$

where K, n, and m are the variables obtained experimentally and are related to the agitator configuration and type of mixer used. This correlation is given as log/log plots of $\Phi = (Po)/(Fr)^m$ versus (Re), shown in Fig. 7.9 [11].

However, the Froude number plays an important role, especially when the vortex is formed in an unbaffled vessel. Hence, it is neglected from Eq. (7.12), and a simpler expression can be used in the following cases:

- In the laminar regime ($Re < 10$), the curve between Φ and Re is a straight line.

$$Po \propto \frac{1}{Re} \tag{7.13}$$

$$(Po)(Re) = \frac{P}{N^2 D^3 \mu} = \text{constant} \quad (7.14)$$

Under these conditions, the energy input depends on the fluid viscosity, not on the fluid density.

- In the turbulent regime ($Re > 10$), Φ does not change with Re. Therefore, Po is constant.

$$Po = \text{constant} = \frac{P}{D^5 N^3 \rho} \quad (7.15)$$

The energy input under these conditions depends on the fluid density, not on the fluid viscosity.

The mixture density is calculated by adding component densities of both dispersed and continuous phases:

$$\rho_m = V_1 \rho_1 + V_2 \rho_2 \quad (7.16)$$

where V is the mixture volume, ρ_1 is the continuous phase density, and ρ_2 is the dispersed phase density.

The mixture viscosity is calculated by using the equation:

For unbaffled mixers:

$$\mu_m(\text{unbaffled}) = \mu_1^{V_1} \mu_2^{V_2} \quad (7.17)$$

For baffled mixers:

$$\mu_m(\text{baffled}) = \frac{\mu_1}{V_1}\left(\frac{1 + 1.5\mu_2 V_2}{\mu_1 + \mu_2}\right) \quad (7.18)$$

Variations in power number (Po) at different Reynolds numbers by propellers [12] are represented in Fig. 7.10.

Problem 7.3 Rapeseed oil and sunflower oil are mixed together in a proportion of 1 to 4 in a cylindrical tank with 2 m diameter at 25° C by using a propeller agitator of 25 cm diameter which operates at 800 rev/min. Calculate the required motor size for blending oils.

Solution:

(Viscosity of sunflower oil at 25° C = 0.049 Ns/m^2, density of sunflower oil at 25° C = 918.8 kg/m^3, viscosity of rapeseed oil at 25° C = 0.118 Ns/m^2, and density of rapeseed oil at 25°C = 900 kg/m^3)

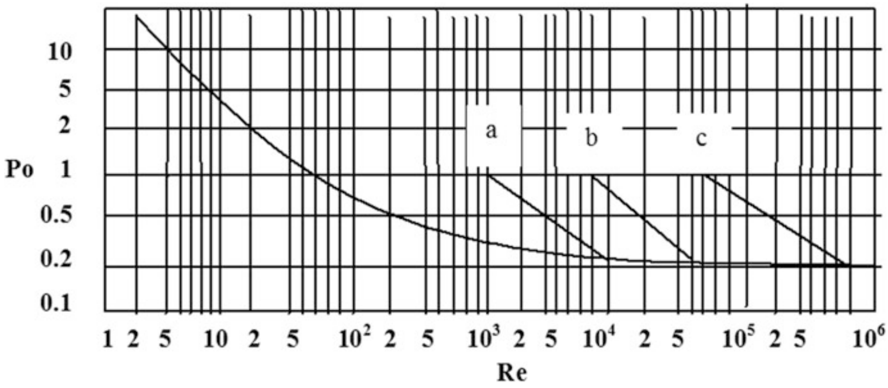


Fig. 7.10 Variations in power number (*Po*) versus Reynolds number (*Re*) for propeller: (**a**) viscosity = 0.189 Nsm^{-2}, (**b**) viscosity = 0.028 Nsm^{-2}, and (**c**) viscosity = 0.109 Nsm^{-2}

From equation

$$\mu_m(\text{unbaffled}) = 0.049^{0.25}0.118^{0.75}$$

$$\mu_m = 0.094\,\text{Ns/m}^2$$

From equation

$$\rho_m = 0.25 * 918.8 + 0.75 * 900$$

$$\rho_m = 904.7\,\text{kg/m}^3$$

From equation

$$Re = \frac{(0.25)^2 * 800 * 904.7}{0.094 * 60}$$

$$Re = 8020.3$$

From Fig. 7.10, for $Re = 8020.3$, $Po = 0.5$.
From equation

$$P = 0.5 * 904.7 * \left(\frac{800}{60}\right)^3 * 0.25^5$$

$$P = 1032.2\,\text{J/s}$$

$$1.032\,\text{kW}$$

As 1 hp = 745.4 J/s, the required motor size is 1032.2/745.4 = 1.38 hp = 1.032 kW.

Problem 7.4 A cylindrical fermenter with an inside diameter of 0.3 m and a height of 0.3 m is fixed with disc flat blade turbine mixer having 0.1 m diameter. The mixer usually rotates at 600 rpm. The process is scaled up to fermenter of 1 m^3 capacity, having similar agitation power per unit volume.

(a) Calculate the speed of revolution.
(b) Will the 5 hp motor be powerful enough to start the mixer?

Solution:
Fermentor with $\rho = 1000\ kg/m^3$ and $\mu = 0.02$ Pa s.
Mixing power per unit volume:

$$Re = \frac{d^2 N \rho}{\mu}$$

$$= \frac{(0.1)^2 * 600 * 1000}{0.02 * 60}$$

$$= 5000$$

The regime is clearly turbulent; therefore, $Po = 5$.

$$Po = \frac{P}{\rho N^3 d^5} = 5$$

$$P = 5 * 1000 * 10^3 * 0.1^5$$

$$= 50\,W.$$

The liquid volume in the fermenter is 0.021 m^3. Therefore, the power per m^3 is 50/0.021 = 2381 W.

In order to have similar agitation power per unit volume, the vessel diameter and impeller diameter will be 1.084 m and 0.361 m. We shall consider that the large fermentor condition will also be turbulent.

$$P = 2381 = 5 * 1000 * N^3 * 0.361^5$$

$$N = 4.2\,s^{-1} = 256\,rpm.$$

b. The required input power necessary in H.P $p = 2381/750 = 3.2$ HP. Therefore, a motor of 5 HP will be sufficient.

Problem 7.5 For blending syrup, a vertical cylindrical vessel is used that is assembled with a three-bladed propeller. The propeller mixer rotates at 60 rpm and has 0.1 m diameter. Experimental result shows that mixing the input energy of 2 J/kg is necessary for suitable mixing. Estimate the mixing time for a 100 kg batch. Viscosity = 4 Pa s and syrup density = 1200 kg/m^3.

Solution:

$$Re = \frac{d^2 N \rho}{\mu}$$

$$= \frac{(0.1)^2 * 1 * 1200}{4}$$

$$= 3$$

The regime is laminar $Po = 14$.

$$Po = \frac{P}{\rho N^3 d^5} = 14$$

$$P = 14 * 1200 * 1^3 * 0.1^5$$

$$= 0.168\,\text{W}$$

$$t = \frac{2 * 100}{0.168}$$

$$= 1190\,\text{s}$$

$$= 19.8\ \text{min}\,.$$

Problem 7.6 A large aqueous-based liquid food is blended in a batch-type vessel. Considering a power number of 5 (for $Re > 5000$), estimate the power input through the impeller if an impeller has a speed of 30 rpm and diameter of 70 cm. The viscosity and density of the liquid food are 0.02 Pa s and 1000 kg m^3, respectively.

Solution:

The power number for an impeller:

$$N_\text{p} = \frac{P}{\rho N^3 D^5}$$

The power for mixing is, therefore:

$$P = 5 \times 1000 \times (30/60)^3 \times 0.7^5 = 105\,\text{W}$$

The power is 105 W; as a check, the Reynolds number is:

$$Re = \frac{\rho N D^2}{\mu} = \frac{1000 \times 30 \times 0.7^2}{0.02 \times 60} = 12250$$

A power number of 5 is therefore valid for Re greater than 5000.

Problem 7.7 A three-bladed propeller with a diameter of 0.25 m is rotated at 1.6 Hz to mix the fluid in the laminar region. However, due to corrosion, the propeller must be replaced by a flat two-bladed blade with a diameter of 0.76 m. At what speed will the paddle rotate if the same motor is used?

Solution:

The power required to mixing in the laminar region is:

$$P = kN^2D^3$$

where k for the propeller and flat paddle are 1964 and 1748.

Thus, the propeller with a diameter of 0.25 m diameter rotates at 1.6 Hz.

$$P = 1964 \times 1.6^2 \times 0.25^3 = 78.43\,\mathrm{W}$$

and for paddle with a diameter of 0.76 m in using the same motor:

$$N^2 = \frac{P}{kD^3}$$

$$N^2 = \frac{78.43}{1748 \times 0.76^3} = 0.104\,\mathrm{Hz} = 6.23\,\mathrm{rpm.}$$

Problem 7.8 For the production of water-in-oil emulsion, two portable mixers with three blades are used, an impeller with a diameter of 0.4 m rotating at 1 Hz and another impeller with a diameter of 0.25 m rotating at 2 Hz. Which unit consumes the least power in turbulent conditions?

Thus, a 0.4 m wheel will consume less energy than a 0.25 m wheel.

Solution:

In turbulent conditions, the power required for mixing is given as:

$$P = KN^3D^5$$

In this case: $P_1 = k1^3 0.4^5 = 0.0102k$ and $P_2 = k2^3 0.25^5 = 0.0776k$.

$$\frac{P_1}{P_2} = \frac{0.0102k}{0.0776k} = 0.131.$$

Thus, the impeller with a diameter of 0.4 m will require less power than the impeller with a diameter of 0.25 m.

Problem 7.9 A small tank 0.28 m in diameter with an impeller 0.11 m in diameter is used for blending two miscible liquids (properties were relatively same to water, i.e., viscosity = 1 mN s/m^2 and density = 1000 kg/m^3). Blending was completed in 1 min using an impeller speed of 220 rev/min. The company plans to scale up the process using the criterion of constant tip speed in a tank of 3 m diameter.

(a) At what speed should the large impeller be driven?
(b) What will be the power required?

Solution:

(a) In a small-scale tank, the impeller with a diameter of 0.11 m is rotated at 220 rev/min.

$$\frac{220}{60} = 3.67\,\text{Hz}$$

The tip speed is then:

$$\pi DN = \pi * 0.11 * 3.67 = 1.26\,\text{m/s}$$

In a large tank, if this is the same, where $D = \frac{3}{3} = 1\,\text{m}$, then,

$$1.26 = \pi * 1 * N$$

In a larger impeller, the speed of rotation is:

$$N = 0.401\,\text{Hz} \quad \text{or} \quad 24.06\,\text{rev/min}.$$

(b) In the large-scale tank, $N = 0.401$ Hz, $D = 1$ m, $\rho = 1000$ kg/m^3, and $\mu = 1 \times 10^{-3}$ Ns/m^2.
Thus,

$$Re = \frac{D^2 N\rho}{\mu} = \frac{1^2 * 0.401 * 1000}{1 \times 10^{-3}} = 401{,}000.$$

For a propeller mixer, the power number $N_p = 0.6$.Thus,

$$0.6 = P/\rho N^3 D^5$$

$$P = 0.6\rho D^3 N^5 = 0.6 * 1000 * 0.401^3 * 1^5$$

$$= 38.6\,\text{W}.$$

Problem 7.10 A tank having a standard Rushton impeller is needed to disperse the gas in a solution with properties similar to water. The tank has a diameter of 2.8 m (1.1 impeller diameter). A power input of 0.72 kW/m^3 is used. Turbulence was assumed during the process, and the presence of gas does not affect significantly the relationship between Reynolds and power number:

(a) What will be the power needed by the impeller?
(b) At what speed, the impeller must be driven?

Solution:

(a) Assume that the liquid depth = tank diameter; then:

$$\text{Volume of liquid} = \left(\pi D^2/4\right)H = \left(\pi * 2.8^2 * 2.8\right)/4$$

$$= 17.23\,\text{m}^3$$

With a power input of 0.72 kW/m^3, the power needed by the impeller is:

$$P = 0.72 * 17.23 = 12.40\,\text{Kw}$$

(b) For turbulent processing conditions, $\mu = 1$ mN s/m^2, and the power number is approximately 0.7.

$$\frac{P}{\rho N^3 D^5} = 0.7$$

$$\frac{12.40 \times 10^3}{1000 \times N^3 \times 1.1^5} = 0.7$$

From which:

$$N = 2.22\,\text{Hz} \quad \text{or} \quad 133.2\,\text{rev/min}.$$

Problem 7.11 With an agitation system, fruit juice having a density of 1100 kg/m^3 and a viscosity of 0.03 Pa s is agitated by using a turbine impeller. The impeller consists of a disc with six blades. The tank diameter is 1.8 m. The liquid height in the tank is equal to the tank diameter. The impeller is of 0.5 m diameter. The width of the blade is 0.1 m. If the turbine is operating at 100 rpm, determine the amount of power required.

Impeller diameter (D) = 0.5 m, tank diameter (T) = 1.8 m, blade width (Wb) = 0.1 m, baffle width (B) = 0.15 m, impeller speed (N) = 100 rpm, fluid density (ρ) = 1100 kg/m^3, and fluid viscosity (μ) = 0.03 Pa s.

Solution:

$$Re = D^2 N\rho/\mu$$

$$0.5^2 * 1.667 * 1100/0.03$$

$$Re = 15,280$$

$$N = 5$$

$$P = N\rho N^3 D^5$$

$$5 * 1100 * 1.667^3 * 0.5^5$$

$$P = 796.2\,\mathrm{J/s} = 0.796\,\mathrm{W}.$$

The power input of 0.796 kW is required by the impeller. Hence, the motor preferred for the mixer should be larger than 0.8 kW.

7.2.7.3 Liquid/Liquid Mixing

Liquid/liquid mixing is the process where two or more liquid ingredients are mixed together to form a mixture. This mixing is divided as miscible and immiscible mixing. The term “blending” is used to define miscible mixing, whereas the term “mixing” is used for the formation of emulsions or for the dispersion of immiscible liquids. Miscible mixing involves the complete mixing of two components to form a stable homogenous mixture (mixing of flavoring in non-carbonated beverages). Immiscible mixing is the dispersion of two liquids that do not form a stable uniform mixture (mixing of water and oil) and leads to the formation of different emulsions.

The type of blending equipment required for the blending of liquids depends on the nature of the liquids. The single-phase blending process includes high-flow, low-shear mixers to form stable mixtures, whereas the multi-phase mixing process involves low-flow, high-shear mixers to form tiny droplets of oil particles in laminar, transitional, or turbulent regimes (depending on Reynolds number of flow). For laminar mixing, anchor/helical mixers are used, and for transitional or turbulent mixing, impellers are commonly used.

7.2.7.4 Solid/Liquid Mixing

Solid/liquid mixing is the process where the solid component is mixed in liquid. When the solid component is non-dissolvable in the mixture, it remains suspended and forms a “slurry.” This process is known as “solid suspension.” This technique is used by wastewater processors to extract beneficial ingredients by suspending heavy metals into the solution, whereas, if the solid component is dissolvable, it forms a homogenous solution. Sugar water and sweetened milk are typical examples of this category.

7.2.7.5 Liquid/Gas Mixing

Liquid/gas mixing is the process where gas bubbles are suspended efficiently in an immiscible liquid. For an effective process, a large surface area is created between the liquid and gas contact point by breaking up the large bubbles into tiny bubbles by using turbine-type impellers. These impellers have been typically used in carbonated beverages and beer industries.

7.2.7.6 Mixing of Gases

Gas mixing is the process where mixing of gases is done for a particular purpose. This process is widely used in modified atmosphere packaging and in brewing industry. In modified atmosphere packaging, fresh produce shelf life is extended and maintains product quality. Depending on the product type, the composition of gas varies. For meat products, high oxygen concentration is used to maintain the red color, and for vegetables and bread, low oxygen concentration is used to reduce mold growth. In the wine industry, a process called "sparging" is done where an inert gas (nitrogen) is bubbled through the wine to remove dissolved oxygen and carbon dioxide [13].

7.2.7.7 Multi-phase Mixing

Multi-phase mixing is the process where all the three phases (solid, liquid, and gas) are combined together in a single step. Usually, this type of mixing predominates in the fermentation process, where gas and solid microbes are required to distribute effectively in the liquid medium, and in the hydrogenation process in which gaseous and liquid reagents are mixed together with solid catalyst.

7.2.8 Selection of Mixing Equipment

Many variables are involved in the selection of mixer for mixing different types of solids, liquids, and paste in order to obtain the desired mixing performance in terms of minimum mixing time and maximum product yield with minimum overall cost. There should be a balance between the mixer used and ingredient characteristics to obtain the desired production quantity with energy efficiency.

Selection of mixer is based on considering several criteria such as:

(a) *Ingredient characteristics*: Ingredients' physical, chemical, and mechanical properties are the prime important consideration.
  - Phases being mixed (solid/solid, solid/liquid, and liquid/liquid)
  - Characteristics of end product (density and viscosity)

(b) *Process setup*: It includes the following factors such as:
  - Usage and application of mixer.
  - Quantity of different ingredients to be mixed.
  - Handling equipment dimensions (diameter and height).
  - Mode of operation: batch or continuous.
  - Pre- and post-blending mixture.
  - Operating multiple operations in mixing equipment such as drying, coating, and liquid addition [14].
  - Charging and discharging of ingredients from the mixer.
  - Mixer operating conditions—As per process requirement, some mixers operate under pressure or vacuum.

Table 7.1 Mixer selection based on different requirements

Sr. no.	Features	Tumbling mixer	Vertical screw	Orbital screw
1	*Mixing requirement*			
	Free-flowing powders	√	√	√
	Cohesive powders	x	√	√
	Paste	x	x	√
	Materials of different sizes	x	x	√
	Materials of different shapes	x	x	√
	Materials of different densities	x	√	√
2	*Shear requirement*			
	High shear	x	x	x
	Low shear	√	√	√
3	*Cleaning requirement*			
	Self-cleaning	√	x	x
	Cleaning by washing	√	√	x
	Cleaning by brushing	√	√	x
	Cleaning by sterilization	x	x	x
	Self-emptying	√	√	x
4	*Power requirement*			
	<5 hp/tone	x	√	√
	5–10 hp/tone	√	x	x
	>10 hp/tone	√	x	x

√ = Yes and x = No

- Mixing accuracy and homogeneity—Depending upon the application, mixing homogeneity and accuracy vary. Mixing accuracy can be assessed by "heap test" where properly mixed mixture is poured with the help of funnel to shape a heap. If the sample composition from the center differs from the composition of the sample from the outer side, then the mixture is likely to segregate in the later process.

(c) *Mixer design selection*: The mixer design should be:
- Hygienic and suitable for cleaning
- Energy-efficient in terms of power consumption and mixing time
- Easy to discharge
- Smooth especially internal surface finish
- Able to use for multipurpose functions

Other factors that must be considered during mixer selection are equipment safety, ease in operation, and plant layout. The selection of mixer is based on different requirements and the different mixing processes (batch/continuous) are given in Tables 7.1 and 7.2, respectively.

Table 7.2 Batch v/s continuous mixing process

Features	Mixing process	
	Batch	Continuous
Mixing	Mixer is charged together with all ingredients or in a predefined sequence and mixed until homogeneity obtained	Ingredients flow steadily from an upstream process into the mixer. Mixing takes place as ingredients move forward from the charging point to discharge point. All steps (weighing, loading, mixing, and discharging) occur continuously and simultaneously
Production flexibility	Many products can be produced on the same production line	Only single product of larger quantities is mixed
Product properties	Changes from batch to batch	Remains the same
Capital cost for mixer Ancillary	Higher Lower	Lower Higher
Throughput	Lower productivity, less efficient	Higher productivity, more efficient
Production quantity	Small	Large
Output measurement	kg/batch	kg/h
Mixing time	High	Low
Advantages	Versatile, interchangeable impellers allow the materials with a wide variety of properties to be mixed, suitable for small-scale processing, changing of product very easy	Variation reduced from batch to batch, low labor requirement
Disadvantages	Variations batch to batch are large, labor-intensive, and time-consuming process	Product wastage, lack of flexibility (continuous mixing process is specifically designed for a particular application and cannot be efficiently tailored to mix different formulations), and higher overall maintenance cost
Applications	Dough	Margarine and carbonation of drinks

7.2.9 Classification of Mixing Equipment

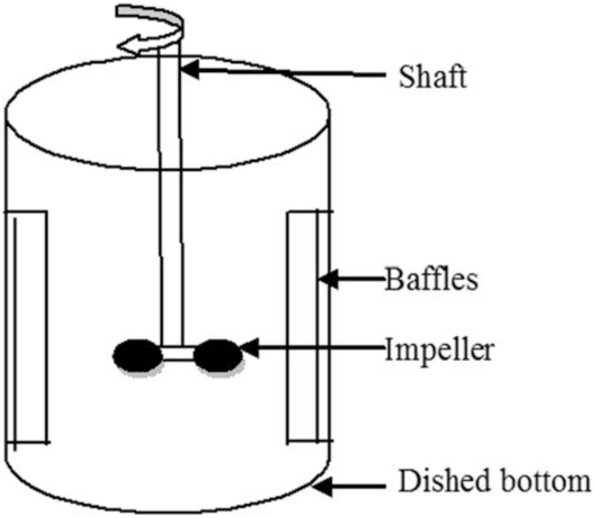
7.2.9.1 On the Basis of the Scale of Mixing

- Batch mixing
- Continuous mixing

7.2.9.2 On the Basis of Flow Properties

- Free-flowing solids
- Cohesive solids

Fig. 7.11 Schematic representation of a vessel-type mixer



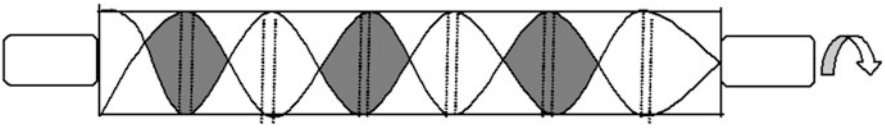


Fig. 7.12 Schematic representation of a pipe-type mixer

7.2.9.3 On the Basis of the Configuration Used

- Vessel-type mixers
- Pipe-type mixers

All equipment used for mixing are having either vessel- or pipe-type configuration. Usually, vessel-type mixers are used for batch process (Fig. 7.11). These mixers are fitted with a rotor which induces mixing by agitating components. In some mixers, the vessel itself rotates periodically that induces mixing. In vessel-type mixer, circulation or back mixing of all the components takes place in all the directions of the vessel.

Pipe-type mixers are typically used for continuous process. These mixers may be static or dynamic and contain stream splitters and turbulence promoters for turbulent mixing and reorientation of components for laminar mixing. For whipping cream, pipe-type mixers are used. In pipe-type mixer, axial flow predominates, but cross-flow is also significant that moves the components in the direction of flow (Fig. 7.12).

7.2.9.4 On the Basis of Speed

- High-speed mixers
- Low-speed mixers

In high-speed mixers, sufficient kinetic energy is imparted during the mixing of material. High-speed mixers consist of small impellers, which are used for mixing low viscosity liquids by creating turbulence throughout the vessel. On the other hand, in low-speed mixers, kinetic energy is not imparted, and it consists of large impellers, which usually sweep the whole vessel for mixing the materials of high viscosity in laminar flow.

7.2.9.5 On the Basis of the Axis of Rotation of Mixing Vessel

- Horizontal mixers
- Vertical mixers

Horizontal mixers consist of impellers, which are mounted on a horizontal shaft that rotates in U-shaped jacketed trough. In horizontal mixers, mixing takes place by kneading and stretching. Different shapes are available in impellers such as sigma, paddle, and *z* along with serrated scraper installed at the edge. In some cases, there are two horizontal shafts fitted with paddles that rotate in opposite directions and at varying speeds. Typically, these mixers are used for processing of chocolate, meat and fish paste, chewing gum, die dough, fondants, and biscuit dough and cream [10].

A screw mixer consists of two shafts fitted with paddles in the elongated horizontal tank, which rotates at varied speed in the opposite direction that leads to intense and thorough mixing. Kneaders consist of a screw, which pushes the material against the baffles and creates high shear stress. These mixers are very useful for high viscous paste. Several bowls may be allocated in horizontal mixers that maximize its availability during mixing.

Vertical mixers consist of paddle agitators of large diameter such as gate and anchor, which ensure that all materials rotate during mixing. In vertical mixers, mixing takes place by cutting and shearing. Planetary mixers are usually of small diameter, which rotate about its axis and also inside the bowl induce vigorous mixing of the entire mixture. These mixers retain low power consumption. In some design, the bowl also rotates or orbits; hence, they are known as “orbital screw mixer.” They require low shear rate during the mixing of materials like sensitive cream and paste.

Recent advances in the commercial production of bread have been taking place, where a slow process of dough formation is replaced by rapid mechanical means by fermentation. Tweedy mixers are special vertical mixers that utilize high power inputs (40 kJ/kg). Spiral kneading mixers provide intermittent processing but mix intensively. This spiral attachment mixes intensively only in one zone, and as the bowl rotates, materials also pass through the processing zone and rest, which reduces overheating. Mixing vessels used for mixing stiff dough are surrounded by water jacket to remove excess heat generated.

For biscuit manufacturing, both hard and soft dough are processed by using a vertical mixer having multiple mixing paddles. These paddles create higher circulation rate that results in the rapid dispersion of ingredients without subjecting to low shear rate so these mixers are important for special and fruit dough [15].

7.2.9.6 On the Basis of Powder Falls

- *Passive mixers*—When the mixture flows under the influence of gravity or without vibration or mechanical agitation, mixing homogeneity is achieved due to the arbitrary motion of particles. Since the mechanism is similar to the diffusion process, hence, it is also known as "diffusive mixers." These mixer types are particularly suitable for fragile material, which includes gentle mixing as it does not produce shear [10].

In continuous processing, particularly in-flow passive mixers are used. In this process, particulate solids, liquids, or gases flow through the pipe, and mixing takes place simply by using turbulence without using any mechanical mixers. This type of mixing process is also called "passive mixing." Devices such as venturi tubes can be used for in-flow mixing for accelerating the fluid. In-flow passive mixers are not adequate for mixing highly viscous liquids.

Besides the mixing, mixers also carry out other functions in the processing of powders such as [14]:

- Particle coating
- Drying
- Agglomeration
- Size reduction and change in particle shape
- Admixture of liquids (e.g., fat in dry soup mixes)

The drum blender has a horizontal cylinder rotating around its axis (Fig. 7.13). It has a diffusive mixing action. In this, continuous mixing operations can be performed by simply tilting the drum. Powder, which is to be mixed, is placed inside the drum. As the drum rotates, powder is lifted up until the angle of repose (i.e., it is interrelated to friction between powder particles. The smaller the angle of repose, the better the powder flow ability) exceeds (NO significant value given in literature). At this point, the powder falls back to the rest of the bulk and then enters again to a new circle (zone) of lifting and falling again. Diffusive mixing (i.e., passive mixing) occurs while falling during the residence time of the powder in the air.

Tumbler mixers are also diffusive-type mixer, which consists of an enclosed vessel that rotates about an axis either inclined or horizontal so that each particle tumbles with each other. These mixers are commonly used for non-cohesive or free-flowing mixtures. But, these mixers are not suitable for agglomerate mixtures and mixtures, which tend to segregate during mixing. The efficiency of tumbler mixer depends on the rotation speed of the vessel, which relies on the shape and size of the vessel and material used for mixing. Double-cone, rotocube, V-cone, and Y-cone blenders are the examples of tumbler-type mixers (Fig. 7.14). In double-cone tumblers, as the vessel rotates, powders undergo repetitive cycles of expansion and

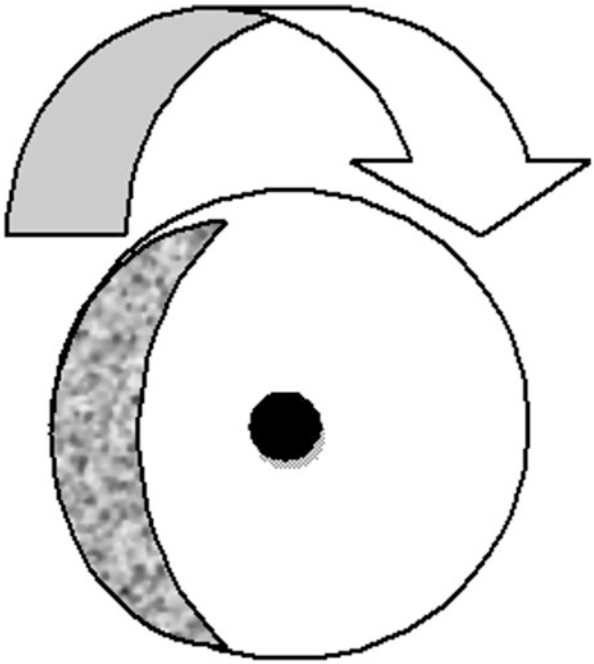


Fig. 7.13 Cross-sectional view of drum blender

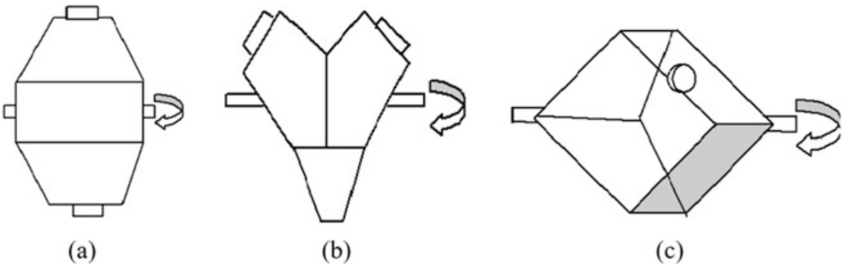


Fig. 7.14 Cross-sectional representation of different tumbler mixers

compaction, whereas in V-shaped tumbler mixer, diffusive mixing takes place by repetitive cycles of division and assembly.

- *Active mixers*—Mixing homogeneity is attained due to mechanical agitation. As the parts of the bulk mixture are carried forward with respect to each other by turbulence or by agitation as shearing forces are induced, hence, it is also known as "convective mixers" (Fig. 7.15).

Convective mixers (Fig. 7.15) (i.e., active mixers) consist of impellers in a static vessel, which rotates the particle from one zone to another within the bulk. Mostly, convective mixers operate at low rotation speed (15–60 rev/min), but some mixer

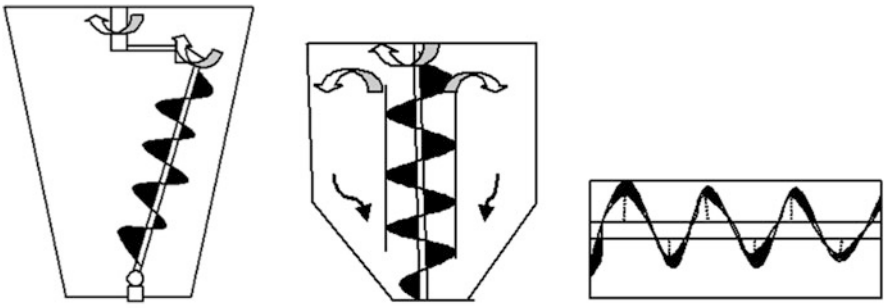


Fig. 7.15 Schematic representation of convective mixers

operates at higher speed (1000 rev/min). These mixers are suitable for free-flowing, cohesive, and segregating mixture. Particularly for difficult mixing, Nutamix, a type of orbital screw mixer, is used. These mixers induce greater shear. Various types of convective mixers are available; some of them are:

- *Paddle mixers*—rotating elements mix the powders by moving bed and by fluidization. These types of mixers are used for both batch and continuous purpose. During mixing, the liquid component can be sprayed. In recent advancement, the entire mixing chamber can be rotated from top to bottom to quickly unload the product and rotate backward to load new material.
- *Trough mixers*—named because it has a U-shaped longitudinal rotating shaft. Ribbon mixer is a type of trough mixers. Agitation takes place by a series of screw or paddles.

7.2.9.7 On the Basis of State and Rheology of Food Material

- Particulate solid mixers (dry powders)
- Viscous liquid mixers (low/medium)
- Highly viscous mixers (liquids and paste)
- Dough mixers (dispersion of powders in liquids)

Particulate Solid Mixers for Dry Powders

The following mixers are particularly used for blending flour and grains, for the preparation of ready-to-eat mixes (such as soups and cake mixes), and for coating purpose.

- Tumbling action of rotating vessel mixers (tumbler mixers)
- Positive movement of ingredients in screw-type mixers (vertical screw mixers)

In tumbler mixers (Sect. 7.2.9.6), blending takes place around a horizontal shaft rotated around an axis, which causes the ingredients to tumble over each other in a

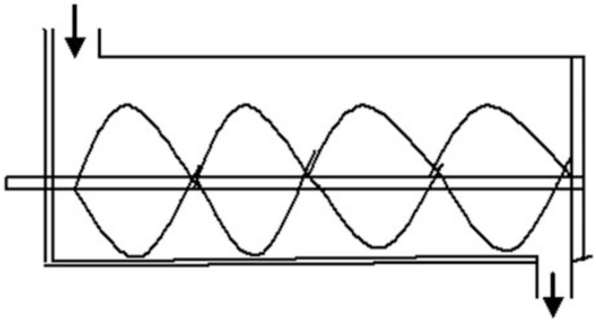


Fig. 7.16 Schematic diagram of a ribbon mixer

fully enclosed rotating vessel. These mixers are operated at a speed of 20–100 rev/min. Optimum mixing of ingredients depends upon speed and the shape of the vessel. If the centrifugal force exceeds gravity, then the maximum operating speed should be lowered than “critical speed.” Mixing efficiency is enhanced either by using counter-rotating arms or by using baffles. These mixers are made of stainless steel, and the rotating vessel is of different shapes such as double-cone, V-cone, Y-cone, cubical, and drum mixers.

Merits of tumbler mixers are as follows: (1) large quantity of materials can be easily mixed; (2) higher production flexibility; (3) even delicate particle can be mixed gently; and (4) easy to clean. Besides these merits, there are few demerits such as agglomerates cannot be broken during mixing, a continuous process cannot be adapted, and cohesive materials are difficult to handle. Tumbler mixers have a wide variety of applications; it includes mixing of functional food ingredients and nutritional supplements; mixing of spices, protein powders, herbs, lactose powder, and sugar beads; and mixing of starter cultures (yeast and lactic acid bacteria) for wine, beer, cheese, and fermented products.

Ribbon mixers (active trough mixer) are an effective powder mixer (Fig. 7.16). It consists of double helix ribbon agitators, which counter-rotate in a fully enclosed U-shaped horizontal vessel. The pitch between the ribbons is mismatched so that one rapidly shifts the ingredients forward through the vessel and the second one moves the ingredients backward, which help to produce net forward movement of ingredients.

The ribbon mixer consists of an agitator and U-shaped horizontal trough, which are made of outer and inner helical ribbons and are pitched to move the mixture axially in the opposite direction as well as radially. The ribbons rotate up to the tip speed of approximately 300 ft/min. This mixer is cost-effective for mixing dry ingredients for muffin and cake mixes, tea, coffee, spices and herbs, flour, cereals, bread improvers, snack bar, and other beverage blends such as chocolate drink, energy drink, whey protein shakes, and powdered juices. The merits of ribbon mixers are as follows: it requires less space and is suitable for the mixing of materials, which tend to agglomerate.

Vertical screw mixers (discussed in Sect. 7.2.9.5) are particularly applicable when minute amount of ingredients are mixed into the bulk material. It consists of a rotating vertical screw enclosed in a conical vessel and that creates gentle blending action around the central axis to mix the ingredients uniformly. As compared to the horizontal mixers, it has several advantages, which include:

- For a wide range of batch sizes, having a range of as small as 10% of the rated capacity, one blender can be used.
- Gentle blending action is ideal for friable (the tendency of solid material to break into smaller size by rubbing action) or shear-sensitive materials.
- After completion of the blend cycle, almost 100% of the blended material is expelled through the bottom valve.
- Require less floor space and are perfectly suitable for multi-story facilities.
- Use lesser power per unit being blended.

These mixers are generally used for applications such as bakery premixes, baby powder, chocolate drink mixes, and dried soups that require minimal heat generation and gentle mixing action both at the same time. The applications, which require high shear mixing, can also be performed by these mixers.

Low or Medium Viscosity Liquid Mixers (Blenders/Agitators)

Various designs of mixers are used for mixing shear-thinning or pseudoplastic liquids in baffled or unbaffled vessels. Large impellers or small clearance at vessel wall is used to minimize the stagnant regions that may form during the mixing of viscous liquids.

Paddle agitators—It is the simplest mixer and consists of one or more flat blades mounted on the shaft, which usually rotate at low speed (20–150 rev/min), and the size is 50–75% of the vessel diameter (Fig. 7.17). Paddle agitators primarily induce

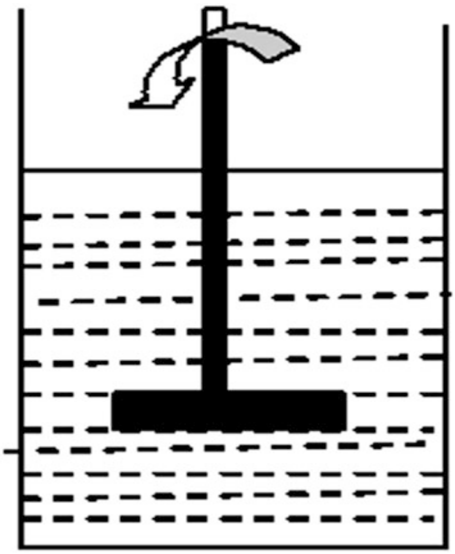


Fig. 7.17 Schematic diagram of a paddle mixer

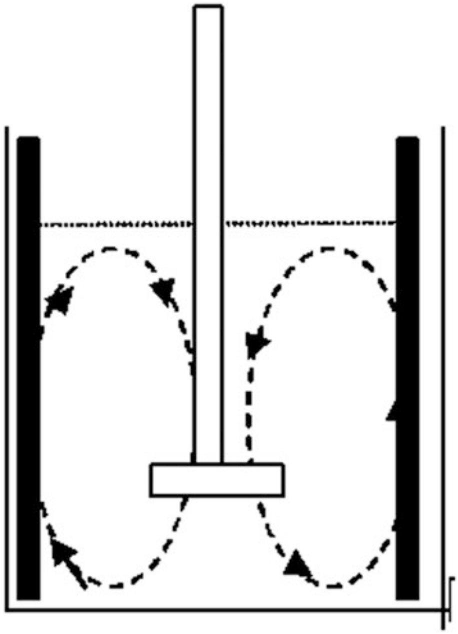


Fig. 7.18 Flow behaviors in agitation vessel in paddle impeller

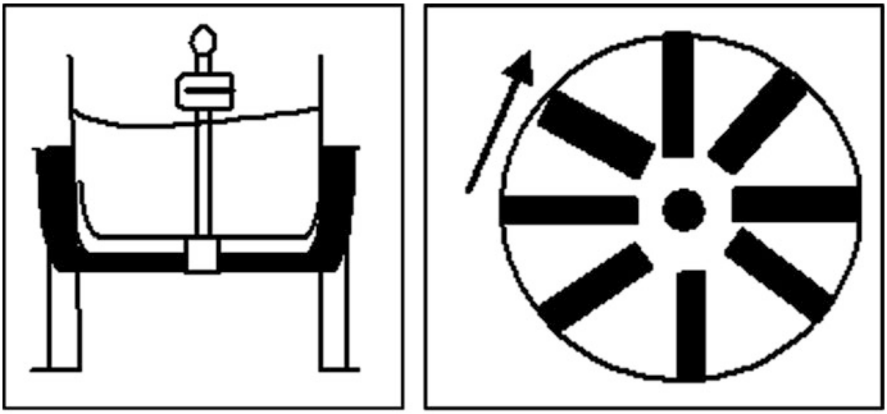


Fig. 7.19 Schematic design of (**a**) an anchor mixer and (**b**) a turbine mixer

radial flow along with little longitudinal flow. Therefore, the mixing action is more concentrated toward the horizontal plane of rotation and does not spread to the remaining liquid bulk in the vessel. Particularly, in unbaffled vessels, blades are pitched to assist in longitudinal flow (Fig. 7.18).

Anchor agitators are used for mixing liquids, particularly in the vessel with bowl-shaped bottom and kettles of hemisphere shape (Fig. 7.19a). Generally, anchor

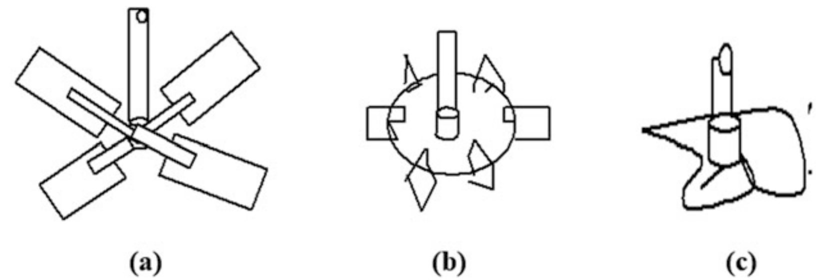
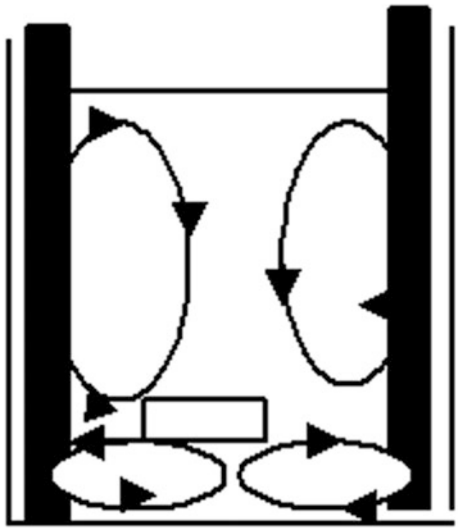


Fig. 7.20 Types of agitators

Fig. 7.21 Flow pattern in agitation vessel in turbine agitators



mixers are used in a jacketed-cooking vessel and are fitted with a wiper, which prevents the product scorching from heated surfaces. It has "close clearance design" for the transfer of heat between the vessel and the mixture. Other agitators such as paddle and gate also have close clearance design that leads to better mixing.

An impeller agitator consists of two or more blades mounted on the rotating shaft (usually vertical). These blades can be flat, curved, or pitched (angled) to promote longitudinal and radial flow (Fig. 7.20). Turbine agitators are a type of impeller agitators, which consist of more than four blades fixed collectively (Fig. 7.19b). It usually operates at high speed (30–500 rev/min), and the size is 30–50% of the vessel diameter. Depending upon the impellers' application, the blades can be fixed either on a flat disc (also known as vaned disc impeller) or fixed vertically in baffled vessels. Impellers induce high shear forces on fluids that evolve at the edges of the blades (Fig. 7.21). Therefore, it is typically used for phase dispersion (such as emulsion premixing and homogenization) and for applications that include mass transfer (such as transfer of oxygen in fermenters).

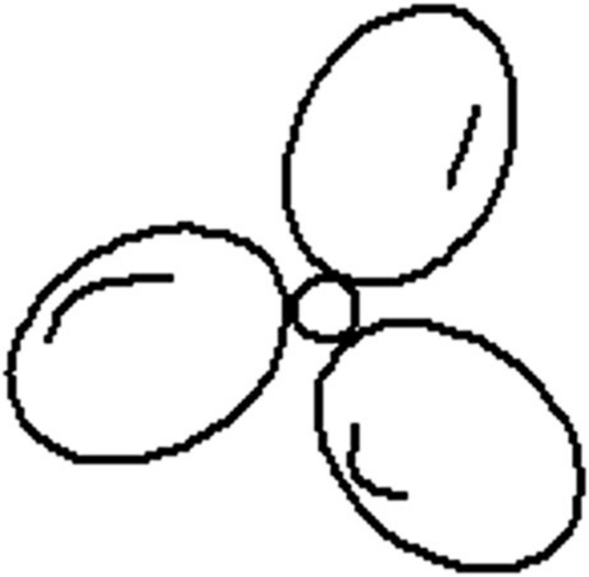


Fig. 7.22 Schematic diagram of a propeller mixer

Table 7.3 Merits and demerits of selected liquid mixers

Mixer type	Merits	Demerits
Paddle agitator	Good radial and rotational flow	Risk of vortex formation at higher speed, poor perpendicular flow
Turbine agitator	Very good mixing	Expensive
Propeller impeller	Good flow in all directions	Expensive than paddle agitator

Table 7.4 Types of agitators used for different range of viscosities

Product viscosity range (Pa s)	Agitator type
<3	Propeller
<100	Turbine
50–500	Anchor
500–1000	Helical and ribbon type

Propeller agitators are the impellers with size less than a quarter of the vessel diameter and have short blades and shaft that is directly coupled with motor (Fig. 7.22). Longitudinal flow predominates in these agitators. Usually, the mixer shaft is located off-center or on an angle. It operates at high rotation speed (400–1500 rev/min). Impeller agitators are also known as portable agitators as its diameter is smaller than turbine agitators; therefore, they are easier to move from one place to another. These agitators are used for blending low viscosity liquids and commonly used for preparing brines or syrups, diluting concentrate solutions, and blending miscible liquids (Tables 7.3 and 7.4).

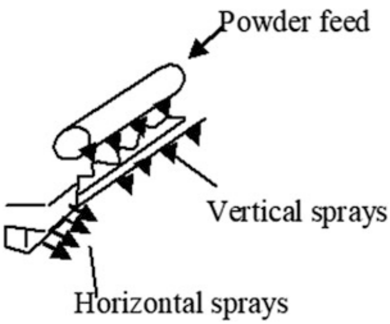


Fig. 7.23 Powder-liquid contacting devices: Neptune Chemix

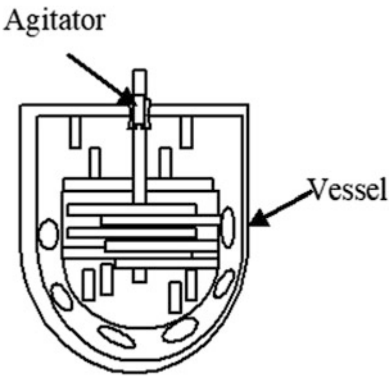


Fig. 7.24 Schematic diagram of anchor and gate mixer

Agitation plays an important role in preventing vortex formation and promoting radial and longitudinal liquid flow in order to achieve efficient liquid mixing. Hence, the agitator is located at different positions in all the impellers (Fig. 7.7). To increase the shearing forces in liquids, baffles are attached to the vessel wall, which also interrupts the rotational flow.

Powder-liquid contacting mixers are commonly used to blend powders with liquids and are also known as short residence time mixers. By using rotors or blades, the powder is uniformly blended into a spray of liquids. Pumps are also used to blend powders with liquids by creating turbulence flow. Commonly used powder contacting-type mixers are Neptune Chemix (Fig. 7.23), buss mixer, and Schugi mixer.

Mixers for High Viscosity Liquids and Pastes

Vertical shaft slow speed mixers are used for mixing viscous liquids. Multiple paddles (gate) or counter-rotating agitators are commonly used to promote high shear force (Fig. 7.24). Gate and anchor agitators are the basic design, which is often used in combination with heating mixing vessels. Scraper blades are fitted along with the anchor to prevent the burning of liquids and pastes. Complex designs are used to increase radial movement in the mixtures by inclined vertical blades and to

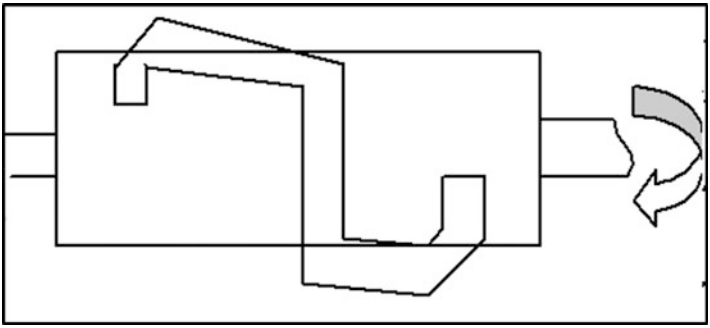


Fig. 7.25 Schematic diagram of a double sigma blade mixer

promote shearing action through the arms on a gate where stationary arms overlap on anchor.

Other configurations adopted to minimize stagnant regions during the mixing of high viscous liquids and pastes are:

- Using a combination of small and large impellers
- Imparting planetary motion in addition to rotatory motion

General configuration of horizontal blade twin shaft mixers is sigma blade (or *z* blade) mixer (Fig. 7.25). This mixer consists of a metal trough in which two heavy-duty blades are mounted horizontally. These two blades overlap and rotate at either different or similar speeds ranging from 14 to 60 rev/min to promote shearing action between the trough and blade and between the blades. These mixers utilize a significant quantity of power during mixing, which is dissipated in the form of heat. Therefore, mixing time may be low to achieve high mixing efficiency. For temperature control, walls of the trough are jacketed if necessary. For mixing and shredding, unique blade configurations are used that include serrated blades and different blade configurations such as double claw and gridlap.

Planetary mixers are used for both domestic and industrial applications. All the vessel parts are in mixing action, and blades rotate at 40–370 rev/min (Fig. 7.26). An alternative design of planetary mixer is also available in which rotating blades are located off-center and are co-current or counter-current to the revolving vessel. A small clearance is there between the vessel wall and the blades in both types. Gate blades are adopted for blending paste, mixing ingredients, and spread formation.

Screw conveyor mixers are continuous-type rotor-stator mixers. Rotor fits horizontally inside the barrel (a stationary slotted casing). It consists of single or twin screws which helps to transfer the viscous liquids and pastes through the barrel and is forced through perforated grids or plates. The small clearance between the barrel and the screw promotes shearing and kneading action. To increase the shearing action, screws are interposed with pins. This mixer is used for manufacturing margarine or butter and also for the extrusion process. Recent advances in mixer include

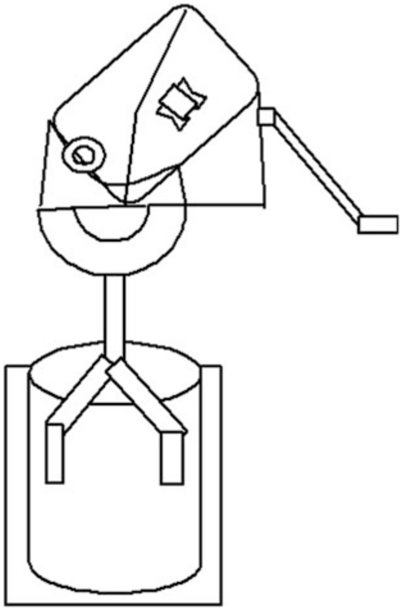


Fig. 7.26 Schematic diagram of a planetary mixer

automatic control of recipe storage with microprocessor control for a swift change of process conditions and products and monitoring and logging of product data and process conditions. The continuous rotor-stator-type mixers are adopted for the preparation of dough for the manufacturing of confectionery, biscuits, cakes, breads, and cracker products.

Currently, many designs are available in a mixer such as bowl rollers and choppers, which are used for specific mixing applications. Colloid and roller mills are used for mixing high viscous liquids and paste in addition to its usage as size reduction equipment.

Recent development includes a motionless or static mixer for viscous liquids and paste. These mixers eliminate the need of agitators, rotating parts, and tanks, which helps to reduce the capital and maintenance cost. These mixers consist of a series of static mixing elements, which are precisely aligned in a housing, which is set up in the processing line. According to the type of food and degree of mixing requirement, mixing elements rotate and integrate the food ingredients in a specific pattern. These mixers are operated using three different mixing patterns which include radial, transient, and flow mixing. In the radial mixing pattern, the liquid is turn aside by the static mixing element by a series of 180° rotations, which reflect back the liquid from the center of the vessel wall. In transient mixing, the spaces between the static mixing elements permit relaxation after rapid radial mixing of viscous material, whereas in flow mixing, the material is divided into two components first by the static mixing element and secondly by rotating 180°, which push the liquid against the center of the vessel wall and back again.

Dough, Batter, and Paste Mixers and Kneaders

These mixers are applied to mixing operation in dough and paste-type products. Mixers of these types induce high rotational momentum. The energy consumption per unit mass or volume of product is considerably higher in spite of having relatively low rotational speed. In order to prevent overheating of the mixture, cooling jackets are used in the kneader as mechanical energy is transformed to heat during mixing. Kneaders include horizontal dough mixers, planetary mixers, cutter mixer, and sigma blade mixers. Particularly, in extruders, both mixing and kneading take place simultaneously. During the kneading operation, considerable shear force is induced that often results in vast changes at the molecular level in product structure [16]. The kneading operation is necessary for gluten development in the dough [17] and butter/margarine plasticization [18].

Problem 7.12 For kneading dough in a batch of 100 kg each, a dough mixer is used. The net input mixing power is 250 W/kg of dough. For cooling purpose, the mixer is fitted with a jacket. The main aim is to maintain a constant dough temperature while mixing.

(a) The cooling water temperature rise must be controlled below 15° C. What is the minimum cooling water flow rate?
(b) Due to the control system failure, the cooling water flow was delayed by 6 min. Calculate the temperature rise of the dough. The dough: $C_p = 2424$ J/kg K.

Solution:

(a) Let G be the water mass flow rate ($C_p = 4180$ J/kg K) and Δ is the increase in the temperature of the water. Then:

$$GC_p * \Delta T = q$$

$$G = \frac{250 * 100}{4180 * 15}$$

$$1435\,\text{kg/h}$$

$$0.4\,\text{kg/s}$$

(b) If during mixing the heat generated is not removed, then:

$$\left(m * C_p * \Delta T\right)_{\text{dough}} = q$$

$$\Delta T_{\text{dough}} = \frac{q}{(mC_{\text{p}})_{\text{dough}}} \frac{250 * 100 * 6 * 60}{100 * 2424}$$

$$37.12^{\circ}\text{C}$$

7.2.10 Effect on Foods

Generally, the mixing process does not directly affect the shelf life or nutritional value of the food products, but it can have an indirect impact as ingredients in food react with each other, which affects the sensory and functional properties of food. The extent and nature of reaction depend on the food components, but the reaction can be accelerated by attaching the heating element along with the mixer. The main effect of mixing is to thoroughly combine all the ingredients of the bulk uniformly, for example, development of gluten during dough formation by folding and stretching action, which leads to swelling and strengthening the continuous network of gluten that leads to the desired texture for the bread manufacturing.

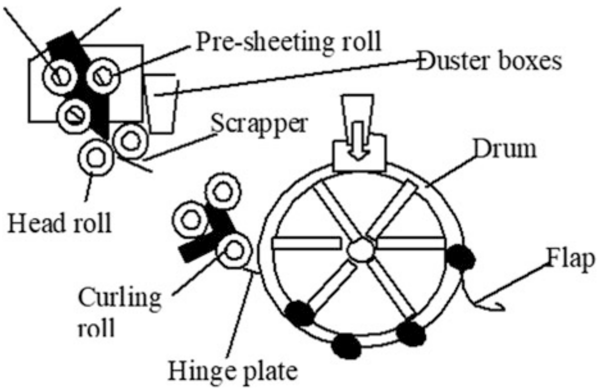
7.3 Forming

Equipment used for forming (molding) have many designs and are specially designed for specific products like biscuits, pie, breads, confectionery, and snack foods.

7.3.1 Bread Molders

The molder shapes the dough pieces into the cylinder, which on proofing expand to desired loaf volume (Fig. 7.27). Three stages are involved in molding bread dough, that is, sheeting, curling, and rolling-sealing. It consists of a set of rollers which have

Fig. 7.27 Drum molder for bread dough



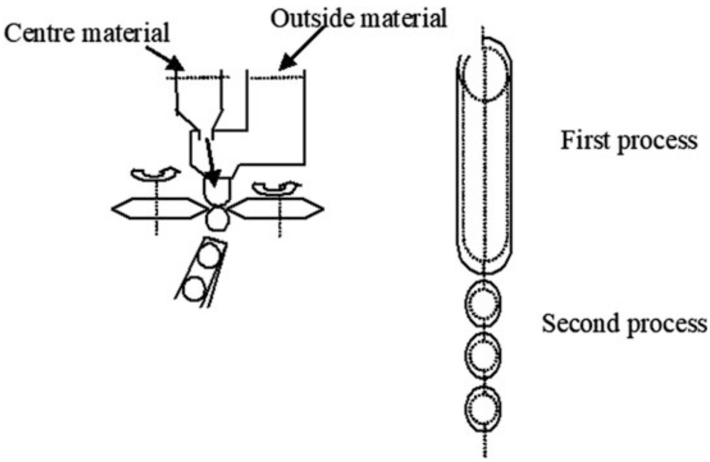


Fig. 7.28 Encrusting discs

small gaps "nips" that successively and gently roll the dough into sheets without tearing it. The sheets are generally curled and rolled into a cylinder followed by sealing through a revolving drum that passes the bread dough against the pressure plate. Then the trapped air is then continuously pressurized to expel out the trapped air, which compresses the dough and increases the sheet moisture content at the trailing end. It is recommended to have moist dough part in the center of the cylinder. Varieties of designs such as reverse sheeting and cross-grain molders are used for changing the direction of the sheet to roll the trailing edge [19].

Equipment used for forming and encasing dough is shown in Fig. 7.28, where both the outer and inner materials are extruded together and then divided and shaped by using two "encrusting discs." These discs help to bring changes in the relative thickness of both layers (inner and outer) just by adjusting the flow rate, which increases the flexibility in production, whereas in the conventional method, the product size is estimated by the feed size, and the thickness is estimated by the flow rate of each material used. Particularly, this equipment was designed by Japan for the cake production where bean paste is used to fill the outer layer of rice dough. This equipment is widely used for the processing of hamburgers filled with cheese, sweetbreads that are filled with jams, fish stuffed with vegetables, meat pie, and doughnuts.

7.3.2 Biscuit Formers and Pie

Biscuits are formed (Fig. 7.29) by using either of the four methods:

- By using a metal molding roller, the dough is gently pushed through cavities of different shapes.

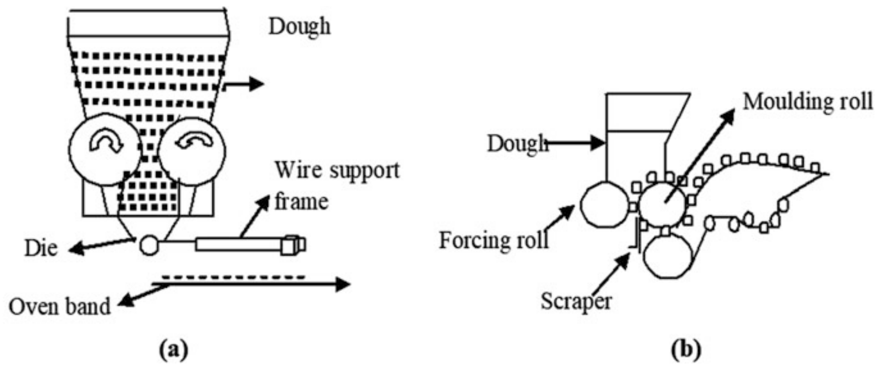


Fig. 7.29 Biscuit formers

- By using a cutting roller, the dough sheet is cut into shapes and simultaneously imprints design on the biscuit upper surface by printing rollers.
- By using a wire cut machine, the soft dough is extruded by a series of dies.
- By using a rout press, a ribbon of dough is extruded continuously, and then the ribbon is cut to the desired length using a reciprocating blade.

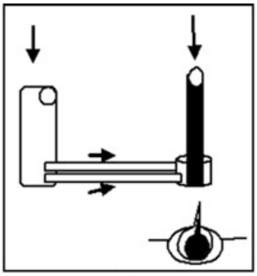
Pie casings are made by placing dough pieces in an aluminum foil container or reusable pie mold and finally pressing with die. The filling is then filled into a casing, and a permanent sheet of flour is placed on top. Finally, the lid is cut with a reciprocal blade.

7.3.3 Confectionary Molders

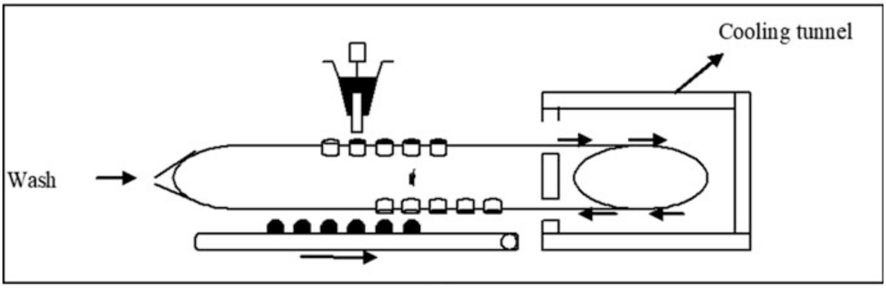
Confectionary molders (Fig. 7.30) are attached to the continuous conveyor, which consist of individual molds that process confectionaries of different desired sizes and shapes. This process takes place at the bottom of the accelerator, which contains a piston filler that fills the molds with the required amount of hot sugar. The depositor can store the food either in a single layer or in the center (Fig. 7.30a). These depositors are used for filling chocolate paste around the hard-boiled confectionary. Finally, the confectionary is cooled into the cooling tunnel. When all the confectionaries harden sufficiently, each confectionary is ejected, and molders restart the process again (Fig. 7.30b).

Chocolate molders are classified into three types on the basis of the material used and the ejection method:

- For butterscotch (hard confectionary), metal molds equipped with ejector pins are used.



(a)



(b)

Fig. 7.30 Chocolate molder. (**a**) Depositing center-filled confectionery. (**b**) Confectionery molding: An air-demolding depositor

- For caramel, toffee, fondant, fudges, and chocolate (soft confectionary), polyvinyl chloride flexible molds are used to eject the confectionary by mechanical means.
- For gums and jellies, polytetrafluoroethylene-coated aluminum molds are used to eject the confectionary by compressed air ejection.

Each type molder is controlled automatically. Other forming equipment extrude sugar confectionary and use a set rollers to shape in form "rope." The individual confectionery is then separated from the rope and formed using a die.

In modern times, depositors are controlled by a microprocessor and are used for processing high viscous liquids for confectionary into different shapes and sizes. The memory can store 99 different confectionery products of various shapes, sizes, and weights, and the operator uses a two-digit product code to store them.

Problem 7.13 A soya meal with moisture content (15%, w.b) is extruded through the extruder with channel dimension (width 6 cm, height 3 cm, length 40 cm). Rheological properties of the extrudate are evaluated as a density of 1300 kg/m^3 and viscosity of 68,000 Pa s. The wall velocity is evaluated as 0.4 m/s. Estimate the extrudate flow rate through die if pressure drop is maintained at 2000 kPa.

Solution:

(Moisture content, 15%; channel length, 40 cm; and cross section, 6*3; density, 1300 kg/m^3; viscosity, 68,000 Pa s; wall velocity, 0.4 m/s; and pressure, 2000 kPa)

The volumetric flow rate in cross section for Newtonian fluid was calculated using equation:

$$V = \frac{\Delta PWH^3}{12\mu L} + \frac{u_{\text{wall}}HW}{2} \tag{7.19}$$

$$V = \frac{(2*10)^6(0.06)(0.03)^3}{(12)(68000)(0.4)} + \frac{(0.4)(0.03)(0.06)}{2}$$

$$V = 1.13 * 10^{-4}\text{m}^3/\text{s}$$

The mass flow rate was calculated using extrudate density 1300 kg/m^3 as follows:

$$\acute{m} = (1.13*10)^{-4}(1300)$$

$$\acute{m} = 0.1469\,\text{kg/s} = 528.84\,\text{kg/h}.$$

Problem 7.14 A corn meal extrudate (non-Newtonian) with a moisture content of 20% (w.b) is pumped through an extruder with channel dimensions (width 4 cm, height 3 cm, length 40 cm). The wall velocity is evaluated at 0.2 m/s. The rheological properties of extrudate are described as a density of 1200 kg/m^3, a coefficient of consistency of 1100 Pa s^n, and a flow behavior index of 0.40. Calculate the pressure drop when a mass flow rate of 700 kg/h is maintained.

Solution:

(Moisture content of corn meal extrudate, 20%; channel length, 40 cm; channel cross section, 4*3 cm; wall velocity, 0.2 m/s; density, 1200 kg/m^3; coefficient consistency, 1100 Pa s^n; flow behavior index, 0.40; and mass flow rate, 700 kg/h)

For non-Newtonian fluids, the volumetric flow rate is used to calculate pressure drop:

$$V = \frac{4+n}{10}WHu_{\text{wall}} - \frac{1}{(1+2n)}\frac{WH^3}{4K}\left(\frac{u_{\text{wall}}}{H}\right)^{1-n}\frac{\Delta P}{L} \tag{7.20}$$

This equation is valid for flow indices from 0.2 and 1.0 and screw pitch angle from 15 and 25°.

$$V = \frac{700}{1200} = 0.583\,\text{m}^3/\text{h} = 1.62*10^{-4}\text{m}^3/\text{s}$$

$$\Delta P = \frac{\left[1.62*10^{-4} - \frac{(4+0.40)0.04*0.03*0.2}{10}\right]*(1+2*0.40)*4*1100*0.4}{0.04*0.03^3}\left[\frac{0.03}{0.2}\right]^{0.40-1}$$

$$\Delta P = 521664\,\text{Pa s} = 144.9\,\text{kPa}.$$

7.4 Recent Advancement in the Science of Mixing

Computer-aided techniques such as computational fluid dynamics (CFD) are used to optimize mixer design settings or to choose a suitable mixer for a specific food. With CFD, it is much easier to explain liquid flow along with heat and mass transfer phenomenon, which leads to better equipment design and process control for the mixing operation. These computer-aided technologies provide optimal configuration settings based on vessel shape, size and type of impeller, power input, and mixing speed. CFD is the numerical simulation of fluid flow. CFD helps to predict the insight flow patterns for both simple and complex geometries. Mixers are modeled using 2D or 3D CFD techniques.

Recently, imaging and monitoring techniques are used to facilitate the mapping of flow pattern within the processing vessel and identification of poor mixing regions. In order to determine the optimum mixing time, nowadays, sensing emerging techniques such as NIR chemical imaging and NIR spectrometry are used. Monitoring is very challenging where mixing continues even after the mixing action has ceased, especially in a process that involves crystallization and gas inclusion.

7.5 Exercise

1. Define mixing. What are the factors affecting mixing?
2. What are the special features of mixing?
3. What is positive mixing?
4. Which types of mixers are used for batter and dough?
5. How does mixing of solids take place? Discuss its mechanism.
6. A three-bladed propeller with a diameter of 0.20 m is rotated at 1.2 Hz to mix the fluid in the laminar region. However, due to corrosion, the propeller must be replaced by a flat two-bladed blade with a diameter of 0.71 m. At what speed will the paddle rotate if the same motor is used? [Solution: 2.21 rpm]
7. For kneading dough in a batch of 110 kg each, a dough mixer is used. The net input mixing power is 270 W/kg of dough. For cooling purpose, the mixer is fitted with a jacket. The main aim is to maintain a constant dough temperature while mixing. The cooling water temperature rise must be controlled below 13° C. What is the minimum cooling water flow rate? [Solution: 0.54 kg/s]
8. A tank having a standard Rushton impeller is needed to disperse the gas in a solution with properties similar to water. The tank has a diameter of 2.5 m (1.2 impeller diameter). A power input of 0.73 kW/m^3 is used. Turbulence was assumed during the process, and the presence of gas does not affect significantly the relationship between Reynolds and power number. What will be the power needed by the impeller? [Solution: 8.59 Kw]

9. In a batch-type vessel, a large aqueous-based liquid food is blended. Considering a power number of 5 (for $Re > 5000$), estimate the power input through the impeller if an impeller has a speed of 20 rpm and diameter of 60 cm. The viscosity and density of the liquid food are 0.01 Pa s and 1000 kg m^3, respectively. [Solution: 13.97 W. A power number of 5 is therefore valid for *Re* greater than 5000.]
10. For blending brine, a vertical cylindrical vessel is used that is assembled with a three-bladed propeller. The propeller mixer rotates at 60 rpm and has 0.1 m diameter. Experimental result shows that mixing the input energy of 2.1 J/kg is necessary for suitable mixing. Estimate the mixing time for a 100 kg batch. Viscosity = 3 Pa s and syrup density = 1100 kg/m^3. [Solution: 21.64 min].

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Cleaning and Separation

8

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Abstract

In this chapter, the importance of cleaning and separation operations is highlighted. Various types of separators based on different principles, viz., disc separator, indented cylinder separator, specific gravity separator, spiral separator, inclined draper, velvet roll separator, magnetic separator, color separator, stone separator, pneumatic separator, and cyclone cylinder separators are explained using simple schematic diagrams. The types and characteristics of screens, viz., grizzly, gyrating and vibrating screens used in separators are also discussed with sieve analysis and worked examples. The basic principle of sedimentation used for separation of particulates from fluids is explained. The gravitational sedimentation and types of sedimentors, viz., gravity settling tank and solid contact unit, are discussed. Different types of centrifugation processes including horizontal bowl, tubular, bowl, and basket centrifuges are discussed with schematic diagrams. Filtration is used to separate suspended particles by application of pressure through porous material. The rate of filtration through the cake is worked out. How batch plate, shell-and-leaf pressure, vacuum, rotary drum and disc, cartridge, and centrifugal filters work is elaborated. The membrane filters that provide solution according to the filtration requirement are also explained. The

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application of centrifugation and filtration processes in food processing industries is also presented to make the students become aware of cleaning and separation operations in these industries.

Keywords

Cleaning (dry and wet) · Separation (types of separators, size of screens and sieve analysis) · Sedimentation (drag force, particle velocity, sedimentors and centrifugation) · Filtration (rate and types of filters)

8.1 Cleaning

Cleaning is a unit operation in agricultural processing, which deals with the removal and separation of undesirable ingredients from food material and provides sound material for further series of operation. The following is the categorization of different undesirable materials (contaminant) and their source (Table 8.1):

Washing of fruits and vegetables, peeling, descaling fish, or removal of skin is also considered as cleaning processes. Cleaning is the foremost food processing operation to prevent damages of the equipment from hard contaminants, e.g., nuts, bolts of farm machineries, and stones from the grower's field. It also saves money spent for processing of undesired contaminants, which are ultimately discarded in further processing operations. Thus, cleaning can be proved as an effective tool to boost the economy of the operation along with reduction in generation of food processing wastes to cater the environmentally friendly solution.

8.1.1 Dry Cleaning

Dry cleanings are mostly used for low moisture foods, which are small in size and possess higher mechanical strength such as grains and nuts. It removes surface adulterant and reduce pest infestation and product contamination. The effective use of dry cleaning gives safe and sound product, enhanced shelf life, and reduction of off color and flavor. The dry cleaning is performed using separators for reduction in product contamination and improvement of process efficiency.

Table 8.1 Different undesirable materials in agricultural produce

S. no.	Organic/inorganic materials	Contaminants
1	Metals	Ferrous/non-ferrous metals, e.g., nut, bolt, and fitting
2	Minerals	Stones, soil, grease, and engine oil
3	Plant	Weeds, seeds and leaves, trashes, twigs, pods, and skin
4	Animal	Insects, larvae, hairs, bones, excreta, and blood
5	Chemicals	Fertilizer, pesticide, and herbicides
6	Microbial cells and product	Fungus, yeasts, soft rots, color, flavor, and toxins

8.1.2 Wet Cleaning

Wet cleaning method utilizes water for rinsing to remove soil or pesticide residues on the surface of fruits and vegetables. It is an appropriate method that has series of pre- and post-detergent rinses to reduce the microbial load. This method is considered more appropriate than dry method for removing dust and soil, but careful control is needed during the processing because the application of water may enhance the chemical and microbiological spoilage. The equipment are designed on the phenomenon of spraying, soaking, floating, and ultrasonic operations, and some of the wet cleaning equipment are flotation tank, ultrasonic cleaners, brush washer, spray washer, drum washer, etc.

8.2 Separation

In the food industry, it is used to separate and purify a specific component from the food material. Generally, it is the separation of undesirable and foreign matters from the desired grains/products. The mechanical separation techniques are mainly based on the difference in the physical properties such as shape, size, and density. Mechanical separation techniques are generally applicable to heterogeneous mixtures, whereas the techniques such as distillation, absorption, and crystallization are used for homogenous mixtures.

1. *Size separation*: Size separation is referred to as the process of passing the material into the series of screens and then dividing it into many fractions.
2. *Unsized separation*: A single screen may separate materials into two fractions only, i.e., undersize and oversize through a single separation, which is referred to as unsized separation/function.

8.2.1 Types of Separators

After harvesting of the produce, there is a need to remove contaminants like weed seed, stalk, stems, trashes, dry leaves, broken seed, and dirt so that good efficiency could be achieved. Attempts are being made to develop equipment, which could be efficient and reduce seed loss.

8.2.1.1 Disc Separator

Disc separator separates grains, based on differences in length. It works on the principle of lifting short seed and rejecting longer seed (Fig. 8.1). Disc separator comprises a series of indented discs or pockets on a revolving horizontal shaft. Each disc contains numerous recesses on each face. Normally the arrangements of disc pockets are furnished in a progressive manner, i.e., smaller pocket disc from intake end to larger pocket disc at the discharge end.

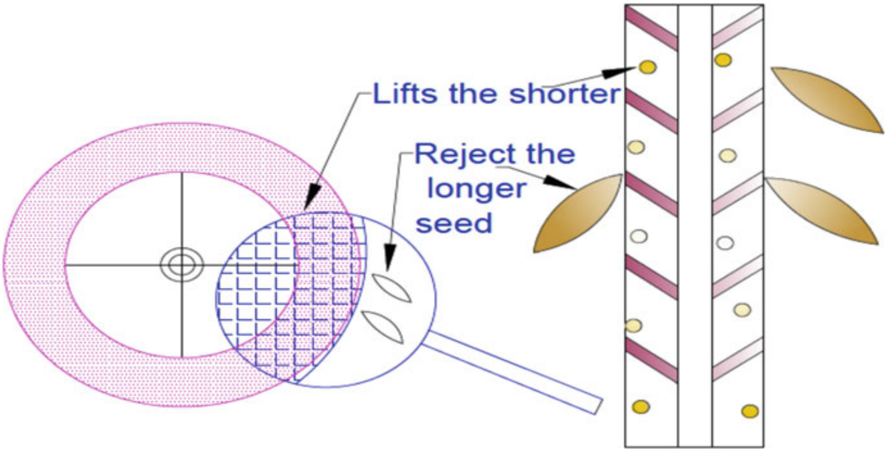


Fig. 8.1 Disc separator

In the center of the disc, there is round opening called core, where three spokes are fastened to the rotor shaft, which carries the disc. Midway on each spoke, there are sheet metal conveyor blades that act as screw conveyor to move bulk of seed from inlet to discharged end of the machine. As the discs revolve, the short seeds are hold by centrifugal force nearby hollow pocket, and longer grains are rejected.

The size of the cavity is made somewhat bigger to the smaller seeds and smaller from the longer seeds, which remains specific to the separation requirements. Some adjustment/variation can be made in the speed of the disc, as slower speed allows material to fall out of the pocket during loading of grains in discs and fast speed prevents the smaller material to unload at discharge outlet from the pocket.

It is used in agricultural and processing industries to clearly differentiate rice, wheat, and mustard from oats. Three different types of disc pockets are used. The name of R pocket is derived from rice, which is utilized for separation of whole and broken rice. A round and flat lifting frame is attached to the pockets. This pocket will reject the round grain and lift cross-broken grain on the flat surface. The V pocket stands for the name of scientist "vetch" and it is used to remove round-shaped grains. Some discs with pockets designated by letter are used to perform specific operations, which are normally square faced and larger than R and V.

8.2.1.2 Indented Cylinder Separator

Indented cylinder separators are used to separate the grains on the basis of difference in relative length. It is used specially for removal of grains like wheat, rye, mustard, and barley. It consists of rotating horizontal cylinder with inner side indents. The inner cylinder is thin, with scattered indents and semi-spherical form. The grains are fed in the inlet of the cylinder, and small grains are grabbed in indents with combined action of indentation and centrifugal force. At the top of rotation, these grains are dropped into an adjustable conical-shaped trough and collected at the bottom for conveying through screw conveyor to the specific outlet.

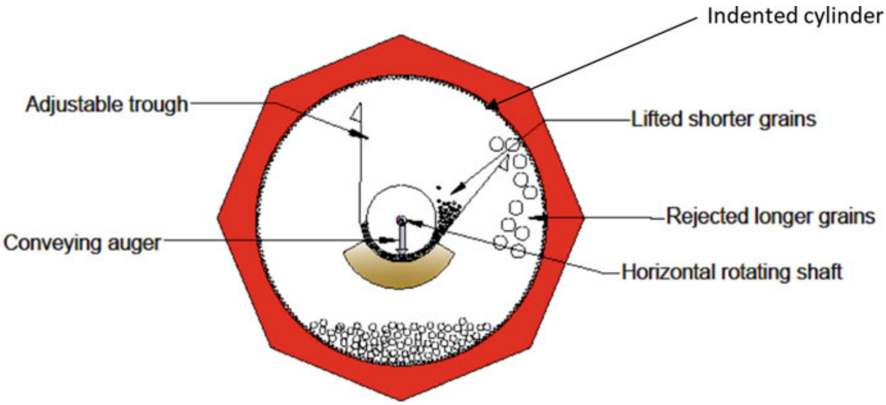


Fig. 8.2 Indented cylinder separator

The longer seeds are discarded by travelling shorter distances due to the effect of gravity. In order to avoid overcrowding of seed mass, the agitations are provided by screw conveyor (Fig. 8.2). The cylinders have identical indents throughout the length; hence, for different separations, different cylinders are needed. Inside the cylinder, the position of adjustable trough and speed of rotation of cylinders play a vital role for obtaining maximum separation efficiency. Centrifugal forces are enough to collect grains in the pocket, but it also influences distance traveled by a specific grain before drop back. Cylinder excessive speeds make the grains stick to the indents and stop it to fall inside of the adjustable trough, whereas too slow speed won't lift short grains out of seed mass.

8.2.1.3 Specific Gravity Separator

The difference in specific gravity or density of a material is prime criteria for separation of grains. The material to flow over a mesh slant edge and flotation of grain mixture due to jet of air generally take place due to the difference in density. The device having different functional parts in that triangular-shaped perforated deck is placed underneath to form a number of small jets, which causes the seed mass lifted as per their densities. The air pressure and velocity of air flowing upward through the deck can be easily controlled (Fig. 8.3).

The raw materials are fed through the hopper, which spread on the upper part of the inclined perforated surface. The air is blown from the triangular perforated deck surface and a jet of air causes lifting of the lightest material from the deck surface and is then conveyed toward the discharged end due to oscillating motion. The heavier particles are not lifted and collected at the upper side. It is mainly used in grain milling industry for the separation and classification of grains into high- and low-density fractions.

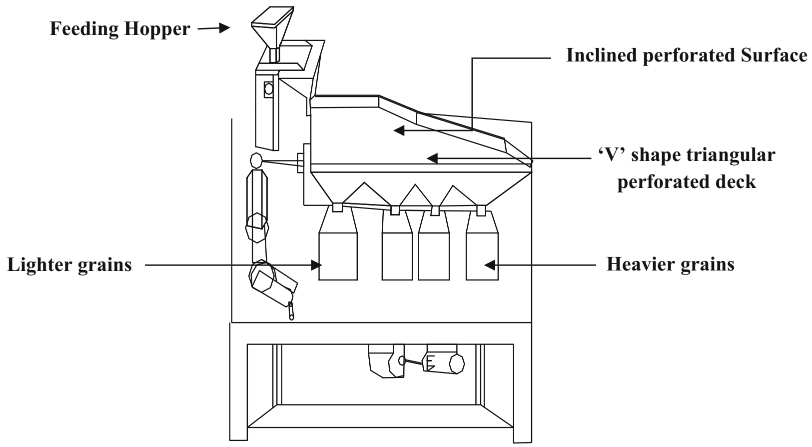


Fig. 8.3 Specific gravity separator

8.2.1.4 Spiral Separator

This separator separates the grains/materials on the basis of shape and ability to slide or roll. It comprises vertical standing, open, helical, straight screw, which is open on top and mixture of grains are poured into the hopper. Round grains revolve on the slope provided, gain the momentum, bounce due to experiencing centrifugal force, travel longer distances, and take the path of the outer helix, while flat material only slides and remains in the inner helix of the spiral and is delivered through a separate outlet (Fig. 8.4).

8.2.1.5 Inclined Draper Separator

Separation across inclined draper occurs on the basis of the ability of seeds to slide or roll. Seeds are dropped through the hopper on a moving canvas, rubber, or synthetic surface of a draper. The mixture is spread over an angled draper belt going upward. The smooth, circular grains roll or slip down the draper at a quicker pace than the upward motion and discharged into the sound grain collector, while the coarse or rough surface particles are transferred to the top of the inclined draper and gathered in impure grain receiver (Fig. 8.5).

The separation of materials is predominantly depending on the degrees of roughness of belt. The rough surface belts are used for attaining separation primarily due to rolling action of grains, while smooth or plastic belts are preferred for attaining separation on sliding action. For the separation of dissimilar materials, important variables such as feed rate, speed of draper, and inclination angle should be taken into account. For optimum separation, the feed rate should be kept low, while inclination angle affects the speed of draper, which should be adjusted for desired level of friction to ensure rolling or sliding.

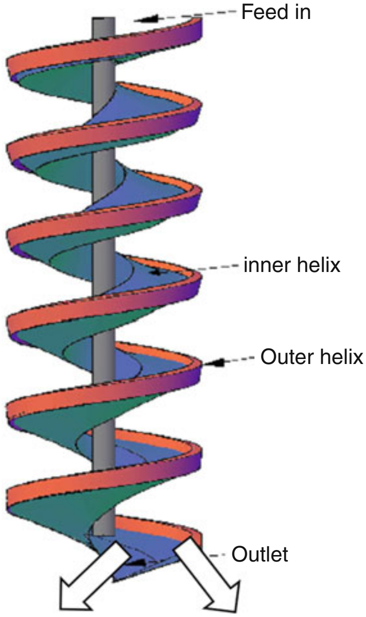


Fig. 8.4 Spiral separator

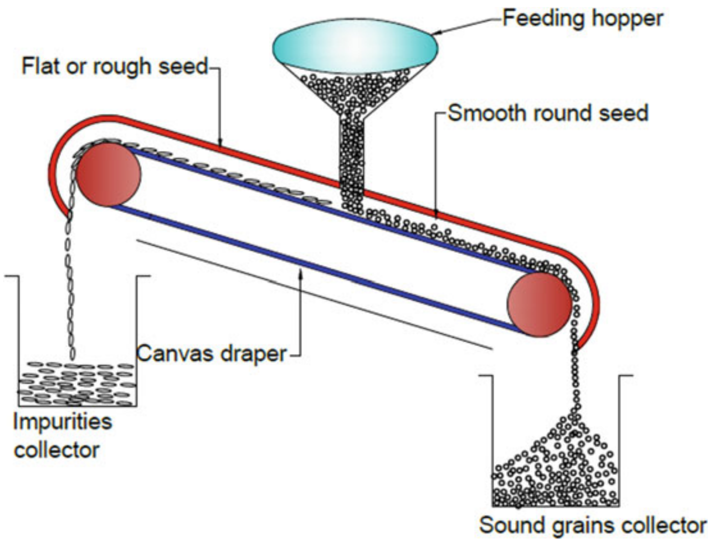


Fig. 8.5 Inclined draper seed separator

8.2.1.6 Velvet Roll Separator

The velvet roll separator differentiates grains based on variation in shape and surface texture. This separator operates after cleaning and separating grains from chaff as well as trash. It is indeed ideally suited to separate rough seed coat, broken seed, and

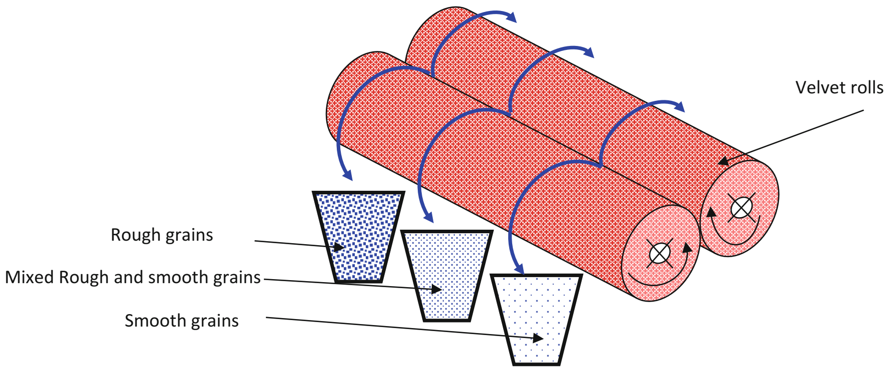


Fig. 8.6 Velvet roll separator

sharp angle seed from smooth and sound grains. It consists of two parallel inclined rolls covered with velvet cloth and placed side by side with each other. The rollers rotate in completely different directions, with adjustable shields above the rollers.

The rollers spin and smooth grains bounce backward to the inclined trough and discharge at the bottom of the separator. The rough surface grains with broken or fractured edges are trapped in the velvet pushed against the shield and accumulated in impurity channel (Fig. 8.6). The velvet roll separator needs balanced adjustments to give the best performance. The mixture of different specifications needs calibration of inclination angle, clearance between shields and rolls, and feed rates.

8.2.1.7 Magnetic Separator

The stickiness and the texture of grains remain prime factors for separation of grains through magnetic separators. In this method, the grain mixture is fed to screw conveyor, where seeds are mixed with water through water spray and then mixed with finely ground iron powder. The cracked, broken, and rough grains adhere with wet iron powder, whereas sound grains remain free from powder due to smooth surface (Fig. 8.7).

The grain mix then is discharged from the mixing screw into revolving drum, which has high magnetic field. The sound grains fall from the drum easily due to gravity and are gathered in clean seed outlets. Grain powder mixtures are attracted and adhered to magnetic drum and are separated by scraper or rotary brush and then deposited in broken seed outlet. To increase the efficiency of operation, the grain mixture is passed over this separator having two or three magnetic drums.

8.2.1.8 Color Separator

Color separator separates numerous foods based on the color attributes. The seeds of peas, garden beans, coffee beans, lemons, peanuts, walnuts, rice, and raisins are separated using color-based separations. Electronic separator can remove the mud balls and defective seed (Fig. 8.8). The grain mixtures are fed through the hopper and convey toward optical chamber by means of conveyor.

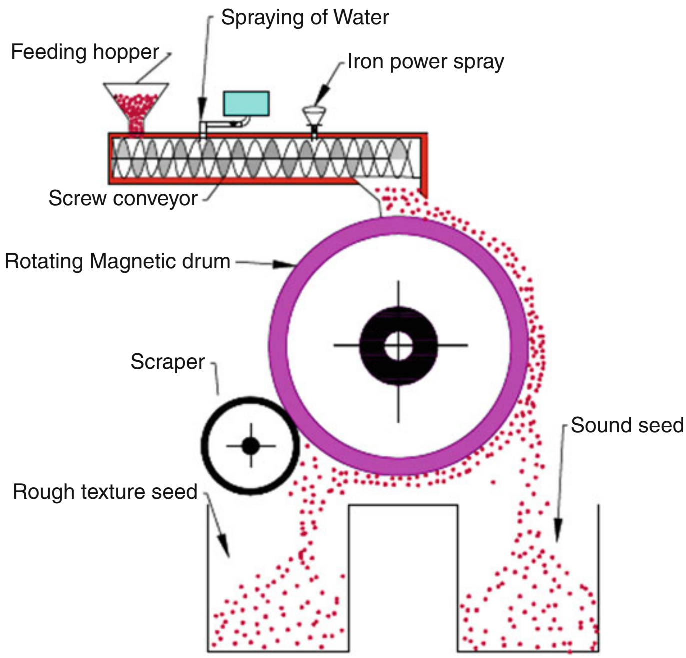


Fig. 8.7 Magnetic separator

Two photocells are set at a particular angle, which receives grains within space and directs beams to picture the grain trajectory. When beams encounter darker objects, it provides current to a high-voltage-operated needle fixed on another side. The grains are then passed through two high - potential difference electrodes, and grains are separated into two fractions. The separation capacity is comparatively low in this method.

8.2.1.9 Stone Separator

It divides grain mass into two fractions according to the specific gravity/density differences. The mixture of grains is placed on the middle portion of the deck, which observes the flow of air through the bottom of a deck and stratifies proportions of material, while the reciprocating motion of the deck separates the lighter particles from the heavier particles. The movement of heavier material toward the upper portion of the deck and lighter material toward the bottom end of the deck is observed without getting any middle-sized material. The calibration or adjustments of feed rate, deck slope, airflow rate, and deck vibration rates need to be performed for effective operation (Fig. 8.9). Separation may be modified by deck vibration, feed rate, deck slope, and airflow intensity.

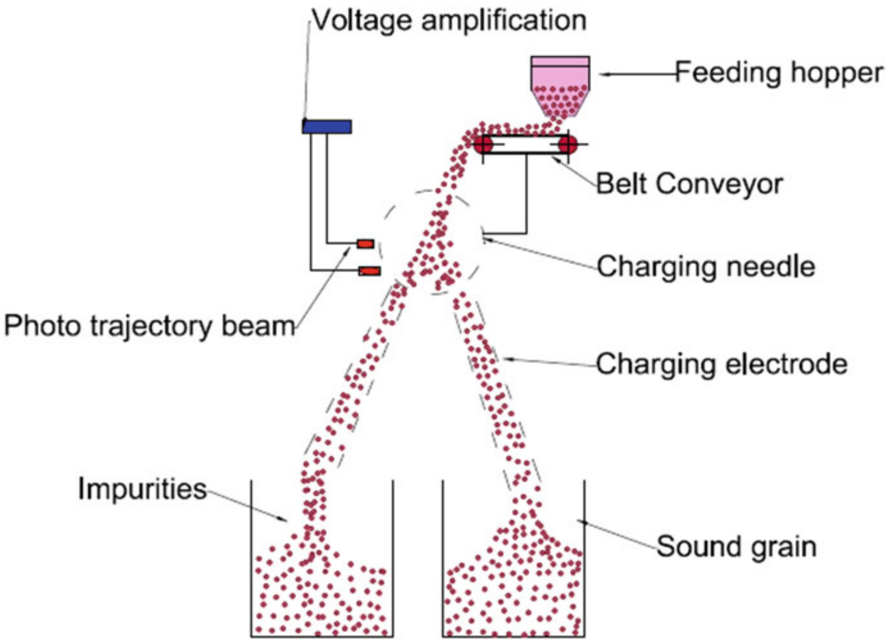


Fig. 8.8 Color separator

8.2.1.10 Pneumatic Separator

The aerodynamic properties of material are used for separating the grains and other material in a mixture. The shape, size, surface area, density, and orientation of material affect the aerodynamic properties of material. Terminal velocity of grain remains important for separating the grains in pneumatic separator. Either the speed of fan or the opening size can be set to obtain the desired air velocity for separation.

The aspirators work on negative pressure and create vacuum in the separation chamber by providing a fan at outlet for creating suction. The rough separation is performed in scalping separators, in which negative pressure can be used for aspirating lighter particles.

In pneumatic separators, the velocity of air is kept marginally lower than terminal velocity of sound or heavy grains so that only undesired lighter material is lifted and moved to the cyclone separator, while the remaining heavy grains are dropped through the clean grain outlet (Fig. 8.10).

Airflow and separation principles remain the same for every pneumatic separator. The movement of lighter material is not affected by the method of blowing air (pneumatic/aspiration), and the difference in pressure from higher to lower moves the lighter material for separation.

8.2.1.11 Cyclone Cylinder Separator

This equipment is used to accumulate dust and lighter waste generated during grain processing operations. It is associated with air screen cleaner to collect light

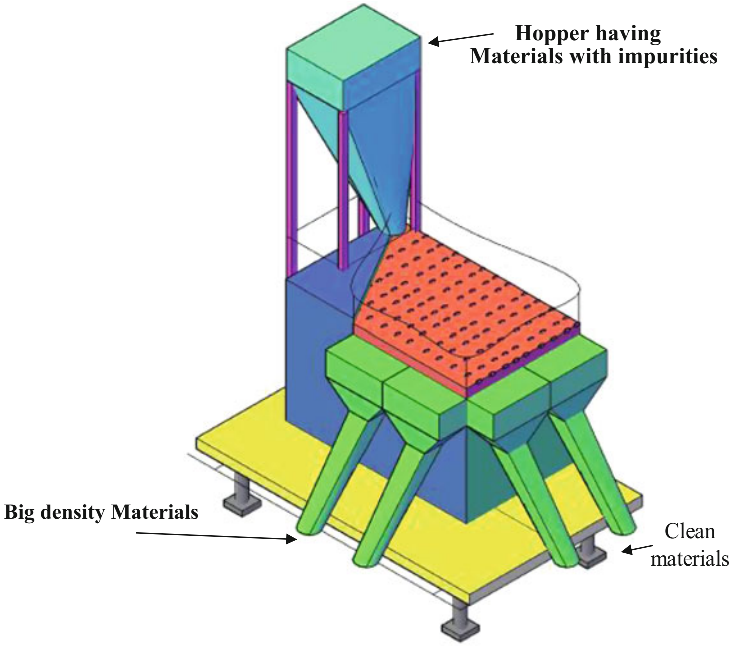
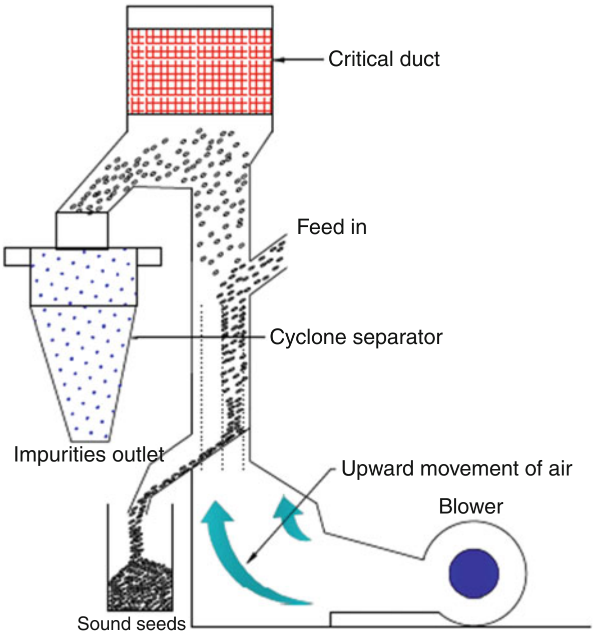


Fig. 8.9 Stone separator

Fig. 8.10 Pneumatic separator



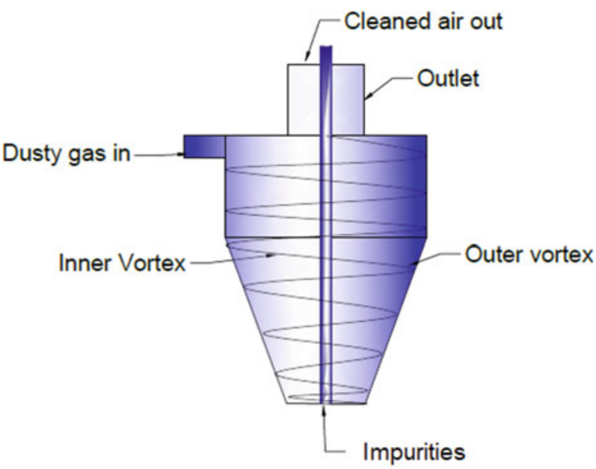


Fig. 8.11 Cyclone cylinder separator

impurities. In the case of pneumatic conveyor, airborne material can be settled in cyclone separator. The tangential entry at the top of cyclone allows forming a vortex and dropping in pressure, which allows materials associated with air to collect at the bottom outlet of the chamber. The air makes an exit from the top of cyclone being lighter in weight than the material (Fig. 8.11).

8.2.2 Size of Screens

Size remains major criteria for separation of grains using screen. The screen with elongated holes/perforations is used for separation based on thickness of material, while screens with round holes are used for width-based separation. The screens are generally kept flat and separate using oscillation. Occasionally revolving cylindrical screens are also used. Brushes, beaters, and other devices are used to remove the choking of screen. The lengthwise separation on screen can be performed by length separators. A fan is used to separate the grains based on aerodynamic properties and gravity. The screen cleaners have only one or two working screens; however, a complex cleaner has several integral parts as screens, sorters, fans, etc.

8.2.2.1 Grizzly Screen

The grizzlies are made with several metallic bars, which are arranged in parallel and fixed on a frame at an inclination of 30 to 50° from the horizontal (Fig. 8.12). Sometimes these bars are fitted horizontally. These handle large particle sizes of about more than 25 mm in size and spacing is set to 50 to 200 mm between the bars. These are used for a coarse or an initial rough separation to identify and separate bigger particles/lumps conveyed along with grains or similar material.

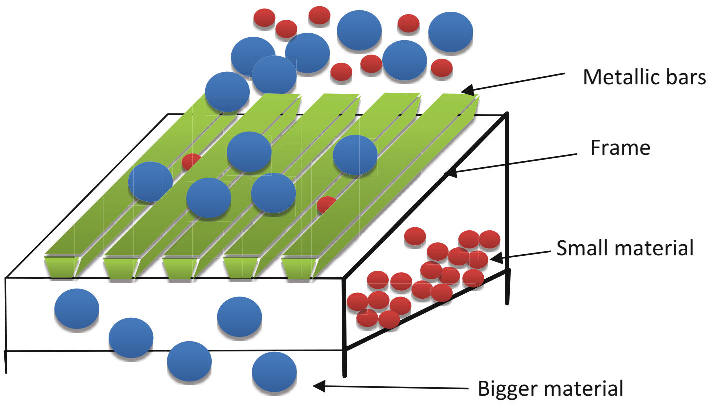


Fig. 8.12 Grizzley screen

8.2.2.2 Gyrating Screen

Gyrating screen consists of two screens, one above the other, and are held in a casing inclined at an angel between 16° and 30° with the horizontal. The rate of gyration is between 600 and 1800 rpm. The screens are rectangular and fairly long, typically 0.5 to 1.2 m and 1.5 to 4.3 m in size.

8.2.2.3 Vibrating Screen

Vibrating screen that is rapidly vibrated with small amplitude is less likely to blind than gyrating screen. The vibration may be generated mechanically or electrically. The vibration rate varies between 30 and 1000 strokes per min, and these are kept sightly inclined for achieving separation. These are used to separate the particles usually in the range of 0.25 to 25 mm.

8.2.3 Sieve Analysis

The sieve analysis is performed to decide the type of screen for maximizing the separation effectiveness [1]. Sometimes, seeds of various sizes are also separated using screens. The basic objective of any screen is the separation of feed, consisting of particles of varying sizes, into different fractions of specific sizes. These fractions are known as undersize and oversize material for a particular sieve. The material that passes through a screen is termed as undersize material, while material retained over the screen is known as oversize material.

8.2.3.1 Sieve Diameter

The maximum size of particles that can be passed through a square sieve is known as sieve diameter and can be represented as d_s, which may be different for the same distance "x." The different sieve diameter, d_s, for the same gap between two wires (x)

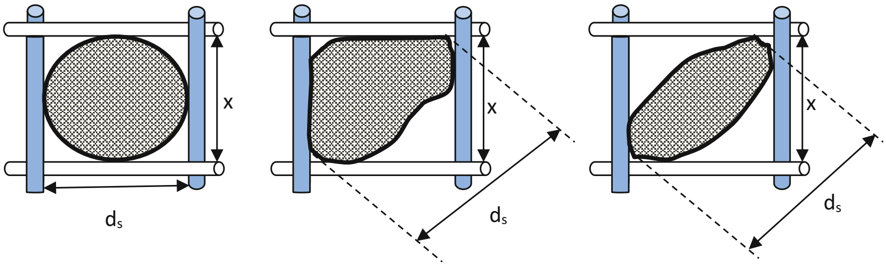


Fig. 8.13 Effect of shape on sieve diameters

is represented in Fig. 8.13, which depends on the shape of the material used for cleaning or separation.

8.2.3.2 Range of Analysis

The smallest sieve size is kept 20 μm according to ISO standards (3310–1:2016) with a maximum size of 125 mm, whereas 40 μm to 125 mm sizes are used in practices for screening dry materials.

8.2.3.3 Sample Preparation and Sieve Analysis

The material is dried in hot air oven for sieve analysis to avoid stickiness due to moisture. A number of sieves, which are either woven or perforated with known specific aperture sizes, are kept in a stack with bigger aperture sieve at the top to the decreasing aperture size to the bottom. The size of aperture is about $\sqrt{2}$ or $2\sqrt{2}$ times from adjacent sieve in a set of 6–8 sieves in a stack. The samples with mass W are poured on the top sieve and the set is shaken for a specific time so that sieving of material takes place. The material is collected by disassembling the sieves and weighed (Table 8.2). The representative plot of percentage retained and the cumulative percentage with logarithm of opening side (d) is represented in Fig. 8.14.

The graphs represent the variation of particles in various samples. It also gives an idea about the size with maximum occurrence and is helpful in deciding the sieve size for separation of specific fractions.

8.2.3.4 Specification of Sieves

The wire mesh sieves are made of wire of uniform and circular cross-sectional area, and these can be represented by (1) the number of sieve, i.e., the number of meshes in unit inch or 25.4 mm in each direction and (2) the clear distance between the wires, which represents diameters of the biggest spherical particles to pass through (Fig. 8.15). The diameter of wire is suitably selected according to the strength required to avoid damage or distortion and is termed as wire nominal diameter.

8.2.3.5 Approximate Screen Area

The screen area is presented as open area in percentage to the total area available on the sieve. It is affected by the diameter of wire and space between the wires and is

Table 8.2 Observations collected for sieve analysis

Sieve number (passed/retained)	Size of opening (passed/retained)	Arithmetic mean size of openings d (μm)	Logarithmic size of opening log (d)	Mass retained on smaller sieve (g)	% Retained on smaller sieve	Cumulative % oversize
(1)	(2)	(3)	(4)	(5)	(6)	(7)
M_1/M_2	d_1/d_2	$1/2(d_1 + d_2)$	log (col. 3)	W_1	$P_1 = 100 \times W_1/W$	P_1
M_2/M_3	d_2/d_3	$1/2(d_2 + d_3)$		W_2	$P_2 = 100 \times W_2/W$	$P_1 + P_2$
M_3/M_4	d_3/d_4	$1/2(d_3 + d_4)$		W_3	$P_3 = 100 \times W_3/W$	$P_1 + P_2 + P_3$
–	–	–		–	–	–
				Total $= W$	Total $= 100$	

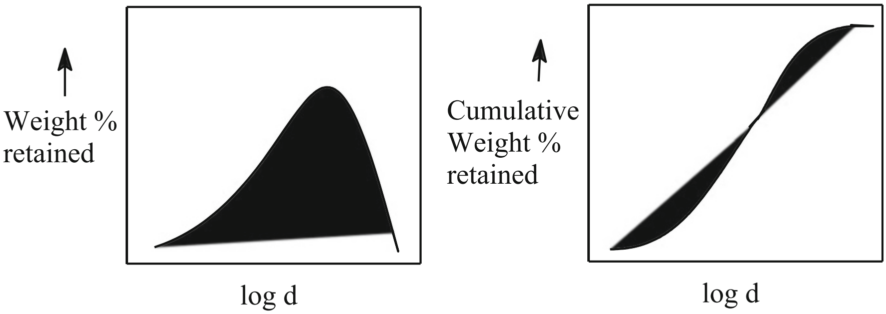


Fig. 8.14 Plots of particle sizes

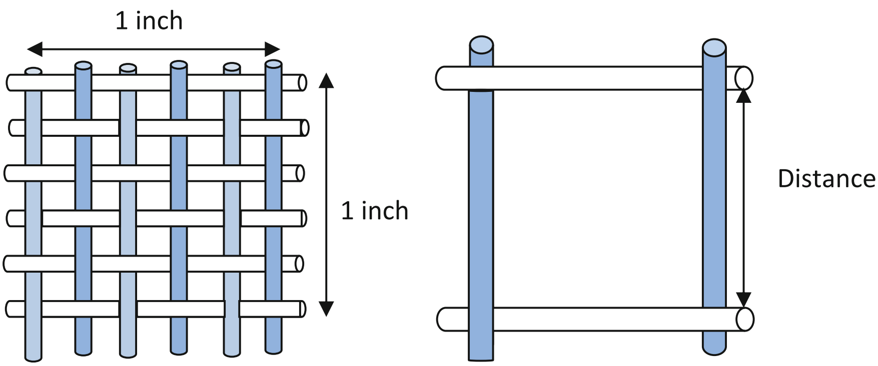


Fig. 8.15 Woven wire mesh

generally kept about 35–40% to provide sufficient and useful perforation. A higher area is desired; however, strength of the mesh remains a limitation in increasing the screen area.

$$\text{Approximate screen area} = \frac{\text{Total area of the sieve} - \text{Area occupied by the wire}}{\text{Total area of the sieve}} \times 100\%$$

8.2.3.6 Aperture Tolerance Average (ATA)

The opening/aperture of screen remains identical in size; however, small tolerance limit is allowed in all the openings. The expression of this variation in percent is known as aperture tolerance average.

8.2.3.7 Capacity of Screen

The capacity of screens is represented in tonnes of material processed in an hour, which depends on the size of machine, screen area, type and variety of crop, amount of foreign material, etc. It may vary from 2 to 10 tonnes per hour in industrial scale units. In industrial practices, generally, the rates are listed for a four-screen machine (size: width 42 in. and length 44 in.).

8.2.3.8 Effectiveness of Screen

Screen efficiency can be described as ability to closely divide feed into plus grain (overflow) and minus grain (underflow) depending on their sizes.

The screen is said to be effective, if all the oversize material in feed (F) passes through overflow outlet (O), while all the undersize material is collected through underflow (U) as shown in Fig. 8.16. Applying material balance for the separation, the following are considered:

$$F = \text{Mass flow rate of feed, kg/h}$$

$$O = \text{Mass flow rate of oversize, kg/h}$$

$$U = \text{Mass flow rate of undersize, kg/h}$$

$$m_f = \text{Mass fraction of materials in a feed}$$

$$m_o = \text{Mass fraction of materials in overflow}$$

$$m_u = \text{Mass fraction of materials in underflow}$$

According to total material balance,

$$F = O + U$$

Or

$$O = F - U$$

Or

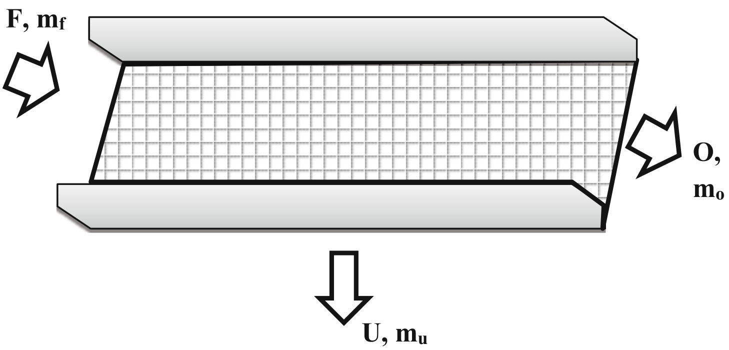


Fig. 8.16 Material balance for screening process

$$U = F - O$$

Applying fractional material balance for desired material,

$$Fm_f = Om_o + Um_u$$

which can be solved to obtain

$$\frac{O}{F} = \frac{m_f - m_u}{m_o - m_u} \tag{8.1}$$

$$\frac{U}{F} = \frac{m_O - m_F}{m_o - m_u} \tag{8.2}$$

The efficiency of receiving oversize material in overflow to the amount of oversize material in feed can be represented as follows:

$$E_O = \frac{Om_o}{Fm_f}$$

Efficiency based on undersize materials is given by the following mathematical form:

$$E_u = \frac{U(1 - m_u)}{F(1 - m_f)}$$

Overall effectiveness E is product of E_o and E_u:

$$E = E_o \times E_u$$

$$E = \frac{OUm_o(1 - m_u)}{F^2 m_f(1 - m_f)} \tag{8.3}$$

Rearranging the Eq. (8.3) by substituting the Eqs. (8.1) and (8.2), we get

$$E = \frac{(m_f - m_u)(m_o - m_f)m_o(1 - m_u)}{(m_o - m_u)^2(1 - m_f)m_f}$$

Problem 8.1 Durum wheat was milled in an attrition mill. The ground product was analyzed with a set of IS screens. Calculate the screen effectiveness of (1) IS 50 mesh and (2) IS 30 mesh. The data are presented in the following table:

Sr. no.	IS screen	Width of opening, mm	% Materials retained over each screen		
			Feed	Overflow	Underflow
1	100	1.00	4.00	0.00	0.00
2	70	0.708	16.00	11.24	0.00
3	50	0.500	23.00	47.87	2.88
4	40	0.420	29.00	23.68	10.65
5	30	0.296	15.00	11.89	44.23
6	20	0.211	8.00	4.32	24.78
7	15	0.1157	5.00	1.00	9.82
8	Pan	0			7.64

Solution: Solving for the cumulative mass fraction smaller than screen opening retained over each screen.

Cumulative mass fraction of material retained over each screen:

Sr. no.	IS screen	Width of opening, mm	% Materials retained over each screen		
			Feed m_f	Overflow m_o	Underflow m_u
1	100	1.00	0.04	0.00	0.00
2	70	0.708	0.20	0.1124	0.00
3	**50**	0.500	**0.43**	**0.5911**	**0.0288**
4	40	0.420	0.72	0.8279	0.1353
5	**30**	0.296	**0.87**	**0.9468**	**0.5776**
6	20	0.211	0.95	0.99	0.8254
7	15	0.1157	1.00	1.00	0.9236
8	Pan	0			1.00

Calculations:

1. For IS mesh 50, the cumulative mass fraction of feed, overflow, and underflow are 0.43, 0.5911, and 0.0288, respectively:

$$m_f = 0.43, \quad m_o = 0.5911 \quad \text{and} \quad m_u = 0.0288$$

$$E = \frac{(m_f - m_u)(m_o - m_f)m_o(1 - m_u)}{(m_o - m_u)^2(1 - m_f)m_f}$$

$$E_{50} = \frac{(0.43 - 0.0288)(0.5911 - 0.43)0.5911(1 - 0.0288)}{(0.5911 - 0.0288)^2(1 - 0.43)0.43}$$

$$E_{50} = 0.4787$$

2. For IS 30 mesh,

$$m_{\mathrm{f}} = 0.87, \quad m_{\mathrm{o}} = 0.9468 \quad \text{and} \quad m_{\mathrm{u}} = 0.5776$$

$$E_{30} = \frac{(0.87 - 0.5776)(0.9468 - 0.87)0.9468(1 - 0.5776)}{(0.9468 - 0.5776)^2(1 - 0.87)0.87}$$

$$E_{30} = 0.5825$$

8.3 Sedimentation

Sedimentation is the process of separation of particulates from fluid streams under the influence of gravity. The gravitational force remains the main reason for separating the particles from the liquids, which may be in the form of solid, liquid droplets, dirt, and debris from inflow of materials. The material has settling velocity due to its size, shape, and mass. The properties of material usually do not change due to formation of aggregates during sedimentation, and the particles settle at the bottom of container under the influence of gravity. The particles accelerate from the start till frictional drag becomes equal to the force exerted by the gravity and move further with a constant velocity, which is termed as terminal velocity [2].

8.3.1 Drag Force

The drag is defined as the force that acts opposite to the motion of a particle, on a body, moving with respect to fluid due to fluid movement. The drag force (F_{d}) depends on projected area (A_{p}), mass density moving through fluid (ρ_{f}), viscosity (η), modulus of elasticity (E), and velocity (V) and can be represented as

$$F_{\mathrm{d}} = f\left(A_{\mathrm{p}}, \rho_{\mathrm{f}}, \eta, E, V\right) \tag{8.4}$$

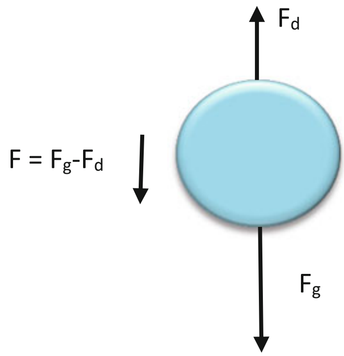
The dimensional analysis provides relation of drag force with various factors:

$$F_{\mathrm{d}} = CA\frac{(\rho_{\mathrm{f}}\, \nu^2)}{2} \tag{8.5}$$

8.3.2 Particle Velocity in a Fluid

Particle, having more density than liquid, is dropped/immersed, and it experiences gravitational force resulting in a downward movement and drag force resisting the movement of particle as represented in Fig. 8.17. The force F_{g} represents

Fig. 8.17 Force on spherical particle for movement



gravitational force, F_d represents drag force, and the effective force is the difference in both the forces, which moves the particle downward.

Gravitational force, $F_g = m \times g$, remains constant during the movement of particle, while the drag force increases with increase in particle velocity (Eq. 8.5). This results in attaining equilibrium at a stage where both the forces become equal ($F_g = F_d$) and no effective force on the particle is observed at this stage. Therefore, no further increase in velocity is observed and particle attains a constant velocity.

The fluid particles accelerate with time due to gravity at constant force and attain a constant maximum velocity named as terminal velocity, which is affected by shape, size, density, drag coefficient, and other physical properties of particles and liquids. The resultant force causing the particles to move can be expressed by deducting the amount the friction offered by the surrounding fluid:

$$F_e = V \times g \times (\rho_P - \rho_f) \tag{8.6}$$

where F_e, V, g, γ_p, and γ_f are net external driving force on the particle, volume of the particle, acceleration due to external force (gravity), particle density, and fluid density, respectively. The particle drag force (F_d) is estimated using the following expression and measures relative velocity of the particle in flowing fluid and projected area of the particle:

$$F_d = \frac{C \times \rho_f \times v^2 \times A}{2} \tag{8.7}$$

where C, ρ_f, ν, and A are drag coefficient, density of the fluid, relative velocity of the particle, and projected area of the particle normal to the direction of motion, respectively.

At equilibrium condition, the gravitational force working in downward direction, which is responsible for downward motion of the particle, becomes equal to the drag force ($F_g = F_d$), which resists the movement and works in upward direction. The acceleration of particle becomes zero, which results in constant velocity (terminal velocity):

$$V \times g \times (\rho_p - \rho_f) = \frac{C \times \rho_f \times v_t^2 \times A}{2}$$

Considering, particle as a spherical shape with diameter D of the particles,

$$\text{Volume of spherical particle, } V = \frac{\pi \times (D)^3}{6}$$

$$\text{Projected area, } A = \frac{\pi \times (D)^2}{4}$$

$$\frac{\pi D^3}{6} \times g \times (\rho_p - \rho_f) = \frac{C\, \rho_f v_t^2\, \pi D^2}{8}$$

Theoretically, the drag coefficient for spherical particles in streamline motion can be represented as

$$C = \frac{24}{R_e} = \frac{24\mu}{D v_t \rho_f},$$

where $R_e = \frac{\rho_f v_t D}{\mu}$

$$\frac{\pi D^3}{6} \times g \times (\rho_p - \rho_f) = \frac{24\mu}{D v_t \rho_f} \frac{\rho_f v_t^2 \pi D^2}{8}$$

$$\frac{\pi D^3}{6} \times g \times (\rho_p - \rho_f) = 3\mu v_t \pi D$$

$$\frac{D^2}{6} \times g \times (\rho_p - \rho_f) = 3\mu v_t$$

$$\frac{D^2}{18\mu} \times (\rho_p - \rho_f) \times g = v_t$$

$$v_t = \frac{D^2 (\rho_p - \rho_f) g}{18\mu}$$

where diameter of particles, density of particles, density of fluid, viscosity of fluid, and gravitational acceleration are represented by D (m), ρ_p (kg/m^3), ρ_f (kg/m^3), μ (Ns/m^2), and g (m/s^2), respectively. The particle will move downward in case particle density remains higher than fluid density, and particles, having less density than fluid, will move in upward direction.

Problem 8.2 The particle stayed starts falling in water from rest. The particle has diameter 50 μm, density of sphere $\rho_s = 2000$ kg/m^3, and density of water 1000 kg/m^3. The viscosity of water can be taken as 1 mN s/m^2. Calculate terminal velocity of the spherical particle.

Solution:
Applying Stokes' law,

$$V_{\mathrm{t}} = \frac{(d^2 g)}{18\mu}(\rho_{\mathrm{s}} - \rho)$$

$$V_{\mathrm{t}} = \frac{\left((50 \times 10^{-6})^2 \times 9.81\right)}{18 \times 1 \times 10^{-3}}(2000 - 1000)$$

$$V_{\mathrm{t}} = 1.3625 \times 10^{-6}\ \mathrm{m/s}$$

8.3.3 Sedimentation in Fluids

8.3.3.1 Gravitational Sedimentation in Liquids

The sedimentation in liquid takes place due to gravity. At low concentration, it is based on the principle of Stokes' law. A sedimentation tank enables suspended particles to settle at the bottom and be taken out, while water moves through the tank gradually and attains some degree of purification. In a continuous settling tank, there are various compartments to separate accumulated solids. The accumulated solids are known as sludge, which is collected at the bottom, while the clarified liquid is received in decanting channels at the top as overflow of tanks (Fig. 8.18).

8.3.3.2 Sedimentation of Particles in Gas

In the food processing industry, an important example of sedimentation of particles includes spray drying. In spray drying, slurry, when forced through the nozzle, is atomized into small droplets. The current of hot gasses gets mixed with droplets of

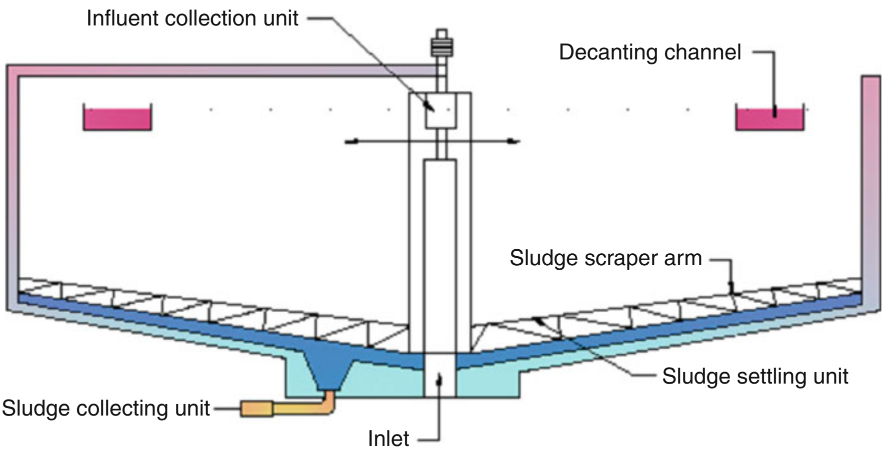


Fig. 8.18 Continuous sedimentation plant

slurry and as a result gets dried. Finally, the dried material settles and gets separated from the air. The area for settling the particles can be calculated in the same manner like sedimentation. The slow rate of sedimentation, which is not desirable, will indicate long contact time between the heated air and particles and large chamber area.

8.3.4 Sedimentors

8.3.4.1 Gravity Settling Tank

Settling is the mechanism by which objects settle down in a liquid and sediment at the bottom. Particles that encounter either gravitational or centrifugal force may have a tendency to move consistently in the direction of force. Length of collection tank is long enough so that all the particles should settle down (Fig. 8.19). Settling velocity of particle depends upon the speed of flow. If the speed of flow is kept too fast, then capacity of tank may not remain enough to settle all the particles.

There are two types of classifiers (a) simple gravity settling tank and (b) Spitzkasten gravity settling chamber. These simple classifiers have large tanks, which are subdivided in several subsections so that settling velocity becomes slower and high-density particles are trapped in the initial section and light particles are collected in last section (Fig. 8.20). In Spitzkasten gravity settling chamber, a series of conical vessels with increasing diameter are placed in the direction of flow. It works on the same principle as that of simple classifier. The coarse material is trapped in the first vessel followed by intermediate and then fine particles.

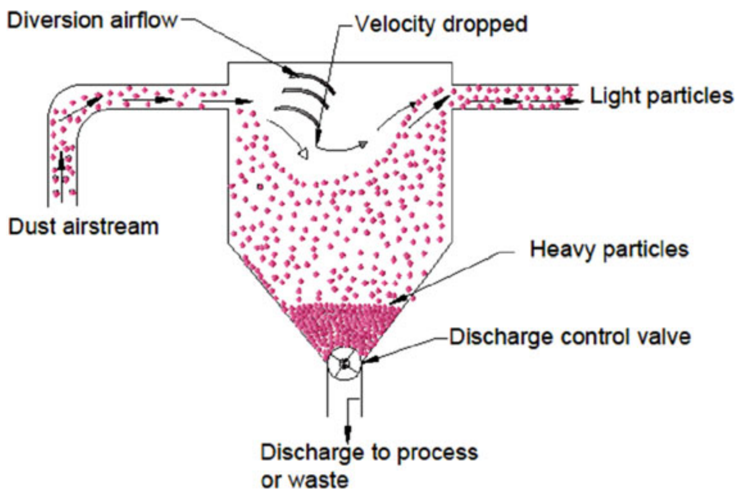


Fig. 8.19 Simple gravity settling tank

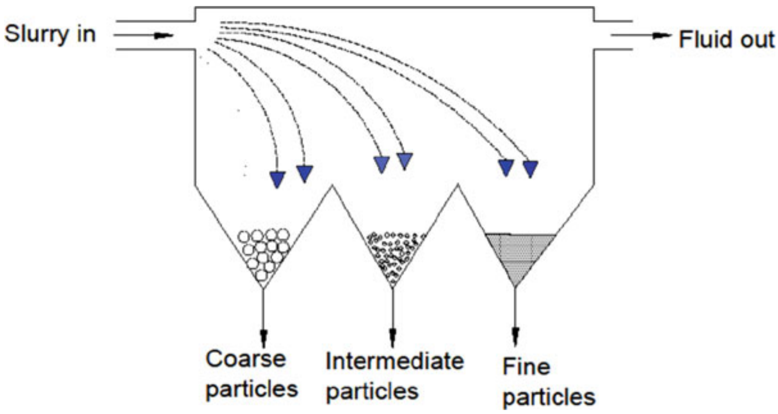


Fig. 8.20 Simple classifier

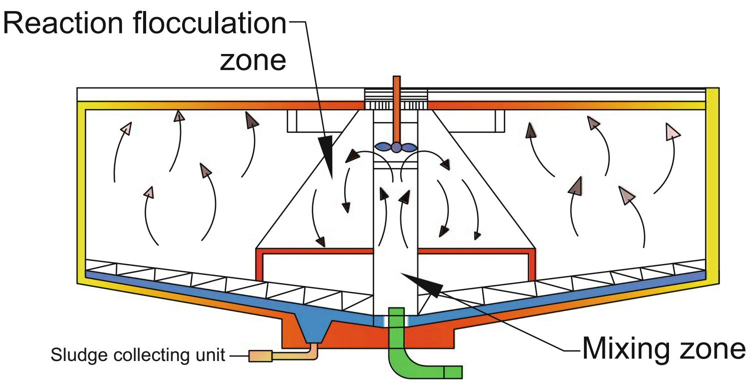


Fig. 8.21 Solid contact unit

8.3.4.2 Solid Contact Unit

In solid contact unit, coagulation and flocculation process is combined to perform separation of colloidal materials by sedimentation. The coagulation/flocculation of smaller particles occurs to form larger mass. It is also called as sludge blanket clarifiers. In flocculation, the mixing is carried out for a fixed period of time to promote agglomeration, which finally assists in settling. The feed enters from the center, wherein coagulation and flocculation take place in conical reaction flocculation zone. Inverted-cone-shaped reaction flocculation zone restricts the rise of water due to less space availability on the top, and as a result, water leaves from the bottom side of flocculation zone and enters the sludge blanket or slurry in the outer chamber (Fig. 8.21). The sludge blanket structure is formed due to previously coagulated solids and solids during sedimentation. The water is required to pass through the sludge and clarified water is being collected at the top of the solid contact units.

8.3.4.3 Settling Under Combined Forces

Mechanical separation in some cases may involve more than one force in combination. In the case of fine particles, the velocity should be kept very low for sedimentation of particles at the bottom of sedimentation unit. The centrifugal force can be combined, which results in deposition of particles at the inner periphery of the tank, which can be separated by scraping. Rotary mechanical classifier and rotary dryers also use the combined force for settling of fine particles.

8.3.5 Centrifugation

Centrifugation is a technique for separating immiscible liquids or solids from a solution by applying centrifugal force on the particles, which makes heavier/denser material (Liquid A) move in the outer space nearing boundary wall, while rotating and lighter/thinner material (Liquid B) remains near to the inner space in the centrifuge (Fig. 8.22). The rotational movement provides centrifugal force to the particles, which assists in accelerated separation.

8.3.5.1 Cyclones

The cyclone is used for the removal of particles of nearly 10 mm or more in size. Cyclone separator is often used to separate airborne material from conveyor discharge. They can also be used for separation of particles from liquids or separation of liquid droplets from air/gases. The air incorporating particles enters tangentially in the cyclone separator at the top, which leads to a pressure drop due to formation of a vortex around the center line of chamber. The heavier particles slide along the cyclone wall and move toward the central bottom exit, whereas the air remains in the center and moves toward top and gets released.

8.3.5.2 Liquid Separation

Separation of one component of a liquid mixture/liquid is a common operation for separation of liquids, which are immiscible as in the case of emulsion. In the dairy industry, the milk is separated into cream and skim milk. The skim milk and cream are separated at some specific surface within the bowl, which can be collected through respective discharge outlets.

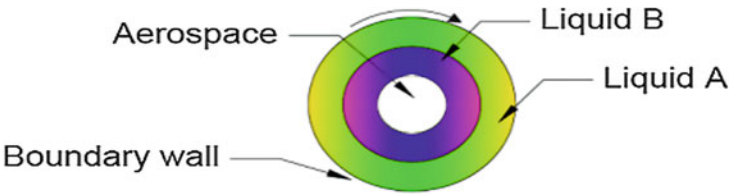


Fig. 8.22 Separation of immiscible liquids in a cylindrical boundary

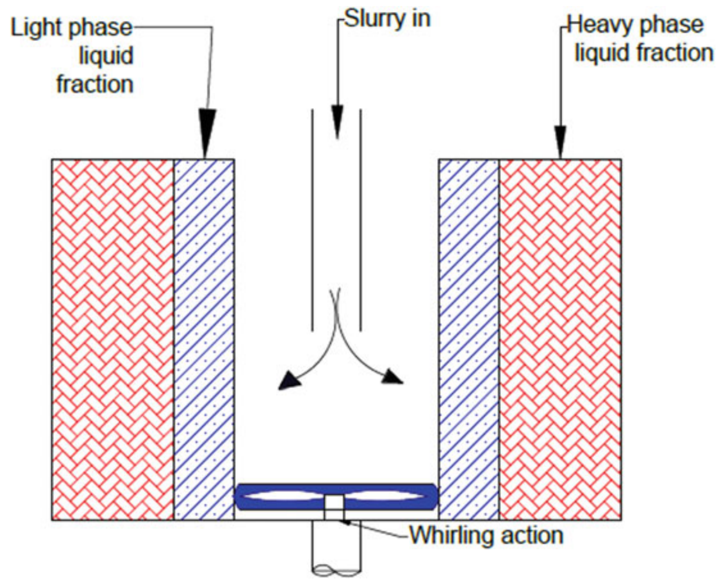


Fig. 8.23 Liquid separation in a centrifuge

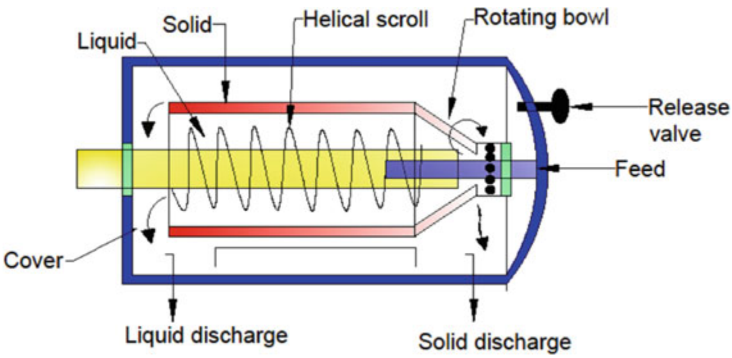


Fig. 8.24 Horizontal bowl centrifuge

Centrifugal equipment rotates the mixtures around a fixed axis, which applies centrifugal force in the outward direction (Fig. 8.23). Several pipes/plates are arranged in a way to separate denser and lighter components present in the liquid.

Horizontal Bowl Centrifuge

These are also known as decanter centrifuges and are used to treat suspension from 40 to a very high solid content of up to 60%. A rotating bowl, horizontal inlet, and helical scroll are fitted in a centrifuge, which separates solid from the liquid phase (Fig. 8.24). It uses the force produced under the rapid rotation of a helical screw conveyor, extracting the liquid from the solid fraction.

The solid particles are forced outward against the wall, whereas liquid can be extracted from the center of the bowl. These can provide acceleration up to 4000 g force. The bowls are conical, and diameters range from 10 to 100 cm. The liquid is fed by a concentric narrow pipe to an appropriate place in the bowl. The solid particles stick on the bowl surface, whereas clear liquid is collected in the bowl.

The solid from the bowl is collected through a helical screw conveyor toward conical section and discharges from the end of conical section. The clear liquid outflow can be obtained from the flow through the outer cavity from the opposite side of feed inflow. Two immiscible liquids can also be separated using specially designed outlets for discharging high volume of thick and thin liquids. The decanters can be used continuously for extraction of solid and liquids.

Tubular Centrifuges

It is considered one of the simplest centrifuges. It consists of a rotor with an inlet for feed and outlets of lighter and heavier phase. The bowl rotates around a vertical axis in stationary casing. The tubular bowl is of 15 to 50 cm, which rotates 15,000 to 50,000 rpm and exerts a force of 10,000 g. The separation of lighter and heavier liquids is performed continuously. The capacities of these centrifuges are limited due to their geometry.

Disc Bowl Centrifuge

The disc bowl centrifuges separate the mixture as lighter liquid and heavier liquid (Fig. 8.25a). Solids remain far more troublesome, while removal of liquid phase remains easier from a centrifuge. The stationary ploughs/scrapers are not used in these centrifuges due to restricting flow pattern. The disc bowl style centrifuge creates dense slurry and produces acceleration up to about 12,000 g forces. The bowl comprises about 50 to 150 conical discs, 2 mm apart. The liquid suspension passes through the gaps between discs to the system axis; solids settle on the underside of every disk, move all along the disk in the outer direction, leave edge of the disc, and are thrown by the centrifugal force to the bowl surface. The clear liquid moves to the bowl center and discharges above or below the weir. These are mostly used to separate oil, water, solids, and especially fuel and lubrication oil on board ships. These possess good separation efficiency; however, generation of shear forces, air mixing, and increase in temperature remains limitation of these centrifuges.

Nozzle Discharge Centrifuge

Nozzle centrifuges are continuously working machines that separate liquids from solids through nozzles. The clear liquids are discharged by in-built centripetal pump. The nozzles are placed on the circumference of centrifuge for handling solids (Fig. 8.25b), and separated solids are continually expelled via nozzles at the bowl periphery. The nozzles are kept open intermittently or under automatic operation for release of separated solids. It consists of a system with 2–24 nozzles around the tank. The nozzle size varies from 0.75 to 2.00 mm, which depends on the particle size of solids in feed. Through these nozzles, dense solids with 5 to 50% concentration are

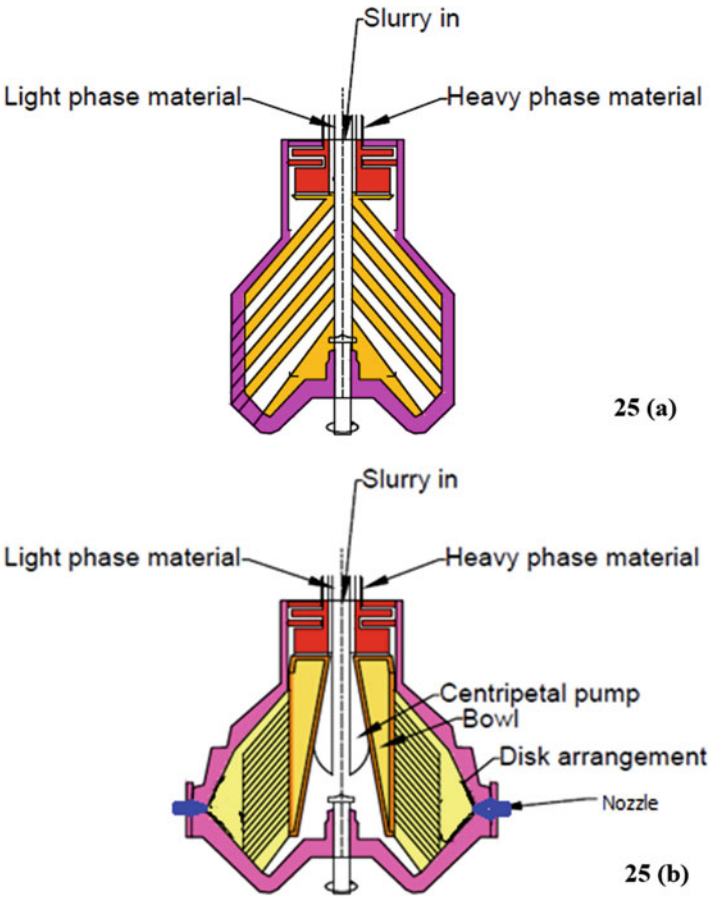


Fig. 8.25 Liquid centrifuge: (**a**) conical bowl and (**b**) nozzle

discharged continuously. These are used in biotechnology, pharmaceutical, and food industries to handle fermented products.

Self-Opening Centrifuge

The centrifuge contains self-cleaning bowl with conical disc stack to increase effective clarification area (Fig. 8.26). The centrifuge may be used for separation or clarification processes, when the solid content is about 30–40% in the feed material. It discharges separated solids while moving at maximum speed. A number of ports are provided at the periphery of bowl, which are opened and closed using movable sliding piston and hydraulically actuated mechanism to eject the particles from the centrifuge. Usually, water is used to control the exits through the ports; however, low-viscosity organic liquid can also be used. The opening mechanism can facilitate total ejections or partial ejections as per the requirement. The complete discharge from the centrifuge can be obtained by closing the feed valve.

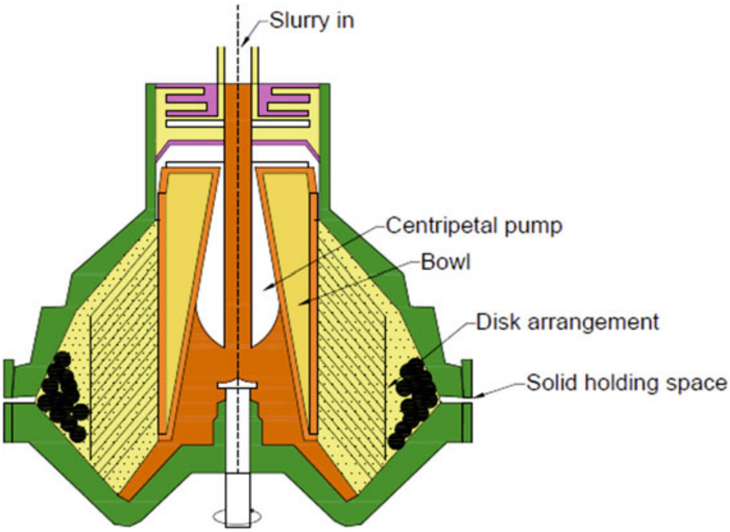


Fig. 8.26 Self-opening Centrifuge

Basket Centrifuges

These centrifuges usually operate in batches and have cylindrical chamber, which rotates rapidly around horizontal, vertical, or any other inclined axis. The centrifuges with solid wall are used for liquid–solid and liquid–liquid separation. The liquid–liquid separation is performed by placing discharge tubes at an appropriate distance from the center. The perforated wall centrifuges use wall as filtration medium and liquid materials are forced to leave the rotating cylinder through perforations. These types of centrifuges are used in sugar industries for separation of mother liquors and sugar crystals.

8.4 Filtration

The filtration is carried out to separate solid particles from a liquid or gas by application of force on the mixture to pass through a porous material, which can retain the particles. There are two types of filtration, i.e., (1) surface filtration and (2) depth filtration. The particles are retained on the surface, when fluid is passed through a filter/porous medium under pressure due to the restriction provided by the small opening on the surface. It includes filter paper, muslin cloth, sintered glass, membranes, etc. Whereas in depth filtration, the fluid is passed through a thick layer of fibrous/ particulate material, e.g., glass/rock wool, sand, etc. The solids are retained due to collision with filter/particles of filter medium or by adsorption. This filtration is mainly there in sand bed filters, air filters, oil filters, etc.

The filtration has several applications in food processing industries. The raw juice is treated with pectolytic enzymes that make colloidal particles in suspension to flocculate. These are then filtered in one or different steps. In the case of wine clarification, the suspended colloidal particles in the form of cloud can be flocculated by addition of protein, which combines with tannins from insoluble complex.

The complex precipitates to the bottom and is separated by filtration. The unrefined oil is mixed with bleaching earth for absorption of unwanted pigments, which is separated using filtration. The sugar crystals are recovered from concentrated juice using filtration followed by several filtrations in the refining of sugar. The brines and syrups are used in canned fruits and vegetables, which needs several filtrations using strainers to remove extraneous material. Nowadays, filtration has become essential for treating the drinking water or water as ingredients. The hygienic and safe environment for food processing industries also requires air filters to create aseptic environments especially in packaging section.

The mixture of liquids and suspended solid particles is passed through a filter, wherein solid particles are deposited on the filter, which reduces the effectiveness of filtration. The resistance of flow increases, and for maintaining constant flow, higher pressure is needed to be applied. The rate of filtration can also be defined as

$$\text{Rate of filtration} = \frac{\text{Driving force}}{\text{Resistance to flow}}$$

The gravitational force is also used for filtration and termed as gravity filtration; however, its application in food processing operation is limited due to slower filtration rates. The driving forces are sometimes enhanced by applying pressure on one side and maintaining vacuum on another side to increase the pressure difference. Sometimes food-grade diatomaceous earth can be mixed as filter aids to improve the filter cake formation.

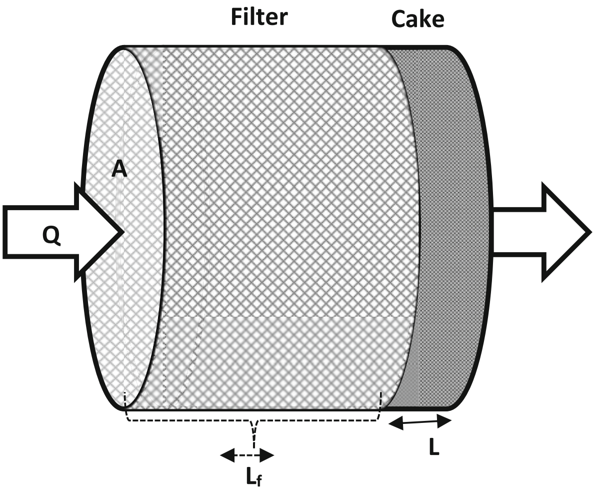
8.4.1 Rate of Filtration

The rate of filtration can be defined as actual filtrate volume received per unit time through the filter. The flow through the filter occurs due to pressure difference between both the faces (Fig. 8.27). The volumetric flow rate Q (m^3/s) for the fluid passing the volume V (m^3) in time t (s) can be given as

$$Q = \frac{dV}{dt}$$

According to Darcy's law, if the flow of liquid passes across the filter area A (m^2), which is normal to flow direction, and through a length of filter L (m), while the pressure drops across the bed length ΔP (Pa), hydraulic conductivity K, length of material to pass through L (m), and resistance offered by porous bed R (per m), and viscosity of fluid μ (Pa s), the volumetric flow rate can also be written as

Fig. 8.27 Flow through the filter and cake



$$Q = \frac{K \times A \times \Delta P}{\mu \times L}$$

Considering resistance offered through medium $R = L/K$

$$Q = \frac{\mathrm{d}V}{\mathrm{d}t} = \frac{A\Delta P}{\mu R}$$

The resistance through the medium depends on the hydraulic conductivity K and length of cake L and can be represented as

$$R_c = L/K = r \times L$$

Considering r is resistance offered by the filter ($r = 1/K$). Similarly, the resistance offered by the filter may be assumed as additional layer of cake with a length L_f and can be represented as

$$R_f = L_f/K = r \times L_f$$

The total resistance in the flow also considers the resistance offered by medium and cake:

$$R = R_c + R_f$$

$$R = r \times L + r \times L_f = r\,(L + L_f)$$

Substituting the value of R, the flow rate becomes

$$Q = \frac{dV}{dt} = \frac{A\Delta P}{\mu r(L + L_f)}$$

The volume of filtrate collected on the filter also adds to the effective length of the filter; considering volume of cake generated per unit volume of filtrate (ν), the effective length of the filter per unit volume can be represented as

$$\text{Volume of cake} = \text{Cross sectional area of cake } (A) \\ \times \text{ Length of cake along the flow } (L)$$

and

$$\text{Volume of cake} = \text{Volume of filterate } (V) \\ \times \text{ Volume of cake deposited per unit volume of filtrate } (\nu)$$

Therefore,

$$\text{Volume of filterate } (V) \times \text{Volume of cake deposited per unit volume of filtrate } (\nu) \\ = \text{Cross sectional area of cake } (A) \times \text{Length of cake along the flow } (L)$$

$$V \times \nu = A \times L$$

$$L = \frac{\nu \times V}{A}$$

Similarly, the length of the filter, while assuming fictitious cake length for resistance offered by the filter, can be represented as

$$L_f = \frac{\nu \times V_f}{A}$$

where V_f = fictitious volume of cake offering resistance.

Substituting the value of L and L_f, the flow rate becomes

$$Q = \frac{dV}{dt} = \frac{A^2\Delta P}{r\mu v(V + V_f)}$$

As per the boundary conditions, the fundamental differential equation of cake filtration has the following solutions [3, 4]:

1. Constant rate filtration: $Q = dV/dt$ is kept constant. Pressure drop is to be increased to overcome the resistance offered by additional cake deposition/buildup.
2. Constant pressure drop filtration: The pressure drop ΔP is kept constant. The rate of filtration $Q = dV/dt$ decreases due to increase in cake resistance.

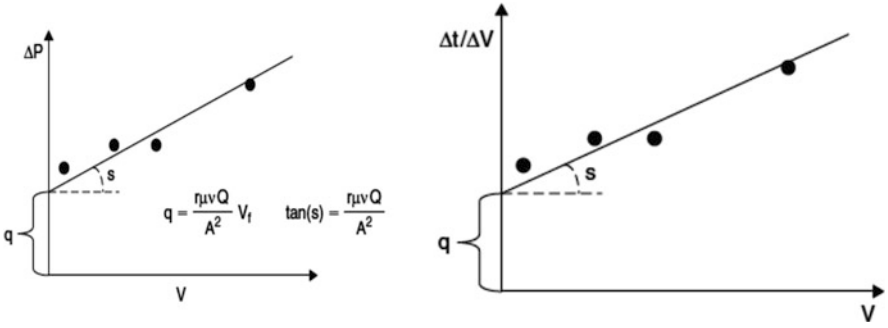


Fig. 8.28 Plots of constant rate and pressure filtration processes

Case 1 The rate of filtration may be assumed as constant. The increase in pressure is needed to nullify the effect of resistance offered by continuous cake buildup. The constant rate filtration has generally met the condition by using a positive displacement pump for feeding at nearly constant rate. The batch system is stopped after reaching at a specified pressure limit and the change in pressure can be represented as

$$\Delta P = \frac{r\mu vQ}{A^2} V + \frac{r\mu vQ}{A^2} V_{\mathrm{f}}$$

Calculation of "*r*" and V_{f}

The values of "*r*" and V_{f} can be obtained by plotting the experimental values of change in pressure with volume and the value of slope (*s*) can be represented as $\frac{r\mu vQ}{A^2}$ and value of intercept on *Y* axis (*q*) can be obtained as $\frac{r\mu vQ}{A^2} V_{\mathrm{f}}$ (Fig. 8.28).

Case 2 The pressure across the filter is constant, which infers decrease in rate of filtration due to increase of resistance by cake buildup; the $Q = \Delta V/\Delta t$ and the time "Δt" can be represented as

$$\Delta t = V\left(\frac{r\,\mu\,v}{A^2\Delta P}\right)\Delta V + \left(\frac{r\,\mu\,v\,V_{\mathrm{f}}}{A^2\Delta P}\right)\Delta V$$

For finding out the values, the equation can be modified as

$$\frac{\Delta t}{\Delta V} = V\left(\frac{r\mu v}{A^2\Delta P}\right) + \left(\frac{r\,\mu\,v}{A^2\Delta P}\right)V_{\mathrm{f}}$$

Ruth's coefficient (*C*) for constant pressure filtration is independent of volume of filtrate at concentration higher than 0.20 g solid/g of slurry [5] and can be represented as

$$C = \frac{2A^2\Delta P}{r\mu v}$$

$$\frac{\Delta t}{\Delta V} = \frac{2V}{C} + \frac{2}{C}V_f$$

Calculation of "r" and V_f

The values of "*r*" and V_f can be obtained by plotting the experimental observation of $\Delta t/\Delta V$ with volume (V), and the value of slope (s) can be represented as $\frac{2}{C}$ and value of intercept on Y axis (q) can be obtained as $\frac{2}{C}V_f$ (Fig. 8.28).

8.4.2 Types of Filters

The following filters are primarily used in food processing industries:

8.4.2.1 Pressure Filters

The pressure is applied to the liquid to pass through the filters. The common filters, which generally have wider applications, are (a) batch-plate-and-frame filter press and (b). shell-and-leaf pressure filter.

Batch-Plate-and-Frame Filter Press

This filter press consists of a paper or cloth as filter, which is supported on vertical plates and fixed in frames (Fig. 8.29). The liquid with suspended insoluble particles is pumped into the press, which allows liquid to pass through the filters and move to the drain provided as an outlet from each plate separately. The pressure is built up to certain prefixed value for flow of liquid. The backwash of the filter is performed with water intermittently, whenever needed. The filter press is dismantled on complete

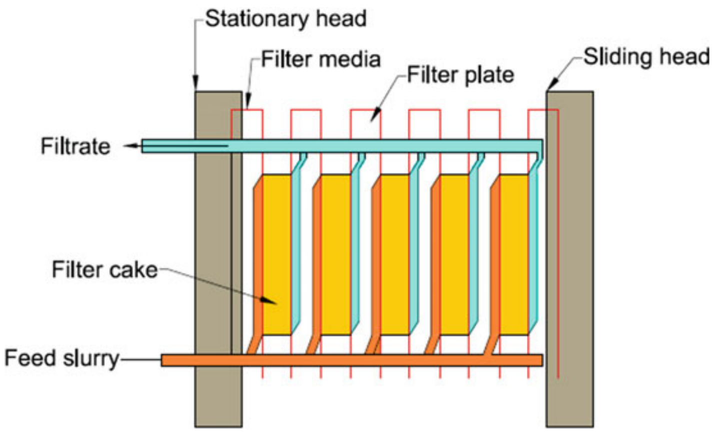


Fig. 8.29 Plate-and-frame filter press

deposition of cake in the space provided, which is removed and thus can be used for the next filtration process.

The cost of filter press is relatively low, and it offers higher flexibility to handle various materials and can be maintained easily. These are used for production of juices and oils. The press requires more labor and time for filtration due to dismantling of plates several times after deposition of cakes on the filter plates. The factors that affect the filtration cycle time are [6]: (1) design factors, (2) chamber thickness, (3) feed pressure, (4) filter cloth design, (5) slurry feed density, (6) composition of slurry, (7) slurry particle size distribution, and (8) dewatering aids.

Problem 8.3 During a filtration process, a plate-and-frame press provided a total of 8 m^3 of filtrate in 1800 s and 11.3 m^3 in 3600 s. Estimate washing period by using 3 m^3 of wash water. Cloth resistance may be neglected, and constant pressure is applied during the complete process.

Solution:

Time taken for constant pressure filtration is

$$t = V^2\left(\frac{r \times \mu \times v}{2 \times A^2 \times \Delta P}\right) + V\left(\frac{r \times \mu \times v \times V_f}{A^2 \Delta P}\right)$$

Since the pressure difference remains constant and negligible cloth resistance is

$$t = \ V^2\left(\frac{r \times \mu \times v}{2 \times A^2 \times (-\Delta P)}\right)$$

For condition 1, $t_1 = 1800$ s and $V_1 = 8$ m^3:

$$1800 = 8^2\left(\frac{r \times \mu \times v}{2 \times A^2 \times (-\Delta P)}\right)$$

For condition 2, $t_2 = 3600$ s and $V_2 = 11$ m^3:

$$3600 = 11^2\left(\frac{r \times \mu \times v}{2 \times A^2 \times (-\Delta P)}\right)$$

Subtracting condition 1 from condition 2,

$$(3600 - 1800) = \frac{r\mu\nu}{2A^2(-\Delta P)}\left(11^2 - 8^2\right)$$

$$\frac{r\mu\nu}{2A^2(-\Delta P)} = 316$$

$$Q = \frac{\mathrm{d}V}{\mathrm{d}t} = \frac{A^2 \Delta P}{r\mu v (V + V_\mathrm{f})}$$

$$Q = \frac{\mathrm{d}V}{\mathrm{d}t} = \frac{A^2 \, (-\Delta P)}{r\mu v V}$$

$$Q = \frac{\mathrm{d}V}{\mathrm{d}t} = \frac{1}{2 \times 316 \times V} = \frac{0.0158}{V}$$

The rate of filtration at $V_2 = 11 \text{ m}^3$.

The final rate of filtration = (0.0158/11) = 1.44×10^{-3} m^{3}s.

The complete washing takes place by penetrating the water of about twice the thickness of cake, and about half of the cross-section area remains available for the flow; therefore, backwash will be applied at a quarter rate of the filtration rate.

$$\text{Rate of washing} = \frac{1.44 \times 10^{-3}}{4} = 3.6 \times 10^{-4} \, \text{m}^3/\text{s}$$

$$\text{Time of washing} = \frac{3}{\left(3.6 \times 10^{-4}\right)} = 8400 \, \text{s} \approx 2.3 \, \text{h}$$

Shell-and-Leaf Pressure Filter

This filter has superiority over plate-and-frame filter press in minimizing the problems of intensive labor requirement and providing convenient operations. This consist of several leaves coated in filter medium and attached on a hollow frame, which act as outlet channel for the filtrate (Fig. 8.30). The arrangement of leaves may be horizontal or vertical. In some cases, leaves may provide rotation of about 1–2 revolutions per minute to have an improvement in the cake buildup. The feed is pumped in the shell at about 0.4 MPa till the completion of filtration and the cake is

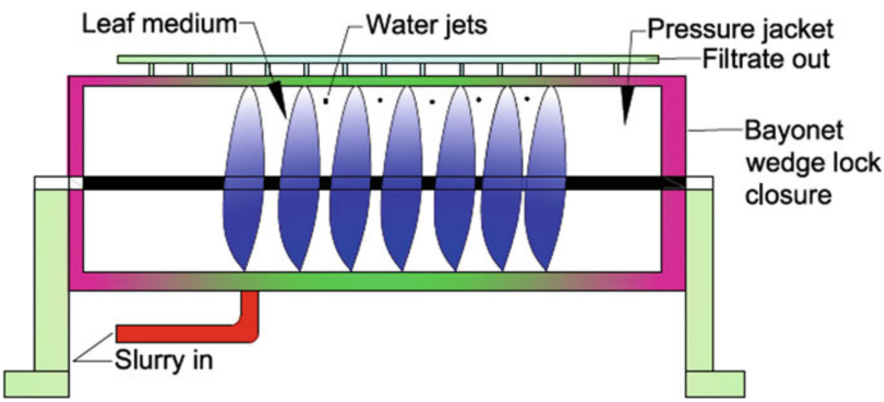


Fig. 8.30 Shell-and-leaf pressure filter

washed from the leaves. The equipment has higher initial cost but remains best suited to routine filtration as compared to filter press.

8.4.2.2 Vacuum Filters

These filters are operated under vacuum for creating a pressure difference of about 0.10 MPa. The filtered cakes are separated at atmospheric pressure, which allows continuous operation of the filter and eliminates the shortcoming of pressure filters. Usually, two vacuum filters are used in food processing industries, namely, (a) rotary drum filter and (b) rotary disc filter.

Rotary Drum Filter

A horizontal rotating drum is fixed on a shaft and the surface is divided into several compartments (Fig. 8.31). Each compartment is covered with a filter cloth and is associated with a centralized vacuum pump. The drum collects the liquor from the reservoir in rotation and filtrate is allowed to pass through the filter and exits from the drum through channels. The cake is deposited on the drum passing through the slurry placed in the sump due to suction created inside the drum. The cake is washed through spray of water while rotating further. Thereafter, the cake is also separated using pressurized air blown for loosening the cake from the screen/cloth prior to scrapping. A scraper is provided to scratch the cake from the drum, which again enters into the reservoir/bath for filtration cycle again. Sometimes, agitator is also provided in the reservoir, which provides mixing of insoluble particles and remains in suspension state in the liquid.

Rotary Disc Filter

These filters have several vertical discs, which rotate gradually in a reservoir/bath containing the liquor like the drum filters. Every disc has several separate portions/

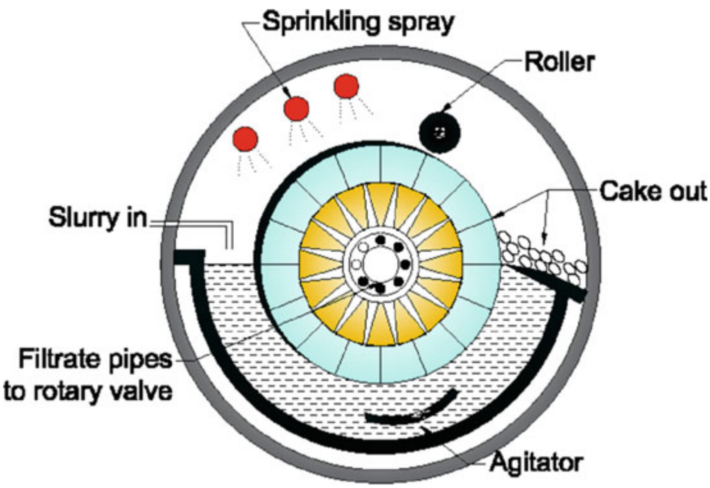


Fig. 8.31 Rotary drum filter

sectors, which are covered with clothes for filtration. The discs are mounted on a central shaft, which connects sectors marked on the discs and create vacuum on the disc surface. The cake is deposited on the discs, which is removed continuously by a scrapper attached. These filters are preferred due to higher capacity of filtration and compact in size and require low labor cost; however, initial capital investment remains a limitation. The cake obtained in these filters has higher moisture, which needs further drying operation.

8.4.2.3 Cartridge Filters

These filters are popular for separating smaller amounts of suspended solids form the liquor using cartridges. These filters are mainly used in the filtration of compressed air, steam filtration, and filtration of clear water to avoid clogging of spray/drip nozzles. A cartridge is made of filtering element, which uses cloth, canvas, paper, mesh, and a series of discs with a tight gap. These are fitted in a container having a provision for flow diversion to and from the filters. The cartridge filter can be easily replaced or disposed.

8.4.2.4 Centrifugal Filters

In centrifugal filters, the flow is induced by centrifugal force. The liquor is fed into the cylindrical bowls rotating at faster speed and has perforated walls to allow filtrate to pass through. The suitable filter is attached to the inner wall of the bowl. The filter cake is formed on the filter surface through which the filtrate has to pass along with the filter and make an exit through the perforation provided on the wall of cylinder. On the basis of working, these can be classified into two types: (a) batch centrifugal filters and (b) continuous filters.

Batch Centrifugal Filters

A vertical shaft is fixed on a frame, which holds the cylindrical metal bowl in suspended form. The slurry is fed into the metal bowl, while the bowl operates at moderate speed (Fig. 8.32). A filtrate starts flowing through the perforated and filter wall of rotating bowl and discharges through the outlet provided in stationary casing. A lining of cake starts to be deposited on the inner side of the wall during the filtration. The speed of bowl is increased to recover the entire amount of filtrate.

Water is sprayed for washing the cake while rotating the bowl at high speed. The speed of the bowl is lowered, and cake is collected through scratching by unloader knife and allowed to pass from the bottom opening. It takes about 330 min to complete one cycle. Automatic version of such batch filters runs around the horizontal axis at a constant speed and completes the operation within 0.5 to 1.5 min. The feed and wash liquid are fed automatically for specific duration, and filtered cake is cut using mechanized/hydraulically controlled knife.

Continuous Centrifugal Filters

These filters have a conical-shaped perforated bowl, which is enclosed in stationary casing and rotates about the vertical axis. The bowl is inclined, which allows the product to move upward to the basket lip and discharges in the casing by vertical

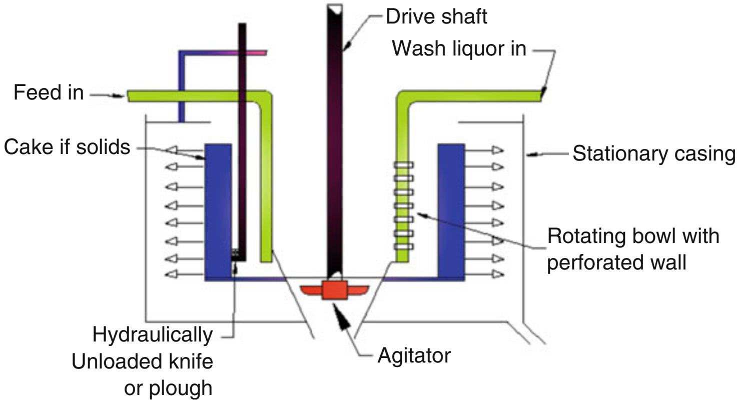


Fig. 8.32 Batch centrifugal filter

component of the force, while horizontal components force liquid to pass through the filter and perforations. These are used for separation of sugar crystal from the mother liquor. The speed of rotation is primarily an important factor for regulating the movement of product as the product may be damaged due to discharge of materials from the lip of the bowl by sliding the product upward at a higher speed of operation. The washing of solid phase is generally avoided during the rotation/motion because it can limit its efficiency.

8.4.2.5 Edge Filters

These filters consist of stacks discs/rings, which act as filters and are attached to a header plate. The discs are fitted one on another using a fluted rod and fastened using boss and a nut (Fig. 8.33).

The clearance is kept as small as 25 to 250 μm between the discs. The filter aid needs to be coated on the edges of the discs. The cake starts to deposit on pre-filter aid locations as soon as the liquor is allowed to flow under pressure, while liquid is allowed to pass through the small clearance and exits through grooves provided on the rod.

Another filter aid may be applied in the feed to increase the effectiveness. The cake is removed soon after the filtration and washing operation by back flushing and removing the cake in the form of sludge through the outlet. This filter does not require filter cloths and requires relatively less labor. Edge filters are applied mainly to remove the fine solids from liquids in smaller quantities.

8.4.2.6 Air Filters

These filters remain very useful for the removal of suspended dust and fine particles. The air is forced to pass through a number of fabric layers, and the dust is removed from the air. A bag air/baghouse filter is prepared using several vertical and cylindrical cloth bags of 15–30 cm diameter, and the air flows through these bags in parallel. The air passes through the cloth and dust remains on the clothes. Air

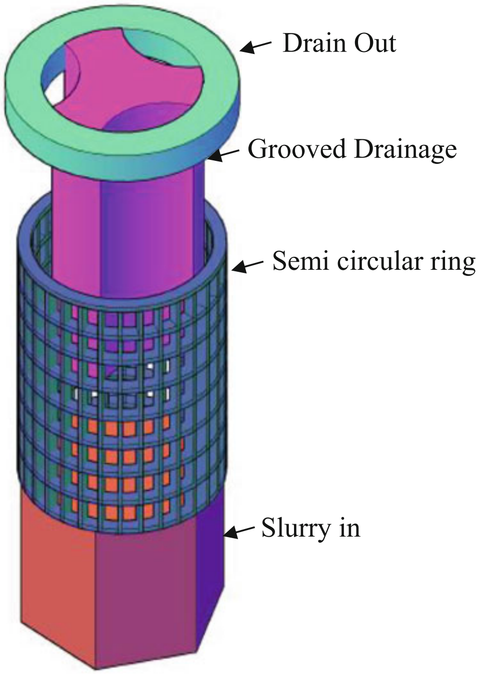


Fig. 8.33 Edge filter

filters are used in flour milling industries and others. Sometimes shaking mechanisms is provided, which removes the accumulated dust in the bags. For removal of particles less than 5 mm diameter, paper or packed tubular filters are also available, which may restrict the flow of spores and bacterial cells too.

8.4.2.7 Membrane Filters

The filtration of liquids according to specific requirements is carried out using a specific filtration technology based on pore size of the filters. Figure 8.34 represents the various components of material, which are removed using different filtration process.

Microfiltration

The microfiltration is used for clarifying the liquids by removal of suspended solids. They are characterized by pore size, ranging from 0.1 μm to 10 μm. The microfiltration restricts the flow of suspended solids, bacteria, fat, and spore through the filter and allows viruses, proteins, macromolecules, monovalent and multivalent salts, acids, caustic, sugars, and water (Fig. 8.34). Microfiltration is used for purification of enzymes, clarification of whole cell broth, dextrose, wine, beer, and fruit juices. These systems are operated at relatively low pressure.

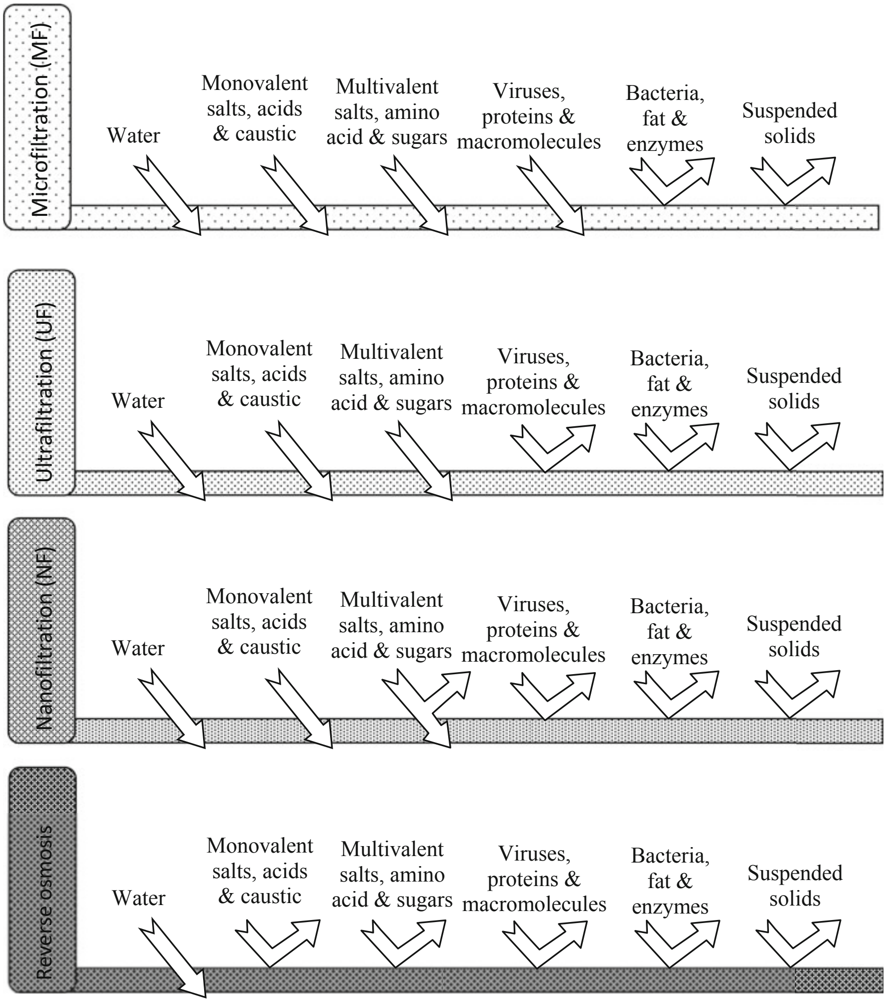


Fig. 8.34 Various filtration processes

Ultrafiltration

It is another hydrostatic pressure–based filtration technique, which forces liquid to pass through a semi-permeable membrane. These are applied for removal of particulate material, organic material, and bacteria and alter the color, taste, and odor of the product. Ultrafiltration works at lower pressure than reverse osmosis (RO) at about 50–1500 kPa.

The feed water flows in the shells or hollow fibers of the membrane, wherein suspended insoluble solids are retained over the membrane and water is allowed to pass through the membrane (Fig. 8.35). The ultrafiltration is allowed to concentrate

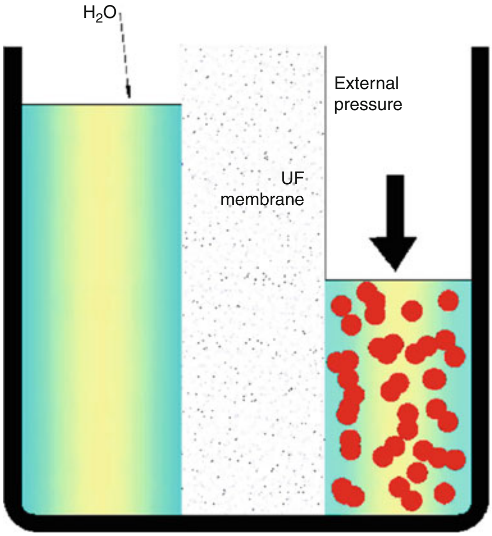


Fig. 8.35 Ultrafiltration process

macromolecular particles, viz., protein, the mass range of 103 to 106 u. The principle of working remains similar to reverse osmosis, but the size of molecules is different.

It has membranes of size varying from 0.005 to 0.1 μm to remove almost all colloidal particles of size 0.001 to 1.0 μm from water. The ultrafiltration membranes are available in the market according to filtration of specific molecular weight cutoff (MWC), which decides the type of solids to be removed from the liquid. The ultrafiltration restricts the flow of suspended solids, bacteria, fat, spore, viruses, proteins, and macromolecules through the filter and allows monovalent and multivalent salts, acids, caustic, sugars, and water (Fig. 8.34). These are used in treatment of drinking water, wastewater, laboratories, solvent exchange of proteins, etc. Ultrafiltration also removes turbidity from water and all colloidal particles, but dissolved solid may pass through the membrane.

Nanofiltration

The nanofiltration uses membranes with pore sizes between 1 and 10 nm, which remains smaller than microfiltration and ultrafiltration. However, its pore size is more than that of reverse osmosis. The factors affecting on pore sizes are time, temperature, and pH. The separation capabilities of this pressure-driven membrane lie in between reverse osmosis and ultrafiltration membranes. Nanofilters can produce water-softening effect by removing hydrated divalent ions Ca^{2+} and Mg^{2+}. It can be used in an industry for concentration and demineralization. The nanofiltration restricts the flow of suspended solids, bacteria, fat, spore, viruses, proteins, macromolecules, and some types of multivalent materials through the filter and allows monovalent salts, acids, caustic, sugars, and water (Fig. 8.34). Nanofiltration is one of the environmentally friendly procedures and can be economically used for concentration, fractionation, and purification in sugar, wine, dairy, and fruit juice industries.

Reverse Osmosis Filtration

Osmosis is a natural phenomenon, which involves diffusion of water across a membrane from a solution of lower concentration to higher concentration. Whereas the process of osmosis is reversed by application of external force for the removal of dissolved solids usually salts from the water (Fig. 8.36). It is used in drinking water solutions and food processing industries for removing the impurities.

The reverse osmosis restricts the flow of almost everything (viz., suspended solids, bacteria, fat, spore, viruses, proteins, macromolecules, monovalent and multivalent salts, acids, caustic, and sugars) except water (Fig. 8.34). The selective separation of reverse osmosis permits water while salts, aroma, and monosaccharide having lower molecular weights are retained through a semi-permeable membrane, which possess higher molecular weights. The dense membrane polymer absorbs water molecule at one side and transports it to another side through diffusion, whereas other solutes remain in the solution due to lower diffusion rate than water. The range of pressure of about 40–80 bars (0.4 to 0.8 MPa) is required to achieve reverse osmosis. RO can be used for concentration and purification of enzymes, juices, etc.

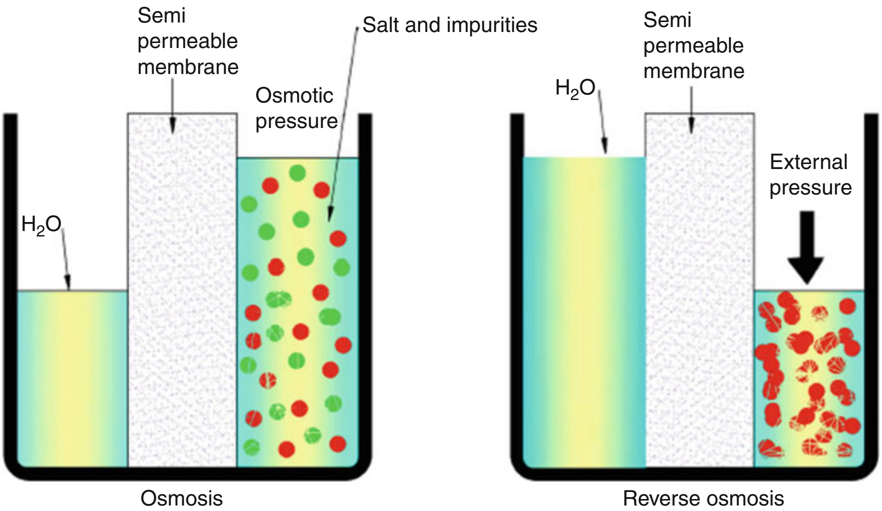


Fig. 8.36 Osmosis and reverse osmosis phenomenon

8.5 Application of Centrifugation/Filtration in Food Processing Industries

Nozzle or self-opening centrifuges can be used for the separation of gums. In neutralization, some pigments, free fatty acids, and phospholipids are treated with alkali to form soap stock, which can be removed by nozzle/self-opening centrifuges. The rotary filters are used for large-scale applications, whereas plate-and-frame filters are used for smaller processes. Rotary or plate filters can be used to clean the bleaching earths, used in decolorizing of edible oils. Filtration also retrieves catalysts involved in hydrogenating fats and oils. Heated filters are applied for recovery of hydrogenated fats due to solidification at normal temperature. The higher melting point fractions after cooling are filtered through plate-and-frame filters.

Nozzle discharge centrifuges are employed to separate rough beer from fermentation vessels and racking reservoirs. The clarification of beer along with mashing the liquid wort may be performed using self-opening centrifuges. The carbon dioxide loss and absorption of oxygen can be restricted using hermetically sealed centrifuges during the processing of beer.

The rotary filters, plate-and-frame press, and shell-and-leaf filter may be employed to recover beer by filtration. The filtration is used at various stages of wine development, e.g., after raking and decolorizing process and before bottling using shell-and-leaf filters, plate-and-frame presses, edge filters, and rotary vacuum drum filters.

The self-opening centrifuges are used to clear juices. Generally, apple juice has cloudy appearance. The apple juice clarification is performed using nozzle, self-operating, and tumbler bowl centrifuges. Hermetically sealed centrifuges avoid undue juice aeration. The oil is also obtained from citrus fruits through centrifugation in two stages. In the first step, the extracted oil is concentrated using nozzle or self-opening centrifuge. The concentrated emulsion can be purified using the second centrifuge to produce the citrus oil.

The clear juice obtained from supernatant is further clarified using rotary vacuum drum filters, plate-and-frame press, or shell-and-leaf filters. The juice recovery from the mud settled at the bottom can be done, using rotary vacuum drum filters or plate-and-frame presses. The fine sugar crystals can be separated using centrifugal filters after attaining the considerable size.

8.6 Exercise

1. State and explain different cleaning and separation equipment for the food processing industry.
2. Derive an expression for effectiveness of screen.
3. Write in detail the different adjustments of indented cylinder separator.
4. State the working principles of specific gravity separator.
5. Define sedimentation and explain different methods of sedimentation for separation.

6. Write in details about mechanical separation devices.
7. Derive an expression for constant rate of filtrations.
8. Draw a neat sketch of plate-and-frame filter press and explain how it works.
9. Write a short note on the following:
   (a) UF (b) RO.
10. Pearl millet was milled in a burr mill. The ground product was later on analyzed in a set of IS screens. The analysis is given in the following table. Calculate the screen effectiveness of (1) IS 50 mesh and (2) IS 30 mesh:

Sr.no.	IS screen	Width of opening, mm	% Materials retained over each screen		
			Feed	Overflow	Underflow
1	100	1.00	0.00	0.00	0.00
2	70	0.708	9.50	12.33	0.00
3	50	0.500	13.52	45.28	2.78
4	40	0.420	26.44	26.26	9.56
5	30	0.296	29.15	10.25	42.14
6	20	0.211	13.88	4.88	26.53
7	15	0.1157	4.51	1.00	11.05
8	Pan	0	3.00	0.00	7.94

[Answer: $E_{50} = 0.7360$ and $E_{30} = 0.6068$]

11. The plate-and-frame presses are used for filtration and provide 10 m^3 and 14 m^3 filtrate in 2000 and 400 s, respectively. The water used for washing is 4.0 m^3; calculate the rate of washing and washing time. The pressure remained constant during the filtration process. The resistance offered by the cloth may be assumed as neglected.
    [Answer: rate of washing = 4.286 × 10–4 and time of washing = 2.59 h].

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Storage

9

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Abstract

In this chapter, the need of storage for perishable, semi-perishable and non-perishable foods is highlighted. The factors affecting the food spoilage are also discussed. The traditional, improved and modern storage structures and economical aspect of storage are discussed. The types of foods according to the shelf life and their specific requirement are also presented. Various destructive agents are also mentioned and factors affecting the food spoilage are discussed. In addition, the mechanism of moisture migration is also explained. Traditional, improved and modern storage structures are presented using line diagrams for easier understanding. The bag storage warehouses are also presented and their stacking arrangement is explained with suitable example. For the storage in bulk, lateral pressure theories are discussed along with step-by-step derivation of Janssen's theorem. The design of silo is also explained with solved examples. Hermetic, modified and controlled storage structures are also discussed. Estimation of refrigeration load is also presented along with economic aspects of storage.

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Keywords

Requirements of storage · Destructive agents · Moisture and temperature changes in stored grains · Causes for spoilage · Traditional storage structures · Improved storage structures · Modern storage structures · Silo design · Bag storage · Controlled atmosphere storage · Cold storage · Calculation of refrigeration requirements · Economic aspects

9.1 Introduction

The shelf life and quality of agricultural produce and value-added products depend mainly upon the raw material quality at harvest. Further, after harvest, several interrelated factors are involved and these form very complex interrelationships during storage. The factors, which influence produce quality during storage, include harvest maturity, variety, application of chemicals, climatic conditions near to the harvesting time, method of harvest, etc. Thus, the agricultural produce has to be stored safely using scientific methods for consistent supply throughout the year.

The farmers store agricultural produce for seed purpose or own consumption, whereas the marketing agencies and traders store the produce for economic gain. Storage by the government agencies provides domestic food security, stabilizes prices in the market, and earns foreign exchange by export. The storage aspect becomes crucial in the present era due to stringent quality standards in national and international markets.

In relation to the shelf life, the foods are grouped as shelf stable (non-perishable) and perishable [1]. Intrinsic properties of foods (pH, structure, texture and water activity) also affect the shelf life. Extrinsic factors, such as gaseous composition, environment temperature and relative humidity (RH), affect the stability of the food products during storage. These environmental factors affect the survival and growth of pathogenic and spoilage organisms in foods. The shelf life depends upon the category of foods, which is given below.

9.1.1 Perishable Foods

Foods, which spoil easily in short duration in the absence of using any special methods to prevent spoilage, are known as perishable. Perishable foods have high water activity and pH. Majority of the fruits and vegetables, high-moisture foods, fish, eggs, poultry meat, meat, milk and milk products are perishable. These foods need proper packaging and storage at low temperature in a specific environment to prevent their spoilage during storage.

9.1.2 Semi-Perishable Foods

The foods that remain acceptable for human consumption for 15–45 days are usually termed as semi-perishable. Their storage life can further increase with proper maintenance of low temperature, requisite RH and treatments. Products of cereal and pulses (flour, semolina, vermicelli and broken wheat), garlic, onions, potato, oranges, apples, oils and fat are the examples of this category.

9.1.3 Non-Perishable Foods

These products are shelf stable and spoilage takes place when handled and stored carelessly. These foods have low pH and low water activity. Most of the low-moisture foods, grains and high sugar/salt products come into this category. Spoilage takes place with increase in moisture, insect attacks and exposure to adverse climatic conditions.

Improper storage results in high quantitative and qualitative losses of agricultural produce. Losses in the storage may be as high as 10–20% of overall production in the absence of proper storage capacities and management. India is losing about Rs. 92,651 crores of agricultural and livestock produce every year during harvest, postharvest operations and storage [2]. Thus, a grain saved with proper storage is a grain produced, which emphasizes the need of proper storage management.

The factors responsible for storage losses include environmental conditions, type of storage structure, storage practices, biotic factors, duration, etc. The environmental factors involve temperature, relative humidity (RH), rainfall, exposure to direct sun, air velocity, etc. Other biotic factors responsible for storage loss are moisture content, insects, mites, spoilage microorganisms and rodents.

9.2 Requirements of Storage

The stored agricultural produce quality depends on several factors; however, the important factors are given as follows [3]:

(a) Initial condition of the material (moisture content, uniformity in size, foreign matter, initial infestation level, surface microflora, damages and injuries, maturity level, etc.)
(b) Environmental conditions inside the store during the storage period (temperature, RH, sanitation, floor and wall conditions, contamination, etc.)
(c) Biotic factors (insects/pest, rodents, microorganisms, respiration rate of stored produce).
(d) Treatments applied on the produce to reduce biotic factors and control physiological changes (aeration, fumigation, controlled environment, ripening agents, coatings, etc.)
(e) Type of packaging used for the storage.

Storage of agricultural produce is done either at normal environmental conditions (cereals, pulses, oilseeds and low-moisture food products) or at low temperature (fruits, vegetables and high-moisture foods). Therefore, the functional requirements for storage structures depend mainly upon the type of material to be stored.

9.2.1 Requirements for Non-Perishable Foods

A quality storage structure along with management practices for grains and other non-perishable foods should provide protection against all possible causes of damages during the storage period. The storage structure should have the following essential features [3]:

(a) Robust to withstand environmental stresses for long time with less maintenance cost.
(b) Prevent entry of rodents, birds and other animals.
(c) Possible to clean and sanitize easily.
(d) Walls, floor and roof must be damp proof and prevent entry of rainwater.
(e) Maintain uniform temperature and relative humidity as far as possible.
(f) Provision for aeration, sampling for observing insect pest incidence, pesticides application and fumigation.
(g) Properly located and connected with roads with sufficient space for entry and exit of trucks. Locations near the kilns, flourmills, garbage dumps, tanneries, slaughterhouses and chemical industries should be avoided.
(h) Facilitate sealing for fumigation with better ventilation arrangement.
(i) Easy in loading and unloading with minimum labour requirement.
(j) Good in-store handling layout and accessibility for inspection of all the stacks.
(k) Easy maintenance.

9.2.2 Requirements for Perishable Foods

For storage of horticultural produce and perishables, in addition to the abovementioned points, the additional requirements of storage are as follows:

(a) Short pre-cooling duration.
(b) Proper circulation of cooled air inside the store.
(c) Precisely controlled environmental conditions.
(d) Bare minimum chances of moisture spots inside the store.
(e) Insulation to reduce the energy requirement.

9.3 Control of Temperature

Temperature is the principal influencing factor for the storage quality of agricultural produce and food products. Change in storage temperature significantly affects the quality of the stored material. Microorganism can grow between −10 °C (cold-hardy mold species) and 60 °C (heat-resistant bacteria). However, the suitable temperature range for insect development is 10–45 °C, and temperatures below 17 °C or above 60 °C reduce insect activity substantially [4]. The mold growth in a stored product is affected only at freezing temperature or below. The rise in temperature increases grain and pest respiration rates as well as enzymatic activity. Therefore, biological activity increases and quality deterioration is rapid at high temperatures.

The rise in temperature of stored product may take place due to several factors, such as environmental conditions, insulation of storage structure, respiration of stored products and insects, molds and microorganisms and oxidation reactions. The rise in temperature due to these factors, except heat gain from the surroundings, is known as self-heating and occurs in two phases. In phase I, biological heating occurs and temperature rises up to 55–75 °C. In phase II, chemical heating occurs and temperature increases to 75–150 °C. Chemical heating also takes place due to oxidation. Chemical reactions may rise the temperature of stored material to the ignition point, which depends on the type of commodity and storage conditions, and fire hazard may occur. This type of fire hazard is known as self-ignition.

Storage temperature change may alter structure of some foods due to the change of physical state of their components. At high temperatures, the fats present in the products may melt. At lower temperatures, sugars present in foods may crystallize and give a gritty texture to the food. Therefore, control of storage temperature precisely is essential for safe storage.

9.4 Control of Relative Humidity (RH)

The relative humidity plays important role in safe storage of any biological materials. In an airtight/sealed storage structure, the RH of the air is liable to increase due to the release of water vapour through biological activities of material and microorganisms. This generates favourable environment for microbial growth and causes spoilage inside the storage. The fruit tissues lose their integrity, which results in the collapse of cellular walls, and tissue browning takes place.

Biological organisms responsible for deterioration of stored products need different RH levels. In general, the optimum level of RH for the growth of bacteria is >90%, spoilage molds grow >70%, storage mites need >60%, and insect need RH of 30–50% [4]. Further, some insects may breed under dry conditions also.

The absorption of moisture from high RH environment by hygroscopic foods may result into undesirable physical changes. Sugar can absorb moisture from the environment at >86% RH leading to formation of sugar solution film around sugar particles. When RH goes <86%, the sugar solution film loses moisture and tiny sugar crystals are formed on the surface of each particle. These tiny crystals bind

Table 9.1 Lower limits of water activity for microorganism growth

Bacteria	Lower limit of a_w	Fungi	Lower limit of a_w
Pseudomonas	0.97	*Mucor*	0.62 (maximum 0.94)
E. coli	0.96	*Botrytis*	0.62
Bacillus subtilis	0.95	*Rhizopus*	0.62
Clostridium botulinum	0.93	*Aspergillus*	0.85
Staphylococcus aureus	0.86	*Penicillium*	0.95
Enterobacter aerogenes	0.94		

together the sugar particles and make the sugar caked in the form of a hard mass. Salts behave in similar way at 75% RH. Saturated common salt solutions are highly corrosive and can damage the walls and floors of the structure. Dehydrated fruit products may also absorb moisture and form sugar crystals, but caking does not occur.

Low RH conditions in fruit and vegetable storage results in physiological loss in weight (PLW), shrinkage and quality deterioration. Thus, apart from optimum temperature, RH of 90–95% is essential for fruits and vegetables except onion, garlic, hard-rind squash and pumpkin where RH should be 60–70% for long-duration storage.

9.4.1 Water Activity (a_w)

The a_w value is generally above 0.90 for most of the fruits and vegetables, which is conducive for the bacterial and fungal growth. Bacteria are more sensitive to a_w, whereas molds can grow at 0.80 a_w also. The lowest a_w for xerophilic fungi, halophilic bacteria and osmophilic yeasts ranges between 0.75 and 0.61. Lower limits of a_w for certain microorganism's growth is given in Table 9.1 [4]:

Moisture content of food and water activity is correlated; however, low moisture does not mean that the food is safe. Protection is required to prevent moisture gain or loss (Table 9.2). Narrowing down the a_w range decreases microbial growth [5].

9.5 Destructive Agents

Stored agricultural produce provides food and environments for many spoilage organisms. These destructive agents include bacteria, mold/fungi, insects/pest, enzymes, mites, rodents and birds.

9.5.1 Molds

Spoilage-causing molds (fungi) are always present in soil and harvesting/handling equipment and within the storage structures in the form of spores and may be with

Table 9.2 Water content and a_w of some foods and required protection

Material	Water content (%)	a_w	Degree of protection required
Ice (0 °C)	100	1.00	Protection in the form of packaging is required to prevent moisture loss during storage
Fresh meat	70	0.98	
Bread	40	0.96	
Marmalade	35	0.86	
Ice (−20 °C)	100	0.82	
Wheat flour	14.5	0.72	Minimum protection in the form of packaging or without packaging
Ice (−50 °C)	100	0.62	
Raisins	27	0.60	
Macaroni	10	0.45	
Cocoa powder	–	0.40	Protection in the form of packaging is required to prevent moisture gain during storage
Boiled sweets	3	0.30	
Biscuits	5	0.20	
Dried milk	3.5	0.11	
Potato crisps	1.5	0.08	

grains. Spoilage fungi require a different temperature and RH level for their growth and development. These affect the grains having moisture content above 14% in general (Table 9.3) [1, 4, 5]. The most favourable temperature for fungus growth is 26–30 °C. Spoilage fungi growth and development during storage affect the food materials, which may change the quality adversely, and aggregation of the material can take place along with production of toxins and allergens and damaging the material due to heat.

Storage fungi invade the germ of the grain mainly for their development (Table 9.3). The fungi kill the germ, discolour the grain and reduce its economic value. The baking and cooking characteristics of grains are degraded. The fungi cause chemical changes, such as hydrolysis of triglycerides, which results in free fatty acids formation. These are also responsible for health risk since many fungi are potent producers of mycotoxins.

9.5.2 Bacteria

The bacteria are not major destructive agents in the storage of food grains because these require high RH (90–95%) for their growth. However, at high-moisture content, growth of bacteria may cause self-heating and produce sour and rotten

Table 9.3 Minimum grain moisture content for possible fungal growth

Fungus	Commodity	Minimum moisture for growth at 20 °C	Type of damage
Aspergillus restrictus	Wheat, corn Sorghum Soybean	13.5% 14% 12%	Kills and discolours germs or damages germs
Aspergillus glaucus	Wheat, corn Sorghum Soybean	14% 14.5% 12.5%	Kills and discolours germs or damages germs, develops mustiness and caking takes place
Aspergillus candidus	Wheat, corn Sorghum Soybean	15% 16% 14.5%	Kills and discolours germs very fast, heats the grains up to 55 °C, discolours the entire kernel, spoilage follows immediately
Aspergillus flavus	Wheat, corn Sorghum Soybean	18% 19% 17%	Kills and discolours germs very fast, heats the grains up to 55 °C, discolours the entire kernel, spoilage follows immediately, produces carcinogenic toxins
Aspergillus ochraceus	Wheat, corn Sorghum Soybean	15% 16% 14.5%	Kills and discolours germs, produces carcinogenic toxins
Penicillium	Wheat, corn Sorghum Soybean	16.5% 17% 16%	Kills and discolours germs and the whole kernel, highly toxic to animals, particularly poultry

odours in the grains. The bacterial activity is not much at low temperatures during the storage.

9.5.3 Insects

Insect infestation is the main criteria for quality assessment in grains, and these are the primary agents for quality deterioration during grain storage. The insects consume dry matter, contaminate the grain lot, broadcast microflora and create conducive environment for spoilage molds. There are more than 100 insect species, which infest stored grains. Most of the insects are beetles, some are moths, and the rest are primitive insects like lice.

Weevils are the main pests of grains in the world. Granary weevil (*Sitophilus granarius*) is an insect of temperate regions; maize weevil (*S. zeamais*) attacks in warm and humid regions where maize is grown; and rice weevil (*S. oryzae*) infests mainly in the tropical climatic conditions. Grain borers (*Prostephanus truncatus*) cause more loss because they make a hole in the grains. *Rhyzopertha dominica* is a serious storage insect of wheat and paddy, particularly in the warm and arid regions.

Khapra beetle (*Trogoderma granarium*) is the most dreaded pest because its larvae hide in the cracks and crevices of stores and survive in adverse conditions. *Khapra* beetle has become tolerant to majority of the pesticides. However, flour beetles are secondary pests and mainly found in grain storage structures [3].

Metabolic activities of insects in grain bulks of <15% moisture may result in heating of grains up to 42 °C. Some of the insects found in stored products may even survive low temperatures (e.g. rusty grain beetle [*Tribolium castaneum*] can tolerate −5 to −10 °C for long durations) but cannot reproduce <17 °C. These cause extensive damage when grain temperatures are >17 °C for long periods. The insect damage becomes serious when moisture content of grains is high [6].

9.5.4 Mites

Mites are delicate creatures and are of <1 mm in size. About 54 species are found in stored grains and flour. The mites withstand low temperatures and grow rapidly in damp and moldy grains. These give a strong minty odour to the grain and makes the grain unpalatable. Mites attack usually on the broken, weed seeds and fungi and survive in moist grain. These may be either saprophytic or parasitic.

9.5.5 Rodents

Rats are the biggest and infamous vertebrates and responsible for direct and indirect losses in storage of food grains. Rodents can cause 1% dry matter loss of grains from the direct consumption, whereas spillage loss may exceed 10%. These contaminate grains by urine (40–50 mL urine daily), faecal pellets (70–80 faecal pellets daily), saliva, hair (hundreds of hairs daily) and body fragments, which is a major issue in storage. Rodents are carrier of insects, mites and microflora and responsible for cross-contamination of grain stocks. Besides grains, rodents can damage structure and essential supply lines. An adult rat eats about 3 g grains daily and discards partly eaten grain. In bag storage system, the stacks may collapse when a severe attack of rats takes place. Rats are adaptable to all environmental conditions and have a high fertility rate.

9.5.6 Birds

Activity of birds starts immediately after harvesting of crops and continues in storage also particularly in the warehouses where bag storage is practiced. The birds also bring grain insects and microflora to the stores. Major birds causing damage are pigeons and sparrow, sometimes parrots, doves and weavers. Pigeons usually fly in flocks and can travel up to 8 km in search of food and usually feed on the spillage. Sparrows are smaller birds and fly in flocks by travelling up to 2–3 km in search of feed.

9.5.7 Factors Affecting Food Spoilage

9.5.7.1 Respiration of Grains

Water availability, environmental conditions, microbial contamination, mechanical damage, condition of storage and infestation level govern the respiration rate of grains. Mature and dry seeds remain dormant with a very low respiration rate. Grain respiration increases with increase in moisture content. This increase is gradual until critical moisture content reaches. Respiration then increases faster, and then the rate of dissipation of heat generated by the respiration and heating of grains take place. Every 1% dry matter loss in 1 tonne grain can produce 37.6 kcal energy and increase the temperature to 65 °C, when the heat is not transmitted [7].

9.5.7.2 Enzymes

The enzymatic activity of freshly harvested seeds having higher-moisture contents is usually high and may increase respiration rates and heat production. Green weed seeds and foreign matter present with grains encourage enzymatic activity also. Some of the enzymatic processes are required to a certain extent (e.g. ripening of fruits and vegetables) after harvest. The natural enzymes present in overripe fruits cause deterioration during storage.

9.5.7.3 Air and Light

Exposure of foods with air may reduce certain vitamins (particularly A and C), affect colour and flavour and promote microbial growth. That is why flushing of food containers with inert gases, such as N_2 or CO_2, is done to prevent deterioration in some foods. Light-sensitive vitamins, such as riboflavin, vitamin A and C, and food colours deteriorate due to exposure to light. Therefore, light-sensitive foods are often packed into dark-coloured glass bottles.

9.5.7.4 Storage Period

The food material quality is at its peak at the time of harvest. The effect of quality-deteriorating factors, such as microorganisms, insects, enzymes, heat, cold, oxygen, light and moisture, increases with storage time. Though the quality of some foods improves with time (e.g. cheeses, pickles, wines), but the quality of majority of foods decreases with time.

9.6 Moisture and Temperature Changes in Stored Grains

Moisture and stored grain temperature interact and even best management practices cannot prevent spoilage if these parameters are too high. The grain stored at 24 °C at 25% moisture content will deteriorate in 4 days, whereas the same grain stored at 15 °C and 15% moisture content will deteriorate after 250 days of storage. Every 10 °C temperature rise increases the activity of microorganisms and enzymes by at least twice in 0–60 °C temperature range [4, 6]. For temperature above 60 °C,

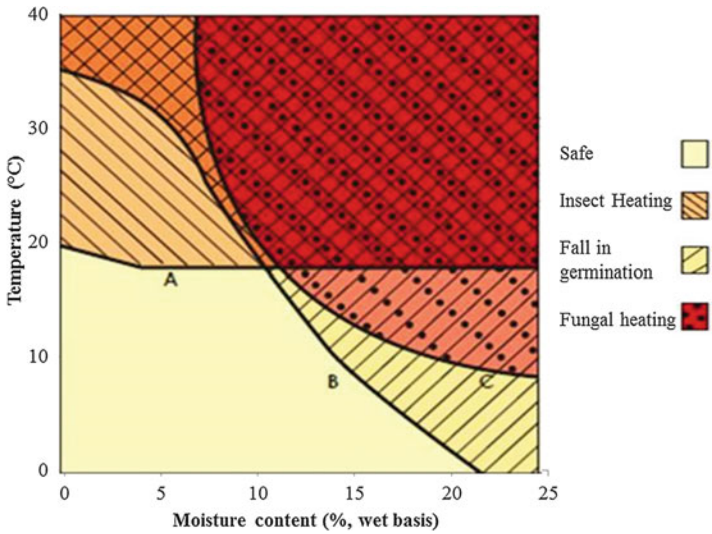


Fig. 9.1 Storage stability of grains at various storage conditions

enzymes may inactivate function of living cells. The influence of grain moisture content and its temperature on storage ability of food grains is shown in Fig. 9.1.

For higher storage temperatures, the grain moisture content must be lower; however, at low storage temperatures, the moisture content may be higher for safe storage. Further, even at 16% grain moisture content, safe storage is possible at temperature of 4 °C or less. When grain is stored at 15 °C or more, cooling of grain is necessary through aeration with adoption of occasional curative measures [3]. For absolutely fungus-free grains, moisture content of 12% or less and temperature below 3 °C are essential. Since the storage of grains is usually done at higher moisture and temperature levels, particularly in tropical regions, good store hygiene and regular disinfestation measures are necessary.

High-moisture grains are at higher risk of damage during storage as it allows molds to develop. A higher grain moisture results in evaporation of moisture into the natural air, which is carried to the other parts in a silo. Natural convection exists in the dry grain though moisture accumulation at the top surface takes longer duration to reach at the spoilage level. In sealed bins, mixing of air in the headspace with external air cannot take place, which allows moisture migration and accumulation to progress. Condensation of moisture in the headspace of the bins filled with freshly harvested grains can result in damage due to moisture accumulation at the top surface. Whenever the bin surface is cooled due to daily changes in environmental temperature, condensation occurs at the top surface. This is termed as 'night top silo cooling' or 'silo sweating'.

The temperature gradient in stored grain is the main cause of moisture movement. Heat loss occurs at the surface in the colder months at a faster rate than that of the inner core of bulk. This creates temperature gradients when the grain bulk is not

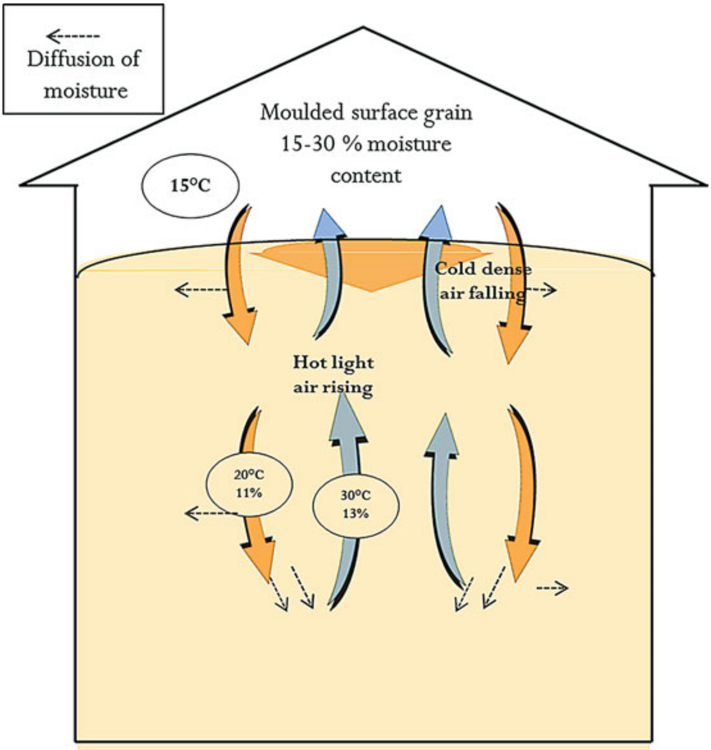


Fig. 9.2 Formation of natural convection currents and moisture accumulation in a silo during cold environmental conditions

disturbed and aerated. In the absence of aeration, cold air moves downward naturally and displaces less dense warmer air. When the grains near to the silo wall cool off, it replaces warmer air in the centre of the bulk leading to the air current formation. This current circulates in a loop from the outer regions up through the warmer inner core (Fig. 9.2) [8].

The cold air gains heat gradually as it moves up through the central core and gains moisture from the grain. The warm, moist air moving upward from the centre of the grain bulk starts to cool when it reaches near the grain surface at the top. Then the capacity of air to hold moisture reduces and moisture condensation at the top grain surface initiates and the cycle continues. This results into moisture migration from the bottom to the top of the bulk. Grain spoilage may take place due to the moisture accumulation at the top surface. In such case, more spoilage can take place when convection currents are established and the grain is not disturbed for long periods.

In hot conditions, the convection current formation is opposite to the cooler conditions and moisture accumulation takes place at the bottom of the bulk.

The presence of peak or ridge (heap formed at the top of grain bulk) influences the air current, which act as a conduit to channelize hot moist air effectively, and

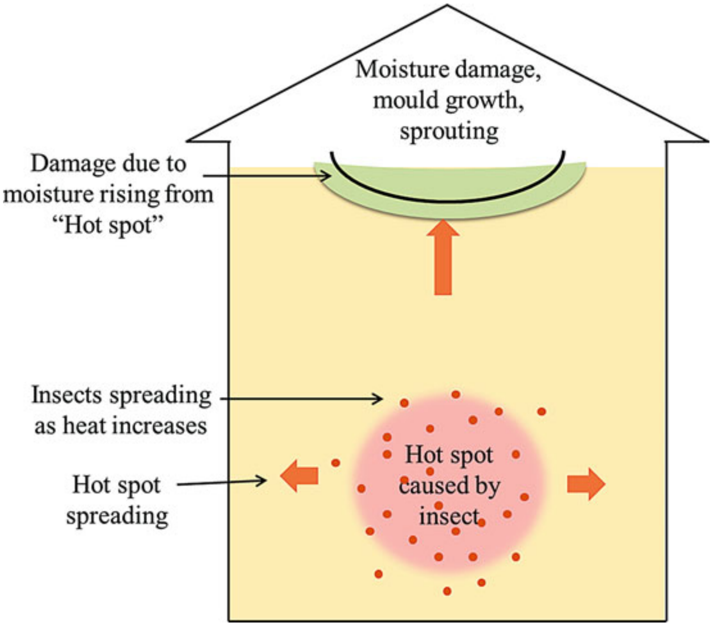


Fig. 9.3 Moisture damage due to mold and insect growth in a grain silo

moisture accumulates in the ridge area. Further, grain bulk density also influences the natural convection current formation rate. Natural convection currents form at faster rates in low-bulk-density clean grains stored in sealed bins. Significant damage due to moisture accumulation takes place when large-seeded pulses are stored in sealed silos.

Moisture migration takes place between the grains by diffusion due to moisture and temperature differences and reaches to the equilibrium gradually in a storage bin. Grain moisture equilibration is beneficial for some seeds, particularly pulses where uniform moisture is an important parameter in processing. Aeration helps in equilibration of grain moisture and disrupts the already formed natural convection currents in the bulk.

In the growth stage, insects also produce heat and moisture. Infestation usually starts below the surface of grain bulk and heat generated by them form a 'hot spot' (Fig. 9.3) [8]. Such localized increase in temperature and moisture creates conducive environment for fast insect and mold growth and raises grain temperatures above 40 °C. Thereafter, insects migrate from the core of the hot spot. The hot, moist air of the hot spot moves towards the top surface and moisture condenses on the cooler grain.

The main cause of damage and spoilage of food grains are summarized in Table 9.4.

Table 9.4 Spoilage agents and cause of damages

Parameters and spoilage agents	Possible damage and spoilage
Storage practices	
Common structural issues like water entry, pest entry, harbour pests	Localized moisture gain, grain heating, risk of contamination, insect and mold growth
Presence of dirt and debris in the food material	Shelter for pests, contaminate incoming stocks, difficulty in proper inspection for pest detection, and obstruction in effective pest control
Presence of infestation in the store prior to storage	It is the main threat to the stored commodity and pest infestation takes place
Improper cleaning and disinfection of stores	Risk of disease transmission to the stored grain
Moisture	
Higher initial moisture content of grain being stored	Chances of spoilage in cereals and oilseeds until dried to safe limits of 14.5% and 7.5% moisture contents, respectively
Change in grain moisture during storage	Grain moisture is associated with RH of the surrounding air. Spoilage due to insect and mold growth is possible
Improper calibration of moisture-measuring instruments	Poor calibration results in wrong information about moisture and therefore may cause spoilage
Control of moisture content	Surface layer moisture can increase or decrease due to environmental conditions and is difficult to control. Moisture above 18% encourages mites' growth
Moisture and market demands	Each food industry has specific demand, for example, wheat industry may accept wheat up to 15% moisture and malt industry asks 13% with a minimum germination of 98%
Drying	
Drying temperature	Drying at high temperature reduces time and increases capacity but damages quality of grains, especially protein and germination
Safety factors for dryers	Deposition of unclean material inside the dryer may cause a hazard. Dust from grain and noise from machines may cause health hazards
Improper cooling after drying	Storage of grains immediately after drying results in insect breeding
Moisture content prior to drying	If grain moisture exceeds dryer limits, spoilage may occur before all material dries uniformly. The capacity of high-quality dryer is reduced by 15% for each 1% moisture increase above 20%
Temperature	
Storage temperature	Most of the insects die within a day at temperature > 40 °C. Favourable temperature for rapid multiplication of most of the insects is 25–33 °C, whereas these do not breed below 15 °C. however, grain weevils (*S. granarius*) may breed at a slow rate even at 12 °C

(continued)

Table 9.4 (continued)

Parameters and spoilage agents	Possible damage and spoilage
Grain heating due to biotic and abiotic factors	Change in environmental temperature may cause moisture accumulation at the top or bottom of a bin. High-moisture surfaces or damp pockets encourage mold growth, heating of grains and sprouting Insect infestation also generates heat and causes spoilage
Improper airflow during aeration	Airflow of less than 10 m^3/h/ton can cause improper cooling during aeration. Insect breeding rate may increase and spoilage is possible
Insects	
Presence of field insects	Field insects like clover weevil can be present in a freshly harvested grain, cause very low damage and die quickly. Incorrect identification may cause spoilage
Presence of primary storage pests (beetles and moths)	Primary insects intrude the grains from the previous stored grains and can breed at low moisture and temperature conditions and damage takes place Some species like the grain weevil develops inside the grain and is difficult to detect at an early stage
Attack of secondary storage insects	These include fungus feeders, spider beetles and booklice, which may enter in the bulk from nearby sources. These insects damage poorly managed or already infested grain only
Development of resistance in pests against pesticides	Resistance to pesticides can develop in some insects, for example, saw-toothed grain beetle, and control is difficult. Resistance development reduces the effective life of treatments or requires more exposure time to control the insects
Mites	
Identification and prevention problems	Mites cannot be distinguished from dust by the naked eye. It directly damages the grain by eating the germ or making a hole in oilseeds. Practically exclusion of mites is not possible from stores
Presence of surface moisture	Mites build up at the moist surfaces. Storage at $<13\%$ moisture minimizes the risk of mites
Control method of mites	A single control option is not sufficient. Combined conveying and cleaning kill 75–90% mites. However, the mites present inside the grain germ survive and grow again quickly; therefore, it is considered as a temporary measure
Fungi	
Detection at the time and level of mycotoxin produced	A visible moldy grain suggests that mycotoxin production may have started. The absence of visible mold growth is not a sign of freedom from mycotoxins
Effect of physical treatment	Cooling grains is not sufficient for longer-duration storage of damp grain. Storage fungi cannot grow if moisture is less than 14.5%
Chemical treatments (only for animal feed)	Sodium hydroxide–treated grains swell during storage and silo storage is not practical. This treatment is not

(continued)

Table 9.4 (continued)

Parameters and spoilage agents	Possible damage and spoilage
	for long-duration storage Propionic acid–treated damp grains can be stored for short-duration storage
Mycotoxin production	Mycotoxins produced by the fungi before harvest are stable and remain with grains during storage. Fungal growth produces mycotoxins when grain moisture is >15% The risk of fungal growth is higher when dried by spreading on the floor (near-ambient drying). Suitable temperature for mycotoxin production varies between 15 and 25 °C
Rodents and birds	
Rats and mouse	A young rodent can enter in the stores from a gap of only 5 mm, damages structures and contaminates food The loss is more in the form of spillage and contamination
Birds	Attack of birds causes direct losses. Birds are attracted to food like spilled grain
Other issues for oilseeds	
Drying to a very low moisture at a faster rate	Hard and brittle grains are formed. This may cause quality deterioration
Slow rate of drying or cooling	This can encourage mold and mites' growth, and mycotoxin production may take place
Non-availability of insecticide	Merchant grain beetle (*Oryzaephilus mercator*) and saw-toothed grain beetle (*O. surinamensis*) may grow to some extent in stored grains. No insecticides are available to control such mixed insect population
Presence of immature seed in storage	It causes heating and rapid deterioration of mature seeds

9.7 Traditional Storage Structures

Indian farmers store food grains for their own consumption, seed purpose and for sale in market during off-season. The farmers in India normally store 65% of their produce in the traditional storage methods at the farm level. The important traditional storage structures are given as follows [8]:

9.7.1 Folding *Kothi*

These structures look like carpets weaved using thin bamboo strips only. It resembles with the woven carpet of thin bamboo strips. Two bamboos are weaved at the ends of carpets and fixed to make a cylindrical bin for storing grains. These structures are about 6 ft. in height and can store about 200–250 kg of grains. These structures do not have fixed lid and base. A base is made on the ground using a fine mixture of soil and cow dung. The structure is placed on this base in such a way that it forms a cylindrical-shaped storage structure. A mixture of cow dung, loam and husk is applied on the top after laying the leaves on the top of grains.

9.7.2 Underground Storage Structure

This type of storage structure is locally known as *Khatti* in northern India, *Khani* in Orissa, *Pain* in Maharashtra, *Patera* in Tamil Nadu and *Khas* in Rajasthan. It is made at places where groundwater level is low and used as indoor and outdoor structures. The depth and diameter of the structure may be up to 5 m with a narrow circular opening at the top. About 24–32 tonnes grain can be stored and suitable for the storage of wheat, maize and pulses. Before storing grains, a layer of straw is placed on all inner walls and the opening is sealed with a lid made of mud to prevent the seepage of moisture (Fig. 9.4).

9.7.3 Earthen Pot Storage Structure

It is a small capacity (100–200 kg) storage structure locally known as *Chod*, *Jadi*, *Kudir*, *Vadai* and *Matka* and made of clay mud. The structure is cylindrical, but the diameter at the middle is more than that at the top and the bottom. There is only one opening on the top of the structure to store and take out the grain. An outlet is sometimes provided near the bottom. After storing grains, the top is sealed with a lid made of moist clay. The life span of the structure is generally 10–15 years.

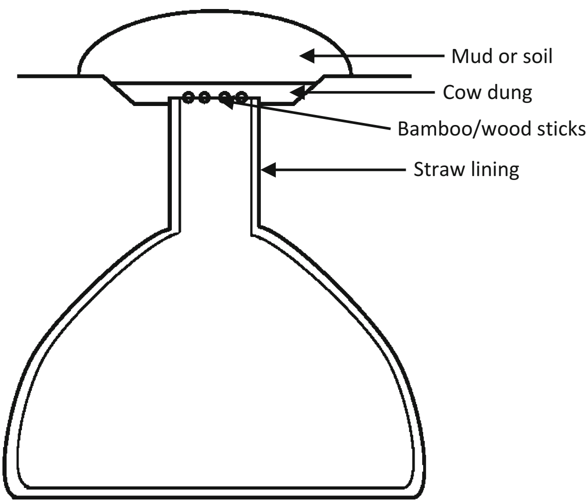


Fig. 9.4 Underground pit type of storage structure

9.7.4 Drum Storage Structure

These are empty drums fabricated for keeping oil and coal tar or similar material, which are used for grain storage after thorough cleaning in a small quantity (100–200 kg) in case of reuse of drums. The structure is low cost and durable. There is only one opening on the top to store and take out grains for use. After storing grains, the opening is sealed with a lid made of mud with moist clay, wood or mild steel.

9.7.5 Straw Storage Structures

These are mostly used in outdoor and in some areas indoor structures locally known as *Morai*, *Puri*, *Mora*, *Oliya*, *Burgi*, *Seru* and *Kotta*. Paddy straw ropes are the construction material, and sometimes, mud plastering is done at the bottom portion of the structures. It is a common structure of Assam, West Bengal, Orissa, Tamil Nadu and Karnataka. The capacity of the structures varies from 3 to 20 tonnes and has a life span of about 1–2 years. The structure is not airtight and rainwater may enter in some occasions. Insects and rodents cause sizeable loss to the stored grains.

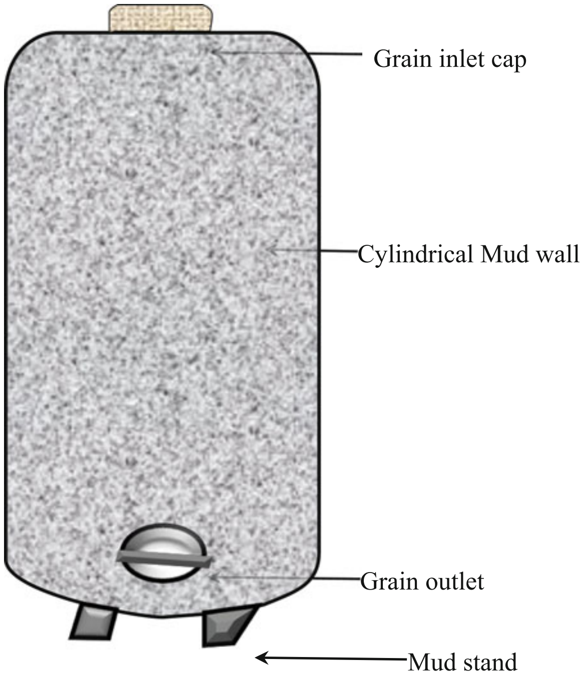
9.7.6 Mud Storage Structures (*Kuthla*)

These structures are made from mud mixed with straw or dry grass with 25–80 mm thick wall and are oval, rectangular or circular in shape and locally known as *Kuthla* or *Kucchi kothi* with a capacity of 100–2000 kg (Fig. 9.5). A circular opening near the bottom is made to take out the grains. A bigger diameter hole at the top is for loading the grains, and then the top opening is sealed with a lid made of mud and straw.

9.7.7 Bamboo or Reed Storage Structure

Local names of such structures are *Borem*, *Gummy*, *Kudir*, *Bakhari*, *Ponaka*, *Gola*, *Thombe*, *Gade* and *Buttas*. It has a cylindrical or rectangular shape made from split bamboo strips or reeds. The wall has only one opening for loading and unloading the grains. The wall and floor of the structure are made of woven bamboo splits or reeds with mud plaster on the inner wall and floor in some regions. A thatched roof is provided on the bin and the capacity varies between 1 and 50 tonnes with a life span of about 10 years. Although the structure is not waterproof, yet fumigation is effective as the structure is airtight. However, the seed storage structure is liable to damage by the rodents and the grains are consequently affected.

Fig. 9.5 Mud bin



9.7.8 Basket-Type Storage Structure

This is a semi-spherical structure of basket shape and widely used in Assam, India. The structure is unsafe to insect and rodent attack and it is not a waterproof structure. The inner surface of the basket is mud plastered and dried before paddy is stored. The capacity of structure depends upon the number of family members because storage is done for their own consumption only. The structure is kept on the raised platform with a suitable cover.

9.7.9 Ground Bag Storage Structure (*Thekka*)

In semi-arid areas, an area is covered by bamboo sticks in which gunny bags or jute cloth bags filled with grain are stored. The top is covered with a thatched roof. This structure is locally known as *Thekka*. The capacity of such structure ranges from 100 to 800 kg.

9.7.10 Box-Like Timber Storage Structure (*Kothar*)

It is very common in the northern regions especially in hilly areas. The floor is made of timber planks and has a timber ceiling with a roof of plank or corrugated

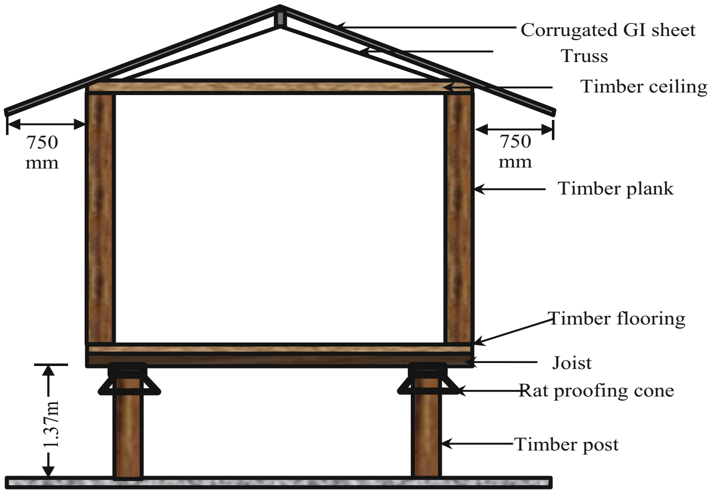


Fig. 9.6 *Kothar* for grain storage

galvanized steel (Fig. 9.6). The construction is done separately and placed over a platform.

9.7.11 Wooden Storage Structures (*Kothi*)

These are mostly wood planks–based indoor storage structures locally known as *Pathayam* and *Kothi*. The structure is normally of rectangular type and consists of various trays, which are placed one over the top of the other. The capacity of the structure ranges between 5 and 10 tonnes with a life span of about 20 years, if maintained properly.

9.7.12 Masonry Storage Structures (*Bakhari*)

These storage structures are locally known as *Kotha*, *Puccikothi*, *Addaw*, *Kalangium*, *Kanaja*, *Amberkani*, *Vaderu*, *Kothi*, *Kainra* and *Bakhari*. Brick is the main construction material, but in some places, wood or bamboo is also used (Fig. 9.7). In brick construction, different materials such as mud, lime or cement are used. The structure is generally circular or rectangular and constructed as a part of the house for use as a living room as well as for storage. The capacity of the bin varies between 8 and 30 tonnes and has a life span of over 20 years. Sometimes, the structure is divided into a number of columns in order to store different grains.

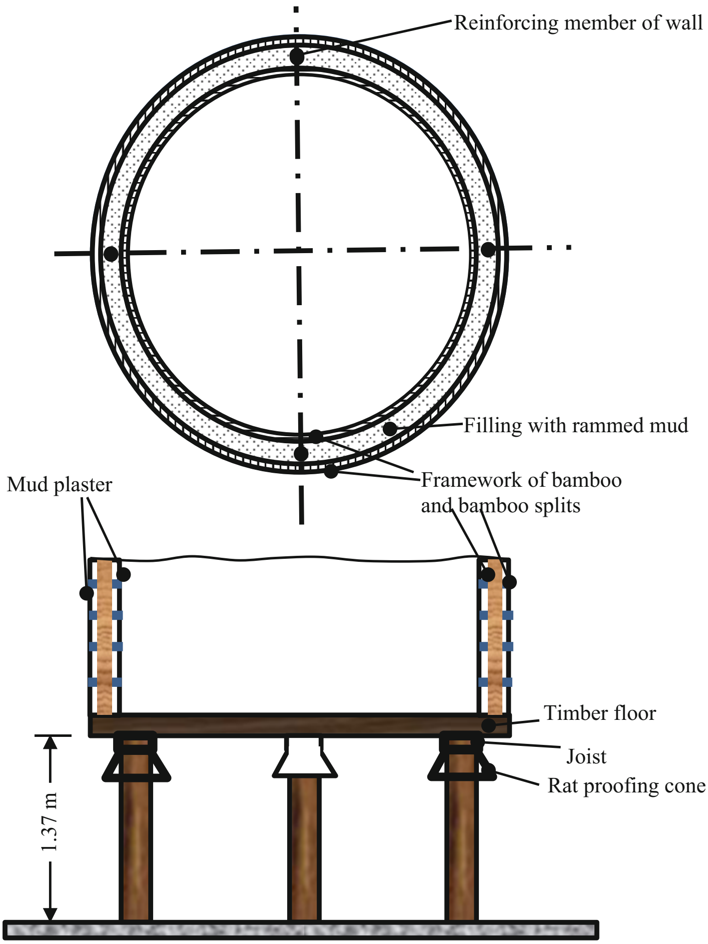


Fig. 9.7 *Bakhari* storage structure

9.8 Improved Storage Structures

9.8.1 Double-Walled Polyethylene-Lined Bamboo Bin

This type of structure is an improved version of bamboo structure in which the bamboo walls are plastered with mud from both sides and fitted with a lid. Such bins are prone to the attack of insect pests. Plastic lining of the walls makes this structure very effective against insect attacks. The structure is placed on a metal tripod having rat barriers. A metal cone fitted at the bottom acts as outlet, which makes unloading of grains easy. The cone always keeps the opening airtight due to constant grain pressure head. Sometimes two rings are placed for easy handling with a capacity of about 125 kg.

9.8.2 Pusa bin

LDPE sand-witched mud bins, also known as Pusa bin, are suitable for short-term storage of food grains and sometimes fruits and vegetables (Fig. 9.8). It is rectangular and depth is usually 1 m. The structure depicts the features of metal or concrete structures due to the similar insulation properties. This bin is made in capacity range of 0.5–4 tonnes.

9.8.3 Welded Wire Mesh Bin

This bin has a capacity of about 3 tonnes for the storage of maize without affecting their quality at the farmers' level. The bin is fabricated using wire mesh hessian cloth lining inside so that the air may circulate freely through it. The structure is mounted on prefabricated steel elevated base to prevent the entry of rodents.

9.8.4 Domestic Cloth Structure

This structure is made of a cylindrical polyester cloth supported by bamboo poles on a metal tub base. The cloth is relatively airtight and impervious to insects and moisture. The metal base is impervious to rodents. Grains discharge from a small opening made near the bottom.

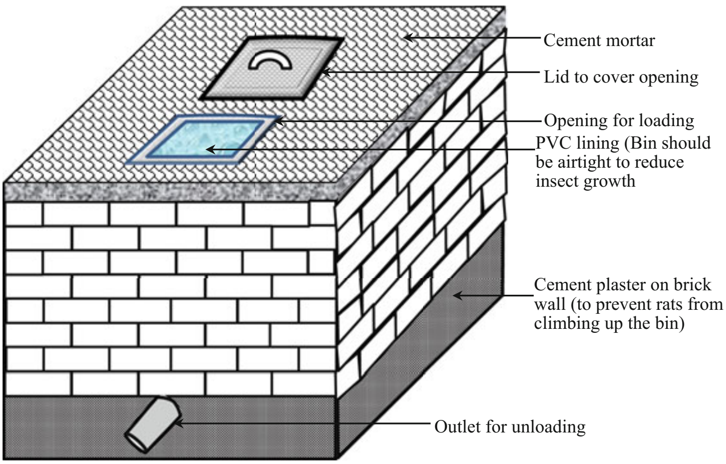


Fig. 9.8 Pusa bin

9.8.5 Masonry Storage Structure

The masonry structure is constructed using brick plastered with cement mortar. The bin is normally constructed in two compartments with a capacity of about 1 tonne each, but it can be extended to have more compartments.

9.8.6 Reinforced Cement Concrete Ring Bin

This design consists of prefabricated reinforced cement concrete rings placed one over the other with gripping joints at the edge. The structure can be created with or without masonry base. The capacity of the bin may be increased by increasing the number of intermediate rings. The bin also suits as an indoor structure with adequate moisture proofing.

9.8.7 Paddy Straw Mud Structure

This structure is an improved version of the straw structure. The paddy straw rope structure is plastered on both sides with specially prepared mud. The structure has a separate inlet and outlet and is constructed on a raised brick masonry platform to prevent the entry of rodents.

9.9 Modern Storage Structures

9.9.1 Flat and Hopper Bottom Metal Bin

This bin is very common and made by either galvanized iron sheets or aluminium sheets in 1.5–2 tonnes capacities. It can also be constructed on brick masonry, brick masonry columns or prefabricated steel elevated base (Fig. 9.9). Adequate facilities are provided for loading grains manually through a simple lifting device. The structure is suitable for storage of wheat, paddy and maize in different climatic conditions. Moreover, aluminium being rust proof, the periodical maintenance of the storage structure is not necessary. Its reflecting surface has an additional advantage in keeping grains cool by radiating heat quickly.

9.9.2 Hermetically Sealed Underground Structure

In this type of storage structure, molds do not develop on damp grains and insects die due to the development of low oxygen concentration. The structure is hermetically sealed. It is made with welded steel structure in 1.4 tonnes capacity and reinforced cement concrete structure in 3 to 4 tonnes capacity. The construction is similar to that

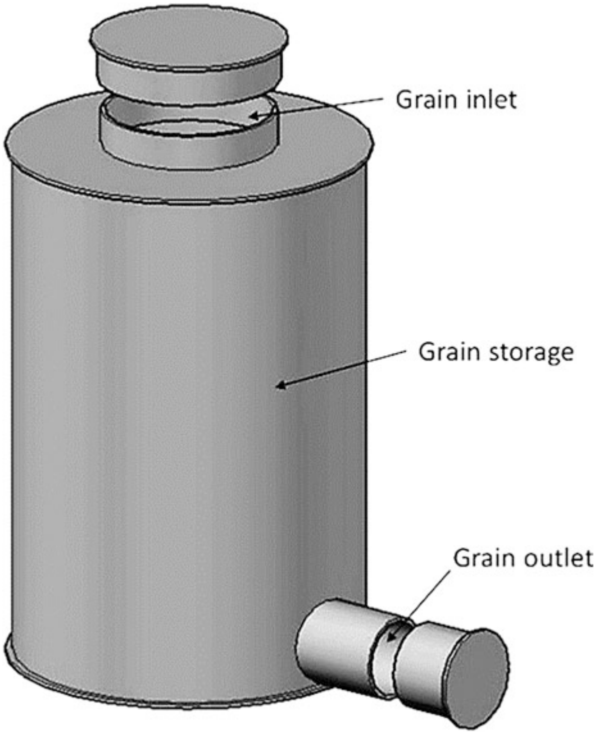


Fig. 9.9 Metal bin used for grain storage

of metal bins with painted external walls. The structure is placed below the ground level leaving the top 500 mm above the ground level.

9.9.3 Reinforced Brick Bin

This design consists of two layers of brick masonry walls of 110 mm thickness with a moisture barrier in between. The outer layer is reinforced by using steel and plastered on both sides with cement mortar. The structure with the capacities varying from 3.5 to 10.25 tonnes may be constructed.

9.9.4 Partly Underground and Partly Aboveground Storage Structure

This structure has a capacity of about 7.5 tonnes and it is partially made underground. The underground part of the structure is of reinforced cement concrete or brick, while the aboveground part of the structure is of galvanized iron sheets. The bin is suitable for construction in shallow water table areas.

9.9.5 Brick-Walled Silo

This type of structure is suitable for 1–50 tonnes capacities. The construction is similar to the underground structure, made from brick and constructed on the ground level. Reinforcement is essential when the height goes beyond 7–8 m, which makes it uneconomical as a farm storage structure. The use of thick walls (gravity walls) can reduce the need of reinforcement.

When the walls of structure are of bricks, mud or cement, moisture absorption from the ambient air is possible. Addition of a moisture barrier material on the walls can protect grains in humid regions. Painting of walls with coal tar or plastic paint improves protection against moisture absorption.

9.10 Cover and Plinth Storage

The need arises on several occasions, particularly at the harvest period, for temporary storages of food grains for short term by the procurement agencies due to the lack of covered storage space, particularly in India. Stacking of bags is done on a wooden frame (dunnage) placed on a raised platform (plinth), and the lot is covered with 800–1000 gauge thick polyethylene sheets (Fig. 9.10). This storage method is known as cover and plinth (CAP) and common for the storage of wheat and paddy at present in India [8, 9].

For CAP storage, the site should be at a higher elevation than adjoining ground and away from drainage, canals and flood-prone area to prevent flooding of the area. Normally the plinth is made with brick and mortar, which is at least 150 mm above the ground level. Anti-termite treatment is essential to avoid termite attacks.

Dunnage is the structure made from wooden planks in general on which the bags are stacked. Polyethylene sheet alone or sandwiched between two layers of mats and bamboo are also suitable for use as dunnage for short-term storage. A wooden dunnage is made using timber planks in which the planks are one over the other and nailed. The lower member of dunnage is of 100×50 mm^2 rectangular shape and 1 m long. In general, five planks at 362 mm distance from centre to centre are used.

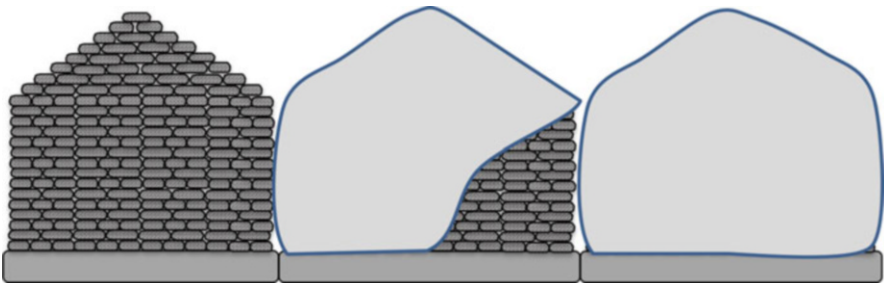


Fig. 9.10 CAP storage

The upper member of dunnage is of 70 × 50 mm^2 cross-section and 1.5 m long, and 5 planks are placed at 237 mm distance from centre to centre.

A stack of 9.3 m × 9.3 m × 6.2 m is generally preferred in CAP storage. The height of stack may go up to 15 bags. The top of stack is made in inverted 'V' shape for easy flow of rainwater after covering. A layer of bags filled with straw may be suitable in some areas to minimize the damage due to rain, birds, temperature and condensation.

After placing the polyethylene cover, the stack is lashed with ropes in some regions where wind velocity is generally high. Plastic-net-type covers on the polyethylene cover are more convenient to tie the stacks.

Aeration of the stack becomes important to control temperature and moisture. Lifting the plastic cover is a common method of aeration in CAP system, and frequency of aeration is once in a week in general when sky is clear. Curative treatments, such as fumigation, are also in practice in some places.

The main disadvantages of CAP are that the fumigation is not very effective and the covers are damaged at the time of high wind and during rains.

9.11 Cocoon Storage

These storage structures are made from plastic and fabrics for short-term storage of food grains. The structures may be flexible or rigid depending upon the construction material and need. The structure is also known as volcanic cubes. The volcanic cube developed in Israel is a cubical structure prepared from 830-μm-thick PVC liners and works as a hermetically sealed structure. These are available in 5–50 tonnes capacities and used for outdoor storage of grains. Plasticity of the PVC liner decreases upon use; however, gas-retention property increases. Rodents rarely damage to the liners [3].

Rectangular-bunker-type structures are also used for temporary storage of wheat. These are constructed on a well-drained and waterproof location using concrete or reinforced sidewalls. Loading and unloading of grains are done with the help of special machines. The bunkers are usually covered with PVC fabric after filling with grains. The capacity may be up to 50,000 tonnes and fumigation is feasible in such structures.

9.12 Bag Storage Godown/Warehouse

Usually warehouses are for the storage of bagged grains or packed food materials to safeguard them from environmental factors. It is a very common grain storage method in many developing countries. Any type of shaded structure or building, such as stone structure, brick wall, walls of corrugated sheet, mud and wattle, walls with or without plaster, earthen walls, floor of stone or cemented with a corrugated sheet and slab or thatched roof can be used for stacking of bagged grains.

The warehouse system requires huge labour for building and liquidating the stacks, and hence, the operating cost is very high. Losses due to pest attacks, spillage during handling and operational difficulties are more. Seepage of water occurs in the poorly constructed floors and ventilators, which increases the RH inside a warehouse. Bag storage systems need less capital investment and sophisticated aeration systems are not required for aeration and fumigation [3, 9].

9.12.1 Requirements of Warehouses

The warehouse facility includes the structure, equipment for packaging of grains in bags, handling, ancillary facilities, quality evaluation equipment and chemicals for pest control. The structures are constructed on a raised platform, well-drained locations and away from flood-prone areas. The location of warehouse should be at least at 500 m distance from waste management industries, such as bone crushing mill, garbage dumping area, slaughterhouse, tanneries, hide curing units, sewage water treatment plants, etc. The structures near a carriage head or a main road are preferred. Typically, a godown or warehouse is made of the dimensions as given in Table 9.5 [9].

The major requirements of a warehouse are as follows:

- Suitable foundation depending upon the site conditions.
- Damp proof and rigid floor, which should be free from cracks and crevices.
- Plinth at 800 mm above the ground level for truck loading and 1060 mm for the rail-fed.
- Platform width of 1830 mm for road-head and 2440 mm for rail-fed.
- Slope of platform 1:40 (minimum).
- Longitudinal walls of brick or stone masonry up to 5.6 m height from the plinth level and 230 mm thick.
- Steel ventilators of opening 1494 × 594 mm^2 placed near the top on the longitudinal walls.
- Air inlets steel ventilator of 620 × 620 mm^2 placed at 600 mm above the floor level.

Table 9.5 Bag storage godown/warehouse capacities and their dimensions

Godown type	Approx. capacity (tonnes)	Internal dimensions (m)		
		Length (m)	Width (m)	Height (m)
Small	1120	100	12	7.5
	2700	250	20	9
	5400	500	34	12
	10,500	1000	35.5	18
	28,510	2500	97.19	14.48
Large	57,020	5000	129.74	21.34

Note: For storage capacity above 2500 tonnes, godowns are divided in suitable compartments

- Suitable number of steel ventilators glazed with fixed wire mesh on the gable walls.
- Single-span structural steel or tubular trusses for roof.
- Cantilever trusses are fixed on to RCC columns at 4000 mm height.

9.12.2 Estimation of Space Requirement for Stacking of Bags

For movement of bags in a godown, a 3 m wide gallery is kept along the width of the warehouse. A gangway of 2 m is kept along the length and in the centre of the warehouse. For inspection of stacks, a 1 m space around the entire stacking area should be kept. In general, storage capacity of a godown is calculated using the following expression:

$$Q = \frac{L \times W \times (H - 1) \times 0.2}{1.6} \tag{9.1}$$

The factor 0.2 is used for the spaces provided between stacks, walls and stack and inspection. Factor 1.6 is the average storage factor for different food grains and equivalent to the space occupied in m^3 by 1 tonne grain packed into the bags. A typical stack arrangement in a godown is shown in Fig. 9.11.

Q. 9.1 Wheat stock of 1600 tonnes is to be stored in a warehouse. Make a stacking arrangement when wheat is packed into 50 kg bags and each stack can accommodate 2000 bags. Calculate the dimensions of the warehouse and total floor area required

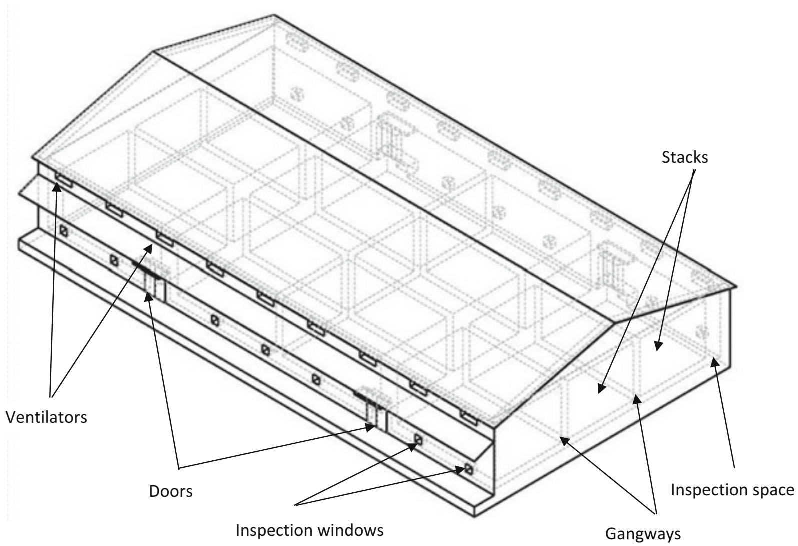


Fig. 9.11 A typical bag storage structure with stacking floor plan

for storage. Show the stack arrangement. The length-to-width ratio of a stack should be 1:0.6, height of a stack is 3.0 m, and size of a filled bag is 1 × 0.6 × 0.3 m.

Solution:

Weight of one stack = 2000 × 50 = 100,000 kg.

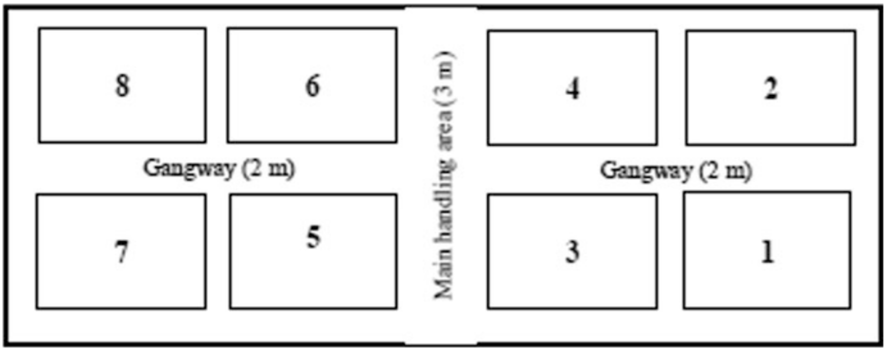
Therefore, number of stack = 16,000 × 1000/100,000 = 16 stacks.

Number of bag layers in a stack = 3/0.3 = 10.

Therefore, the number of bag in each layer = number of bag in a stack/total layers = 2000/10 = 200.

Considering the length: width, floor dimension (length × width) of each stack will be 10 m × 6 m to accommodate 2000 bags in a stack of height 3 m on the basis of bag size.

The stack arrangement is given as follows:



The inspection area is the space between the stacks and walls and between two stacks, which is 1 m from all sides.

Total length of warehouse = stack length (10 m × 4) + inspection space (1 m × 4) + main handling space (3 m) = 47 m.

Total width of warehouse = stack width (6 m × 2) + gangway (2 m) + inspection space (1 m × 2) = 16 m.

Height of the warehouse = stack height (3 m) + space between top of stack and truss (1 m) = 4 m.

Therefore, the floor area for the warehouse = 47 × 16 = 4716 m^2.

9.13 Bulk Storage

Food grains are granular material, and therefore, individual grain has characteristics of solids, whereas its composite mass characteristics are a combination of liquid and solid. The composite mass of grains forms the shape of container in which it is placed, but it does not flow downward to a slope unless the angle of slope is more than a characteristic angle (angle of repose). Therefore, the flow characteristics of food grains are studied as bulk materials. The theory of hydrodynamics is not applicable to the flow of granular materials because of non-uniform pressure distribution, definite grain size and shape and independence of flow rate on head (except when head is less than the container diameter). Therefore, the properties of bulk materials are discussed prior to the bulk storage systems.

9.13.1 Flow of Granular Material Through Orifice

The gravity flow behaviour of granular materials through small opening at the bottom of a container is of great importance in the food industry. Extensive studies are available on the flow pattern. Flow problems of different nature are encountered during the discharge of granular materials. It includes jamming due to the formation of arches, rat holing by the formation of stable open channel within a bin, overflowing due to aeration and flow rate limitation by counter flowing air and segregation due to different physical characteristics. When the granular material is free flowing, two types of flow pattern are observed as shown in Fig. 9.12 [8].

Funnel flow (Fig. 9.12a) occurs in flat bottom bins or conical bottom bins when the angle between the bottom of the bin and vertical is less than the critical angle (hopper angle). The flow of material starts from the centre of the exit at initial stage similar to the flow from a funnel, and then diameter expends slowly with the height above the opening. Bin arching or jamming may occur in the case of fine particles and material will flow erratically from the bin.

Mass flow (Fig. 9.12b) takes place when grain mass starts flowing towards the exit at same time. The material flow and densities are uniform and first-in-first-out

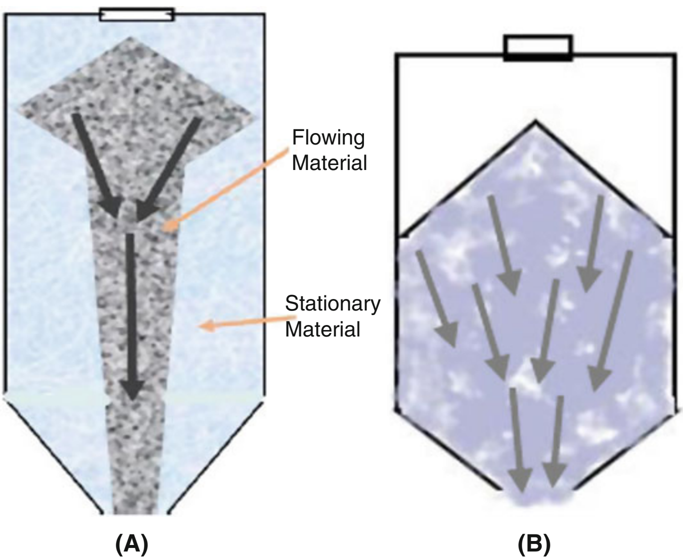


Fig. 9.12 Flow patterns of granular materials. (**a**) Funnel flow. (**b**) Mass flow

flow is ensured. This flow is suitable for feed hoppers of processing equipment where material is loaded in the hopper from the top of the bin and discharge continues from the exit.

9.13.2 Flow Rate Through Orifice

The flow of granular material forms an outlet at the flat bottom of a hopper or silo, which is similar to the orifice flow. Several models and equations are available in literature to obtain the flow rate through orifices. The granular flow through orifice is continuous when orifice diameter is ≥5 times of the characteristic seed size, and it is known as continuous flow regime of orifice flow. The flow is intermittent and orifice clogs when orifice diameter is <5 times of the characteristic seed size and termed as clogged regime of orifice flow. A correlation is proposed by Beverloo et al. for outflow rate of material from the orifice [10]:

$$Q = C\rho g^{\frac{1}{2}}(D_o - kd)^{5/2} \tag{9.2}$$

where Q is the discharge rate (kg/s); ρ is the bulk density of granular material (kg/m^3); g is the gravitational acceleration (m/s^2); d is the equivalent grain diameter; D_o is the orifice diameter (m); C is the discharge coefficient and k is the empirical parametric constant.

The value of C varies between 0.52 and 0.64 and K varies in the range 1–2 for mono-sized spherical particles. Other factors, such as friction, elasticity and shape of the grain, hopper geometry external perturbations interstitial, etc., have only a minor effect on flow rate. The Beverloo law is now the most applicable equation to determine flow rate in continuous flow regime of orifice flow.

The continuous flow of grain through orifice is attained by the use of arch breaking systems, which includes providing sinusoidal oscillation at hopper, oscillation at orifice, obstacle placed above the orifice, electrical or magnetic field application, etc. The rate of flow can also be increased by placing the orifice at off-centres or by providing rotation to the orifice plate. The mass flow rate through orifice increases with the increase in off-centre distances and rotational speeds. The following equation can be used to estimate the flow rates through rotating orifices [10]:

$$Q = \beta\left(\frac{(2R + D_o - kd)^2\omega^2}{g(D_o - kd)}\right)^{\left(\alpha+\frac{1}{2}\right)} \sqrt{g}\,\rho(D_o - Kd)^{5/2} \tag{9.3}$$

where R is the distance between hopper bottom centre and centre of the orifice (m); ϖ is the rotation rate (rad/s) and α and β are the characteristic constants obtained by experiments and depend upon the orifice location.

9.13.3 Deep Bins and Shallow Bins

The classification of bins is based on the concept of plane of rupture. A bin is called shallow bin in which the plane of rupture meets the grain surface before it reaches to the opposite side wall (Fig. 9.13a). When the plane of rupture coincides the wall of opposite side before it emerges from grain surface (Fig. 9.13b), the bin is called deep bin [8].

The shallow or deep bins are also defined based on the angle of repose as per **Rankine's theory**. In a silo of diameter L with grain depth of H and angle of repose of grain as φ, the bins are defined as:

Shallow bin if

$$H < L \tan\left(\frac{90 + \varnothing}{2}\right) \tag{9.4}$$

and deep bin when

$$H > L \tan\left(\frac{90 + \varnothing}{2}\right) \tag{9.5}$$

In case the bins are not circular, the concept of equivalent diameter (4 times of hydraulic radius) is used to define deep or shallow bins and given as follows:

For deep bin $H \geq 4R$.
For shallow bin $H < 4R$.
The hydraulic radius (R) is defined as

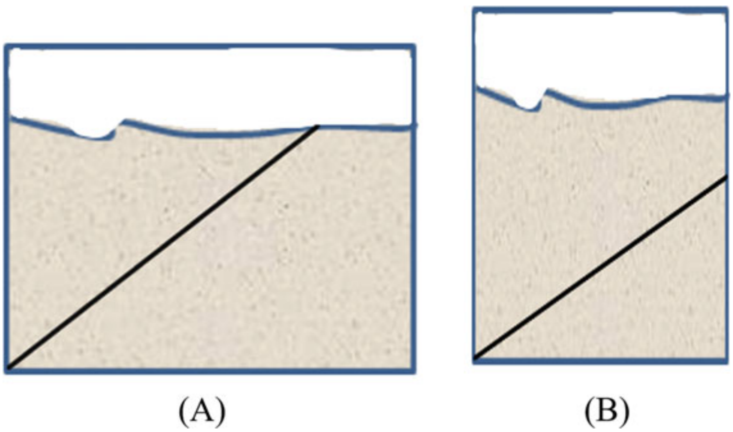


Fig. 9.13 Location of plane of rupture in a bin. (**a**) Shallow bin. (**b**) Deep bin

$$R = \text{hydraulic radius} = \frac{\text{Cross sectional area of bin}}{\text{Perimeter of bin}} \quad (9.6)$$

9.13.4 Silo

Silo is a vertical container used for storing food grains and other granular materials. Bins and silos of varying capacities along with bulk handling, aeration and fumigation systems are very popular worldwide for grain storage. These structures are made of masonry or reinforced concrete, or from metals (plain or corrugated), with conical hopper or flat bottom (Fig. 9.14). In hopper bottom bins, the grains flow under gravity and do not deposit in the bin while unloading (self-cleaning system) and shovelling equipment is not required. The hopper slope angle of 60–70° is necessary for continuous flow of material. Flat-bottomed bins are economical to construct and accommodate more grain, but shovelling is required while emptying the bin, which delays the operation. Cylindrical structures are preferred in place of shapes due to better mechanical strength of the structure.

At present, silos have facilities for temperature recording and monitoring at different grain depths. Temperature gradients in metal silos are high in comparison to the wood or concrete bins due to high thermal conductivity of the metals, which causes more moisture transfers inside the silo. Spout lines are also a concern in bulk storages when unclean grain is stored. During filling of the bin, fine particles, admixtures and small grains usually concentrate at the centre of a heap, whereas whole grains flow away towards periphery. This core of high dockage in the centre of the pile is known as spout line. It acts as a source of heat development and pest propagation in the silo. The spout lines obstruct the air circulation during aeration, which may affect the shelf life of grain.

Nowadays, the silos are coming sufficiently airtight so that controlled atmosphere storage practices may be adopted and effective fumigations can be achieved. Flexible polyurethane-based sealant, acrylic-based or elastic adhesive sealants are now used in the silos to make the joints airtight. The functioning of silos is further

Fig. 9.14 Commercial hopper bottom and flat bottom storage silos

improved using acoustic pest detection system, automated aeration and grain cooling systems along with automatic pest control measures.

9.13.5 Silo Design

Silos are designed to bear all stresses while considering the properties of stored grain, silo shape, material handling methods, etc. The foundation for silos is designed to take the stresses from the upper structures, grain pressure (in the case of flat bottom silo) and their supports. The internal surfaces of silos are finished as per the food safety and sanitary standards.

The applicable loads include stresses from the grain, static pressure, dynamic overpressure during filling and dynamic underpressure during discharge, arch formation during discharge, collapse of arch, aeration and provision of eccentric discharge (when applicable). The silo walls are the crucial from a design point of view because the walls have to bear the lateral, vertical, shear, impact during filling and self-weight. The characteristics of granular material are taken into account for the design of silo walls [8, 11].

The static (lateral) grain pressure at any point of bin can be given as

$$P_l = \rho H \tag{9.7}$$

where P_l is the lateral pressure exerted by grains on the wall (kg/m^2); ρ is the bulk density (kg/m^3) and H is the grain depth from the top of grain surface (m).

However, Eq. (9.7) did not consider the effects of friction. Therefore, Rankine modified the above equation using a factor 'K', which is called Rankine's earth pressure coefficient. The Rankine's equation is based on a principle which states that 'the resistance to displacement by sliding along a specific plane in a non-cohesive granular material is equal to the normal pressure exerted between the parts of the mass on either side of the plane' multiplied by specific coefficient, and Rankine's formula is given as

$$P_l = K\rho H \tag{9.8}$$

$$K = \frac{1 - \sin \varnothing}{1 + \sin \varnothing} \tag{9.9}$$

where Φ is the angle of internal friction of granular material.

Using Mohr circle diagram (Fig. 9.15), the maximum and minimum principal stresses can be calculated as:

$$\sin \varnothing = \frac{\frac{1}{2}(P_v - P_l)}{\frac{1}{2}(P_v + P_l)} \tag{9.10}$$

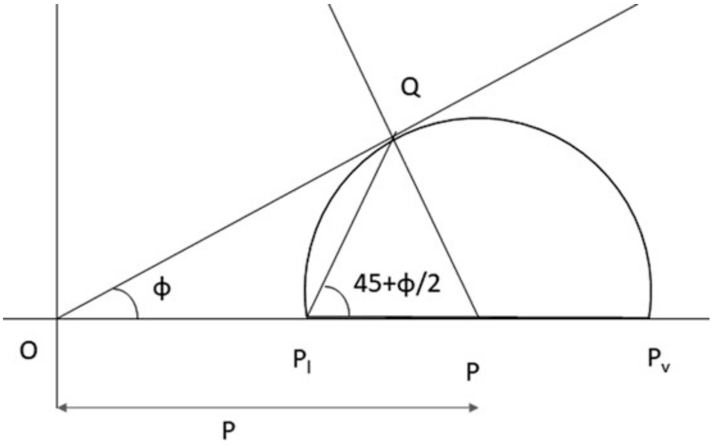


Fig. 9.15 Mohr circle diagram for Rankine's theory

Therefore, P_l can be given as

$$P_l = \frac{(1 - \sin \varnothing)}{(1 + \sin \varnothing)} P_v$$

From Eq. (9.9) and Eq. (9.10), the relationship between P_l and P_v can be given as

$$P_l = KP_v \tag{9.11}$$

Airy proposed a theory to calculate the pressure exerted by the granular materials in a shallow bin, which is given as follows:

$$P_l = \rho H \left\{ \frac{1}{\sqrt{\mu(\mu + \mu')} + \sqrt{(1 + \mu^2)}} \right\}^2 \tag{9.12}$$

where μ is the internal coefficient of friction and μ' is the coefficient of friction of grain against the wall surface.

However, the above theories do not give the actual pressure in a silo or bin. Then, Janssen proposed a theory to calculate pressure by accounting friction between grain wall and grain mass. Jansen's theory is applied for pressure distribution in deep bins, which uses the friction between the grain and bin wall into consideration. It is widely used for bins due to a higher safety factor.

Considering the distribution of pressure on a thin layer of grain in a bin (Fig. 9.16), where

h = Depth of bin (m)
μ = Coefficient of friction of the grain on the wall
K = Safety factor
P_v = Vertical pressure (kg/m^2)
P_l = Lateral pressure (kg/m^2)

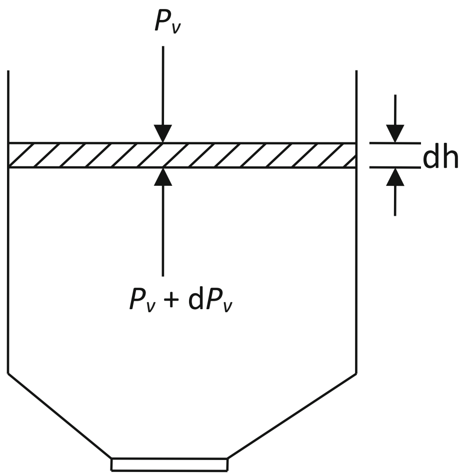


Fig. 9.16 Distribution of pressure on thin layer in a bin

P = Total lateral wall load (kg/m^2)
ρ = Bulk density of grain (kg/m^3)
R = Hydraulic mean radius (m)
r = Radius of small disc of height dh (m)
π = Constant
During storage, forces acting are:

1. Vertical downward force:
   Due to mass of material = bulk density × volume of material
   $= \rho \times \pi r^2 dh$
2. Vertical upward forces:
   (a) Effective upward force = unit upward force × cross-sectional area.
   $= dP_{\text{v}} \times \pi r^2$
   (b) Due to friction factor grain and wall of grain:
   = Force due to friction × area of the bin surface
   $= \mu P_1 \times 2\pi r dh$

In case of equilibrium, all the downward forces will be equal to the upward forces, so

$$\rho \times \pi r^2 dh = \left(dP_{\text{v}} \times \pi r^2\right) + (\mu \cdot P_1 \times 2\pi r dh)$$

Dividing by πr,

$$\rho\ r\ dh = (r\ dP_{\text{v}}) + (2\mu P_1\ dh)$$

Rearranging (dh) terms on one side,

$$(\rho r\, dh) - (2\mu P_\mathrm{l}\, dh) = r\, dP_\mathrm{v}$$

$$(\rho r - 2\mu P_\mathrm{l})dh = rdP_\mathrm{v}$$

$$dh = (rdP_\mathrm{v})/(\rho r - 2\mu P_\mathrm{l})$$

$$K = P_\mathrm{l}/P_\mathrm{v}$$

$$dh = (rdP_\mathrm{v})/(\rho r - 2\mu KP_\mathrm{v})$$

Integrating the above expression for the limits $h \geq (0, h)$*;* $P_\mathrm{v} \geq (0, P_\mathrm{v})$,

$$\int_0^h dh = \int_0^{P_\mathrm{v}} \frac{r}{\rho r - 2\mu KP_\mathrm{v}} dP_\mathrm{v}$$

Let,

$$x = (\rho r - 2\mu KP_\mathrm{v})$$

$$dx = -2\mu K \cdot dP_\mathrm{v}$$

$$dP_\mathrm{v} = -\frac{dx}{2\mu K}$$

Changing the limits with respect to x, $P_\mathrm{v} = 0$, $x = \rho r$; $P_\mathrm{v} = P_\mathrm{V}$, $x = (\rho r - 2\mu KP_\mathrm{v})$,

$$\int_0^h dh = \int_{\rho r}^{\rho r - 2\mu KP_\mathrm{v}} \frac{r}{x} \frac{dx}{(-2\mu K)}$$

$$\int_0^h dh = \int_{\rho r}^{\rho r - 2\mu KP_\mathrm{v}} \frac{-r}{(2\mu K)} \frac{dx}{x}$$

$$\int_0^h dh = -\frac{r}{2\mu K} \int_{\rho r}^{\rho r - 2\mu KP_\mathrm{v}} \frac{1}{x} dx$$

$$[h - 0] = -\frac{r}{2\mu K}[\log_\mathrm{e}(\rho r - 2\mu KP_\mathrm{v}) - \log_\mathrm{e}\rho r]$$

$$h = -\frac{r}{2\mu K}\left[\log_\mathrm{e}\frac{\rho r - 2\mu KP_\mathrm{v}}{\rho r}\right]$$

$$h = -\frac{r}{2\mu K}\log_{\mathrm{e}}\left[1 - \frac{2\mu K P_{\mathrm{v}}}{\rho r}\right]$$

$$-\frac{2\mu K h}{r} = \log_{\mathrm{e}}\left[1 - \frac{2\mu K P_{\mathrm{v}}}{\rho r}\right]$$

Since hydraulic radius $R = r/2$,

$$-\frac{\mu K h}{R} = \log_{\mathrm{e}}\left[1 - \frac{\mu K P_{\mathrm{v}}}{\rho R}\right]$$

$$e^{-\frac{\mu K h}{R}} = \left[1 - \frac{\mu K P_{\mathrm{v}}}{\rho R}\right]$$

$$\frac{\mu K P_{\mathrm{v}}}{\rho R} = \left[1 - e^{-\frac{\mu K h}{R}}\right]$$

$$K P_{\mathrm{v}} = \frac{\rho R}{\mu}\left[1 - e^{-\frac{\mu K h}{R}}\right]$$

The vertical pressure (P_{v}) below the top free surface at a depth 'x' is

$$P_{\mathrm{v}} = \frac{\rho R}{\mu K}[1 - e^{-\frac{\mu K h}{R}}]$$

Since $K = P_{\mathrm{l}}/P_{\mathrm{v}}$; $P_{\mathrm{l}} = K.P_{\mathrm{v}}$

$$P_{\mathrm{l}} = \frac{\rho R}{\mu}\left[1 - e^{-\frac{\mu K h}{R}}\right] \tag{9.13}$$

9.13.5.1 Maximum Lateral and Vertical Pressures

Equation (9.13) is valid for a relationship between lateral and vertical pressures as the equation is derived by the extension of the same theory. Therefore, substituting the values and rearranging gives

$$\frac{P_{\mathrm{l}}}{P_{\mathrm{v}}} = \frac{1 - \sin\varnothing}{1 + \sin\varnothing} = \tan^2\left(\frac{\pi}{4} - \frac{\varnothing}{2}\right) \tag{9.14}$$

and

$$P_{\mathrm{v\ max}} = \frac{\rho R}{\mu}\frac{1}{\tan^2\left(\frac{\pi}{4} - \frac{\varnothing}{2}\right)} \tag{9.15}$$

It is considered that the pressure at the top grain surface is zero. But practically a cone is formed at the top surface. While calculating the pressure on silo walls and bottom of silo, the height of upper cone is calculated as

$$Z = r \tan \varnothing \tag{9.16}$$

where r is the radius of bin.

Reimberts defined a characteristic abscissa 'A' as a function of internal friction between grains and angle of friction between wall and grain, which is given as

$$A = \frac{R}{\mu K} \tag{9.17}$$

The equations for 'A' for large bin wall can be given as

$$A = \frac{D}{4\ tan\, \varnothing'\ tan^2\left(\frac{\pi}{4} - \frac{\varnothing}{2}\right)} - \frac{Z}{3} \tag{9.18}$$

where D is the internal diameter of cylindrical silo or diameter of the inscribed circle of a polygon.

The maximum pressure of a bin is expressed as

$$P_{\max} = \frac{\rho R}{\mu} \tag{9.19}$$

The grain load (F_1) balanced due to friction on the walls is a function of the depth of grain (H) and expressed as

$$F_1 = \frac{\rho S H^2}{H + A} \tag{9.20}$$

where S is the cross-sectional area of the silo (m^2).

Lateral pressure at a depth 'h' of the grain in a silo is given as

$$P_h = P_{\max}\left[1 - \left(\frac{h}{A} + 1\right)^{-2}\right] \tag{9.21}$$

Total load at the bottom of silo is expressed as

$$F = \rho S\left[H\left(\frac{H}{A} + 1\right)^{-1} + \frac{Z}{3}\right] \tag{9.22}$$

Q. 9.2 Wheat is loaded in a smooth sheet metal silo having 4 m internal diameter up to a height of 8 m. The bulk density of wheat, angle of internal friction and angle of external friction are 925 kg/m^3, 26° and 15°, respectively. Estimate the lateral load at the bottom using Airy's theory.

Solution:

$$\mu = \tan 26^{\circ} = 0.488$$

$$\mu' = \tan 15^{\circ} = 0.268$$

$$P_1 = \rho H \left\{ \frac{1}{\sqrt{\mu(\mu + \mu')} + \sqrt{(1 + \mu^2)}} \right\}^2$$

$$P_8 = 750 \times 8 \times \left\{ \frac{1}{\sqrt{0.488 \times (0.488 + 0.268)} + \sqrt{\left(1 + 0.488^2\right)}} \right\}^2$$

$$P_8 = 750 \times 8 \times \left\{ \frac{1}{0.6074 + 1.1127} \right\}^2$$

$$P_8 = 750 \times 8 \times 0.338$$

$$P_8 = 2028.00\,\text{kg/m}^2$$

Q. 9.3 Paddy is loaded in a concrete silo having 3 m internal diameter up to a height of 7 m. The bulk density of paddy, angle of internal friction and angle of external friction are 750 kg/m^3, 26° and 24°, respectively. Calculate the lateral load at every meter using Airy's theory from top to bottom and plot lateral pressure with depth of grains.

Solution:

$$\mu = \tan 26^{\circ} = 0.488$$

$$\mu' = \tan 24^{\circ} = 0.445$$

$$P_1 = \rho H \left\{ \frac{1}{\sqrt{\mu(\mu + \mu')} + \sqrt{(1 + \mu^2)}} \right\}^2$$

$$P_{11} = 750 \times 1 \times \left\{ \frac{1}{\sqrt{0.488 \times (0.488 + 0.445)} + \sqrt{\left(1 + 0.488^2\right)}} \right\}^2$$

$$P_{11} = 750 \times 1 \times \left\{ \frac{1}{0.6748 + 1.1127} \right\}^2$$

$$P_{11} = 750 \times 1 \times 0.313$$

$$P_{11} = 234.74\,\text{kg/m}^2$$

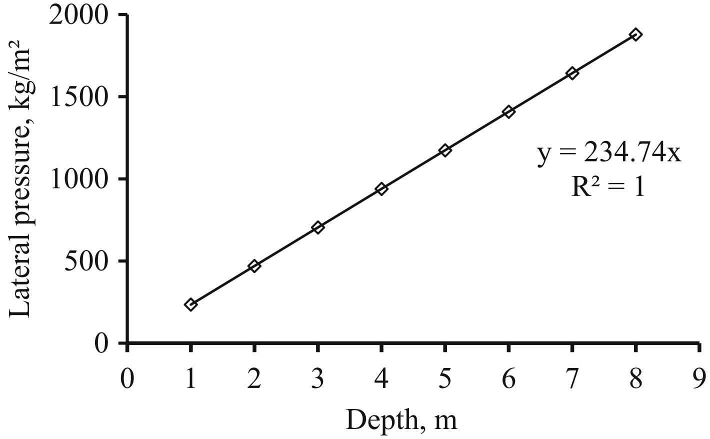


Fig. 9.17 Variation of lateral pressure with increase in depth of grains

$$P_{l2} = 469.47\,\text{kg/m}^2; \quad P_{l3} = 704.21\,\text{kg/m}^2; \quad P_{l4} = 938.94\,\text{kg/m}^2;$$

$$P_{l5} = 1173.68\ \ \text{kg/m}^2; \quad P_{l6} = 1408.41\,\text{kg/m}^2 \quad P_{l7} = 1643.15\,\text{kg/m}^2.$$

The variation of pressure with respect to depth of grain in silo is presented in Fig. 9.17.

Q. 4 Wheat is loaded in a smooth sheet metal silo having 4 m internal diameter up to a height of 8 m. The bulk density of wheat, angle of internal friction and angle of external friction are 925 kg/m^3, 26° and 15°, respectively. Estimate the lateral load at the bottom using Janssen's theory if the ratio of horizontal and vertical pressure k is 0.40.

Solution:

$$\rho = 925\,\text{kg/m}^3$$

$$\mu = \tan 15^\circ = 0.268$$

$$k = 0.4$$

$$R = D/4 = 4/4 = 1$$

$$P_l = \frac{\rho R}{\mu}\left[1 - e^{-\frac{\mu K h}{R}}\right]$$

$$P_l = \frac{925 \times 1}{0.268}\left[1 - e^{-\frac{0.268 \times 0.4 \times 8}{1}}\right]$$

$$P_1 = 3451.49\,[1 - 0.424]$$

$$P_1 = 1988.1\,\text{kg/m}^2$$

Q. 5 Paddy is loaded in a concrete silo having 3 m internal diameter up to a height of 10 m. The bulk density of paddy, angle of internal friction and angle of external friction are 750 kg/m^3, 26° and 24°, respectively. Calculate the lateral load at every meter using Janssen's theory from top to bottom and plot lateral pressure with depth of grains ($k = 0.4$).

Solution:

$$\rho = 750\,\text{kg/m}^3$$

$$\mu = \tan 24^\circ = 0.445$$

$$k = 0.4.$$

$$R = D/4 = 3/4 = 0.75$$

$$P_1 = \frac{\rho R}{\mu}\left[1 - e^{-\frac{\mu K h}{R}}\right]$$

$$P_{11} = \frac{750 \times 0.75}{0.445}\left[1 - e^{-\frac{0.445 \times 0.4 \times 1}{0.75}}\right]$$

$$P_{11} = 1264.05\,[1 - 0.789]$$

$$P_{11} = 266.7\,\text{kg/m}^2$$

$$P_{12} = 477.8\,\text{kg/m}^2;\quad P_{13} = 643.4\,\text{kg/m}^2;\quad P_{14} = 774.9\,\text{kg/m}^2;$$

$$P_{15} = 878.5\,\text{kg/m}^2;\quad P_{16} = 959.4\,\text{kg/m}^2;\quad P_{17} = 1023.9\,\text{kg/m}^2;$$

$$P_{18} = 1074.4\,\text{kg/m}^2;\quad P_{19} = 1114.9\,\text{kg/m}^2;\quad P_{110} = 1146.5\,\text{kg/m}^2.$$

The variation of pressure with respect to depth of grain in silo is presented in Fig. 9.18.

Q. 6 A silo of cylindrical shape with 2 m diameter and 20 m height is filled with rice. Minimum and maximum bulk densities of rice are 750 and 850 kg/m^3, respectively. The angle of repose of rice is 25°, minimum and maximum angle of internal friction are 25° and 30°, respectively, and coefficient of friction against the wall material is 18°. Calculate the load on the bottom and the lateral thrust at 4 m below the top surface on the walls.

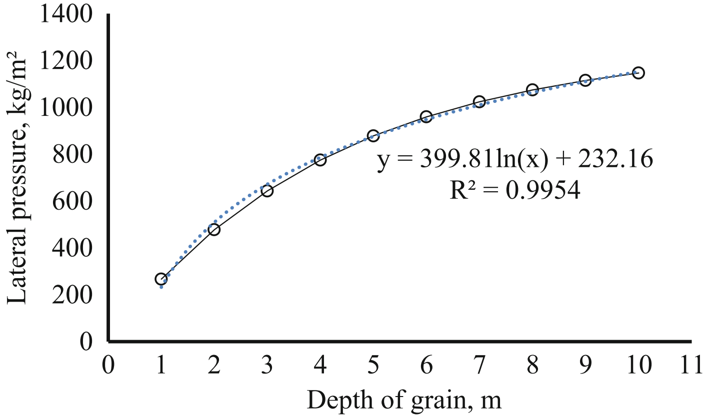


Fig. 9.18 Variation of lateral pressure with increase in depth of grains

Solution:

Height of upper cone surface of rice $Z = r \times \tan 25° = (D/2) \times \tan 25° = 0.4663$ m.
Hydraulic radius $R = D/4 = 2/4 = 0.5$ m.
Earth pressure coefficient (Eq. 9.9) $K = 0.4058$.
Characteristic abscissa (Eq. 9.17) $= 0.5/(\tan 18° \times 0.4058) = 3.79$ m.
Therefore, maximum pressure (Eq. 9.19) $P_{\max} = (850 \times 0.5)/\tan 18° = 1308$ kg/m^2.
For load at the bottom,
Height of grain against the wall H = bin height $- Z = 20–0.4663 = 19.534$ m.
Therefore, load at the bottom (Eq. 9.22) $F = 8891.16$ kg.
For lateral pressure at 4 m below the top surface (Eq. 9.21) $P_{4\text{m}} = 998.39$ kg/m^2.

9.14 Hermetic Storage

When grain is stored in airtight containers, the CO_2 concentration increases and the O_2 depletes naturally because of respiration of grains and organisms, and therefore, grains remain safe. It is an old method of safe grain storage and termed as 'hermetic storage'. However, it is not cost-effective when grains to be stored are dry because of rare chances of insect and mold growth. The hermetic structures can be made underground or aboveground level in the form of sealed silos. The air exchange from the environment into the grain bulk should not take place in hermetic storage structures. The hermetic storage, particularly silos, can be equipped with fumigation or controlled atmosphere systems. In semi-underground hermetic bins, condensation of moisture may take place in the store when grain is stored for 3 years. The grain losses are quite low (0.5%) for 2–3 years in hermetic storage.

Underground hermetic structures are cost-effective for small capacities; however, for large capacities, grain handling is an issue. Economical airtight storage of grain can also be made from PVC sheets when storage period is greater than 3 months.

Table 9.6 Material handling and ancillary equipment in a high-capacity silo storage system

Equipment type	Intended use	List of equipment
Transport equipment	Conveying	Chutes, conveyors (chain, flat belt, magnetic belt, trough belt), bucket elevator, vibrating conveyor, screw conveyor/elevator, pneumatic conveyor, vertical lift, monorail or sortation conveyors
	Lift heavy object	Jib, bridge, gantry/stacker cranes
	Transport of material	Hand trucks, pallet truck, jacks, walkie stacker, platform truck, picker, side-loader, tractor trailer, automatic guided vehicle
Positioning equipment	Single location handling	Lift/tilt/turn table, ball transfer table, dock leveler, parts feeder, rotary index table, hoist, manipulator, balancer, industrial robot
Unit load formation equipment	Restrict material load to maintain integrity	Pallets, skids, slip-sheets, tote pans, pallet/skid boxes, bins/baskets/racks, bags, cartons, crates, bulk load containers, strapping/tape/glue, intermodal containers, shrink-wrap/stretch-wrap machine, palletizers
Storage equipment	Proper storage of materials	Pallet racks, push-back rack, drive-in rack, drive-through rack, sliding rack, cantilever rack, flow-through rack, bin shelving, stacking frame, storage drawers, storage container
Modern identification and control equipment	Collect and communicate the information	Barcodes, radio frequency identification tags (RFID), magnetic stripes, voice recognition, portable data terminals, machine vision, public address system, etc.

9.15 Material Handling and Ancillary Equipment

Several equipment and material handling devices are required for efficient operations of a storage system as given in Table 9.6.

9.16 Modified Atmosphere Storage

Changing the environment of a food package or store by introduction of gases (not air) and no further modification or control are modified atmosphere (MA) storage. Sometimes passive atmosphere modification (PAM) or equilibrium-modified atmosphere (EMA) is also used for food packaging when gas modification is not done by external means and it is allowed to establish gas equilibrium due to respiration. Airtight packaging is the main requirement of MA operation [12, 13].

The major gases used in MA storage are N_2, O_2 and CO_2. Nitrogen gas is used to reduce the oxygen level that inhibits oxidation and aerobic microorganism's growth. A concentration of 10–15% CO_2 in a food packet controls decay in fruits and vegetables. Higher CO_2 concentration can prevent mold growth in oilcakes with a shelf life of 3–6 months.

9.17 Controlled Atmosphere Storage

Storage of produce at an altered but controlled atmosphere in respect of CO_2 and O_2 gas levels is controlled atmosphere (CA) storage [12, 13]. The gas composition inside a sealed chamber changes continuously due to metabolic activity of the stored materials and gas leakage through the minor opening in doors and walls. Therefore, in CA storage, the gas concentrations are monitored periodically, and a preset concentration is maintained by introducing fresh air, N_2, CO_2 and O_2 or by using chemical to remove CO_2. CA storages are of two types depending mainly on methods to control gas concentration inside the store. 'Static control' is a CA system where the stored produce generates the required gas concentration. 'Flushed control' is a CA system in which the requisite gases are added into the store from an outer source. A combination of both systems is better, in which O_2 content is reduced initially by flushing the nitrogen gas followed by CO_2 injection in the store or buildup of CO_2 through respiration. Thereafter, the preset concentration of gases is maintained in the store through ventilation and scrubbing.

9.17.1 Advantages of Storage Under CA

(a) Respiration rate of produce decreases considerably.
(b) Ethylene effect on metabolism is reduced, which delays the deterioration.
(c) Maintains fruit firmness because high CO_2 concentration reduces enzymatic activities on cellular membranes.
(d) Low nutrient loss.
(e) Reduces the degradation rate of chlorophyll and consequently the colour of commodity remains stable for longer duration.
(f) Reduces damage due to physiological changes, such as chill injuries, formation of spots, decay loss, enzymatic browning, water core formation and scald.
(g) Reduces growth of molds and insect due to low O_2 and high CO_2 in the atmosphere.
(h) Increases shelf life of the commodity.

9.17.2 Disadvantages of CA Storage

(a) At less than 1% O_2 and very low CO_2, anaerobic condition prevails resulting in alcohol formation and physiological changes in the commodity.
(b) Higher CO_2 and lower O_2 concentrations in the storage environment cause abnormal metabolism of the commodities.

(c) CA storage is an expensive technology, and hence, only quality fruits are stored.
(d) CA storage suits more for small- and medium-sized fruits.

CA storage is a successful technology for food grain storage at normal temperatures. However, in the case of perishables, low temperature storage is essential. In commercial practice for fruits and vegetables, the temperature is 0 °C for initial 1 week of storage, and then required storage temperature (Table 9.7) may be maintained. Further, the designed capacity of the refrigeration system for CA storage chamber should not take more than 1 day to cool the produce to 0 °C after filling.

Most of the fruits and vegetables require high RH conditions during storage. Therefore, the difference between temperature of refrigerant and temperature at which the commodity is to be stored should be less. Humidification equipment are useful to maintain RH of air. Secondary cooling system (a system in which cooling coils of refrigeration system do not come into direct contact with the store air) is a better option for maintaining air humidity.

CO_2 scrubbing materials, such as NaOH, $Ca(OH)_2$, zeolites, H_2O and activated charcoals, are generally used to absorb excess CO_2 generated in the store. Activated charcoal-based scrubbers with PLC-controlled CO_2 analyzer are popular nowadays.

No or very low oxygen and >20% CO_2 concentrations are the best combination for grain storage in a CA system, which destroys all the insects and inhibits mold growth. In the case of CA storage of fruits and vegetables, higher O_2 level is essential to prevent the anaerobic respiration. CA storage conditions recommended for different crops are given in Table 9.7 [14].

9.18 Cold Storage

Majority of perishables (fruits, vegetables, flowers, etc.) respire even after harvest. Therefore, the most common method to increase the storage life and maintain quality is low temperature storage. Further, the fruits and vegetables (except citrus and chilling injury-prone crops) have longer shelf life when the storage temperature is lower than their freezing point. The respiration rate of such commodities, within their physiological temperature range, increases with temperature and 2–3 times increase in metabolism rate takes place with every 10 °C increase in temperature [14, 15].

Thus, the cold storage is a complete system in which the store is equipped with thermal insulation, and environmental temperature of store is controlled by a refrigeration system. The cold storage for the perishables requires low temperature and high RH environment.

A produce is said to be ‘half cool’ when product temperature reaches to 50% of the difference between initial produce temperature and temperature of cooling media. After another half-cooling period, the product is said as ‘three-quarters’ cool.

Table 9.7 Recommended CA storage environments for some fruits and vegetables

Commodity	Cooling method (s)[a]	Storage temp (°C)	Freezing point (°C)	Optimum humidity (%)	Storage life (week)	CO_2 (%)	O_2 (%)
Fruits							
Apples	F	10	−1.70	90–95	8–12	1–5	1–3
Banana	F	13–14	−0.5	90–95	6	2–5	2–5
Lemon	F	9–10	−3	85–90	6–8	0–10	5–10
Mosambi	F	3–4	−3	85–90	2–4	0–10	5–10
Orange	F	5–7	−3 to −20	85–90	4–8	0–5	5–10
Grapes	F	0–1	−3 to −2	90–95	5–12	1–3	2–5
Guava	F	7–10	−2	85–90	3	8–10	5–20
Litchi	F	1–2	−1.2	90–95	3–5	2–5	5–10
Mango	F	13	−1	85–90	2–3	5–8	3–7
Papaya	F	10–13	−2 to −1	85–90	1–3		
Pineapple	F	7–10	−10	85–95	2–4		
Pomegranate	F	11	−3	90–95	2–3	15–20	–
Sapota	F	15–20	−2	85–90	2–3		
Strawberries	R, F	0	−1	90–95	1	15–20	5–10
Vegetables							
Brinjal	R, F	8–12	−1	90–95	1		
Cabbage	R, F	0	−1	98–100	4–24		
Cauliflower	R, H	0	−1	85–90	2–4		
Green onion	H, I	0	−1	95–100	3–4		
Leafy vegetable	H, I	0	−1	95–100	1–2		
Lady finger	R, F	7–10	−2	90–95	1–2	4–10	
Onion	R, H	0–2	−1	65–70	2–3		
Green pea	F, H	0	−1	95–98	1–2		
Field pea	F, H	4–5	−1	95	1		
Capsicum	R, F	7–10	−1	90–95	2–3		
Potato	R, F	3–4	−1	90–95	20–32		
Tomato	R, F	7–10	−1	90–95	1	0–3	3–5

Source: Indian Horticultural database (2013)

[a]*R* room cooling, *H* hydro-cooling, *F* forced-air cooling, *I* icing

9.18.1 Factors Responsible for Effective Cold Storage

1. *Product quality*: High initial quality of produce ensures longer storage life with sustained quality.
2. *Temperature*: Reduction of time between harvest and precooling is a critical factor. Storage at lower temperature is essential for the perishable commodities to lower down the respiration rate and metabolic activities, softening, colour changes, spoilage due to sprouting/cooling and moisture loss and maintain textural integrity.
3. *Relative humidity (RH)*: Very low RH results in wilting or shrivelling of perishables, whereas very high RH favours decay in some cases.
4. *Air circulation and package spacing*: Proper air circulation ensures uniform temperature inside the store and maintains uniform storage quality by removing respiration heat. In the case of pellets storage, circulation of atmospheric air with properly spaced containers/pellets is crucial.
5. *Respiration rates, heat evolution and refrigeration:* Respiration rate mainly influences the refrigeration load of a cold store. Thus, calculation of heat generation is crucial.

9.18.2 Precooling

It is the first step and an integral part of the fresh produce supply chain. Precooling is essential to remove the field heat and cool the produce to safe storage temperature as quickly as possible. For most of the horticulture produce harvested at 35 °C temperature, 1-h delay in precooling can deteriorate quality equivalent to 20 h in storage at safe storage temperature. The features of precooling are as follows:

- Reduces the respiration rate of produce.
- Retards ethylene production rate leading to delayed ripening.
- Loss of moisture and shrivelling of produce is reduced.
- Inhibits growth of microorganisms responsible for decay.
- Load on the refrigeration system of transport or storage facility is reduced.

Several methods of precooling on commercial scale are given as follows:

9.18.2.1 Icing

It is a common method for cooling of produce kept in boxes in which crushed ice layer is placed on the top of the boxes. The ice melts by taking heat from the produce and then cold water goes down and cools the produce at the bottom of the box. Sometimes ice slurry is spread on the top of produce, which constitutes 60% fine crushed ice, 40% chilled water and 0.1% NaCl. The water–ice ratios of slurry may be altered from 1:1 to 1:4 depending upon the need. Top icing is a preferred method of cooling during road transport. This method is also used for short-time cooling immediately after harvest (e.g. initiating precooling of lettuce packed in the field).

9.18.2.2 Room Cooling

In room cooling, the produce is loaded in the cold store initially in the same compartment where products are to be stored for long periods or in a separate room and transferred to the storage compartment after precooling. The room has high-capacity refrigeration system and cold air is passed across the produce using normal air circulation fans. The cold air should come from the roof of the store and circulate through the commodity by convection currents. It is a cost-effective method but takes longer duration for cooling the produce.

9.18.2.3 Forced-Air Cooling

It is similar to that of room cooling with a difference that high-velocity blast fans are used for air circulation. The air passes through the produce at high speed and high temperature gradient results in rapid cooling.

9.18.2.4 Hydro-Cooling

The heat transfer between a solid and a liquid is rapid in comparison to that from a solid material to air. In hydro-cooling, the produce is immersed in the chilled water and the water is circulated through the chiller. It cleans the produce also during the cooling process; however, the water may be contaminated and chances of spoilage may increase. Two types of hydro-cooler, namely shower type and immersion types, are commonly available. This method is not suitable for the produce, which absorbs water and spoil.

9.18.2.5 Vacuum and Hydro-Vacuum Cooling

In vacuum cooling, partial vacuum is created and cooling takes place due to the latent heat of vaporization in place of conduction. In leafy vegetables, the reduced pressure around the leaves and in the centre is the same, and hence, cooling is quick throughout the commodity. Vacuum cooling is not used for cooling the crops like tomato. These coolers have strong construction to withstand the vacuum, and hence, it is very expensive. Further, vacuum cooling is not effective for pellets.

9.18.2.6 Merits and Demerits of Different Precooling Methods

A comparison of different precooling methods is given in Table 9.8. Comparative performances of these precooling methods are given in Table 9.9 [15–17].

The safe storage temperatures with their shelf life of selected fruits and vegetables are given in Table 9.10 [14].

9.18.3 Cold Storage Layout

The required floor area of a cold store depends upon the ratio of volume of produce to be handled and the possible stack height along with space required for material handling and overhead space. In general, a height of 2 m is recommended, which is equivalent to a pallet height. The vertical storage space may increase by using racks or by stacking pallets up to 3 m height (when boxes are strong enough). Metal pallet

Table 9.8 Merits and demerits of various precooling methods

S. no.	Methods	Merits	Demerits	Commodities
1.	Room cooling	Relatively less expensive	Slow, water loss is very high	All types of produce
2.	Forced air cooling	6 to 10 times faster than room cooling	Requires more power to force the air circulation/speed, a higher refrigeration capacity system in comparison to the room cooling	Grapes, strawberries, mango and other fruits, melons, tomato, cucumber, capsicum, cabbage, cauliflower, okra, brinjal, beans, radish, carrot, mushroom, etc
3.	Hydro–cooling	2 to 3 times faster than room cooling, no weight loss	Accumulation of decay-causing microorganisms; water-resistant containers are needed; high refrigeration system required; economical only when used round the year; good only for water-resistant commodities	Leafy vegetable, lettuce, asparagus, sweet corn, celery, topped carrot, radish and muskmelon
4.	Package icing	Lesser expensive, suitable during transport	Package and produce should be water resistant; need replenishment of ice for long-distance transport	Prepackaged carrot and radish, lettuce, celery and leafy vegetables, cauliflower, broccoli, baby corn, asparagus, etc
5.	Vacuum cooling and hydro-vacuum cooling	Quick and uniform cooling, reduced labour cost	Expensive equipment, suitable only for high-surface-to-volume-ratio produce, high water loss	Celery, lettuce and other leafy vegetables, asparagus, sweet peas, broccoli, Brussels sprout, mushroom, sweetcorn, cauliflower

bins can be stored vertically above 3 m height also. Overhead space of the height of a box or more is also added into space for loading and unloading of pallets. Insulation of walls, roof and floor is done with high-heat-flow-resistant materials. A layer of vapour barrier materials between the walls and insulating material (6 mm polyethylene film to protect loose-fill cellulose, fibreglass, porous board of bead board and fibreglass board) is sufficient to prevent moisture loss [18].

9.18.4 Airflow Design

Adequate airflow is an essential component of a cold storage for distributing cold air throughout the storage area so that uniform air temperature is maintained. The airflow design requirements for a cold storage are as follows:

Table 9.9 Effect of cooling on product and cost

Factors	Forced-air	Hydro-cooling	Vacuum cooling	Water spray cooling	Ice cooling	Room cooling
Cooling duration (h)	1–10	0.1–1.0	0.3–2.0	0.3–2.0	0.1–0.3[a]	20–100
Moisture loss (%)	0.1–2.0	0–0.5	2.0–4.0	–	–	0.1–2.0
Contact of water and product	None	Yes	None	Yes	Yes, unless packed in watertight packets	None
Chances of decay due to contamination	Less	None	High[b]	High[b]	Less	Less
Capital investment	Less	Less	Medium	Medium	High	Less[c]
System energy efficiency	Less	High	High	Medium	Less	Less
Requirement of water-resistant packaging	No	Required	No	Required	Required	No
Portability	Sometimes	Not common	Common	Common	Common	No
Feasibility for in-line cooling	Rare	Feasible	No	No	Rare	No

[a]Longer time is required when top icing is done
[b]Sanitization of recirculated water is essential to reduce decay-causing pathogen load
[c]Less chances when product is also stored in the same room; else long cooling times make it an expensive system

- Designed airflow rate should be 0.3 m^3/min/ton of commodity to be stored.
- The time required to achieve safe storage temperature of produce is less than 7 days after loading the store and airflow is maximum during this period.
- After 1 week of filling the commodity in store, airflow rate should be 20–40% of the design capacity.
- Slow airflow rate reduces the chances of product moisture loss.
- Uniform distribution of air throughout the cold room is essential.
- In the case of pallets, a gap of 100–150 mm should be maintained between two pallets.
- When the air travel length is more than 15 m in a room, air distribution through ceiling ducts or a plenum is better.

Table 9.10 Safe storage temperature and shelf life during cold storage

Commodity	Safe storage temperature (°C)	Minimum RH (%)	Storage life (days)	Ethylene sensitivity	Chilling injury temperature (°C)
Apple	−1–4	90–95	30–180		2–3
Banana	13–15	90–95	7–28		11.5–13
Grapes	0.5–0	90–95	14–56	Sensitive	
Guava	5–10	90	14–21	Sensitive	5
Mango	13	90–95	14–21		10–13
Oranges	0–9	85–90	56–84		3
Papaya	7–13	85–90	7–21		7
Peach	−0.5–0	90–95	14–28		Sensitive to freezing temperature
Pear	−1.5–0.5	90–95	60–210		
Plum	−0.5–0	90–95	14–35		
Strawberries	0–0.5	90–95	5–7		
Asparagus	0–2	95–100	14–21	Sensitive	0–2
Broad beans	0–2	90–98	7–14	Sensitive	0
Beet (topped)	0	98–100	120–180		
Cabbage	0	98–100	150–180	Sensitive	
Carrots	0–2	98–100	210–270	Sensitive	
Cauliflower	0	95–98	21–28	Sensitive	
Capsicum	7–10	85–90	14–21		7
Cucumber	10–13	95	10–14	Sensitive	7
Eggplant	8–12	90–95	7	Sensitive	7
Ginger	13	65	180		
Lettuce	0–2	98–100	14–21	Sensitive	
Lemon	10–13	85–90	30–180		10
Melons	7–10	90–95	12–21		4–5
Onions (dry)	0	65–70	30–240	Sensitive	0
Peas	0	95–98	7–14	Sensitive	
Potato	4.5–13	90–95	150–300		
Pumpkin	10–15	50–70	60–160		10
Spinach	0	95–100	10–14	Sensitive	
Tomato	8–10	90–95	8–10	Sensitive	7–10
Fresh-cut vegetables	0	>95	2–3 weeks	Sensitive	0

(Source: NHB, 2013)

9.18.5 Ventilation

Ventilation is an essential component of the cold storage to maintain proper gas composition inside the cold storage. The ventilation can be provided on the walls or at the roof (attic). Rooftop mounted ventilation system reduces the moisture accumulation under the roof. In flat roofs, the space is ventilated passively or mechanical ventilation systems are used for improved air exchange efficiency. A passive system requires 0.16 m^2 area for air inlet for each ceiling area of 90m^2 in cold storage.

9.19 Calculation of Refrigeration Requirements

The refrigeration capacity of a cooling system is given in kW or in terms of tons of refrigeration. A ton of refrigeration is the heat required to convert one ton of ice into 0 °C water in 24 h and it is equivalent to 12,660 kJ h. The refrigeration load for a storage accounts for all the sources from where heat is entering into the room and going out. The main sources of heat load are as follows [8, 15, 18]:

(a) Produce itself (heat produced due to respiration, transpiration or field heat).
(b) Walls, roof and floor through which heat loss is due to conduction or leakage.
(c) Equipment used in the store.
(d) Capacity and type of equipment selection depend upon the refrigeration load, environmental temperature and RH of the store.

9.19.1 Field Heat

Field heat is the energy required for reducing the commodity temperature from its harvest temperature to the recommended temperature for storage. Produce weight, harvest temperature and cooling rate affect the field heat load. It is calculated using the following expression:

$$Q_1 = M \cdot C \cdot \Delta T \tag{9.23}$$

where Q_1 is the rate of field heat removal (kcal/24 h); M is the weight of the produce to be cooled in 24 h (tons); C is the specific heat of the produce (kcal/kg °C) and ΔT is the temperature drop of produce in 24 h (°C).

9.19.2 Heat of Respiration

It is the heat produced by the produce during respiration. Respiration heat load decreases with decrease in produce temperature, and it stabilizes when the required preset temperature is reached. The respiration load is calculated using the following expression:

$$Q_2 = M \cdot K \tag{9.24}$$

where Q_2 is the respiration heat load (kcal/24 h) and K is the respiration heat production rate (kcal/24 h).

The K value for calculation is given as the average value of heat production respiration rates at the average produce temperature during the initial 24 h of cooling.

9.19.3 Conductive Heat Gain/Loss

Heat loss in a cold storage takes place due to conduction through the floor, store walls and ceiling. Heat loss due to conduction is a function of the temperature gradient between the inside wall of cold storage and atmospheric temperature, thermal resistance to heat transfer of the floor, walls and ceiling. Heat gain may take place when the store temperature is less than the surroundings, and heat loss takes place when outside air is colder than that of the cold storage. The gain or loss from each side of the room is calculated separately and then summed up. Total conductive heat gain or loss is calculated as

$$Q_3 = 24 \cdot A \cdot (T_\mathrm{o} - T_\mathrm{i})/R \tag{9.25}$$

where Q_3 is the total conductive heat gain or loss (kcal/24 h); A is the area of floor, wall or ceiling (m^2); T_o is the outside environment temperature (°C); T_i is the temperature inside the cold storage (°C) and R is the resistance value of the respective component (h m^2 K)/kcal.

9.19.4 Equipment Heat Load

Equipment used for handling operations in the storage area generates heat, which adds heat load to the refrigeration system. Some permanent equipment installations and lights in the cold storage are considered for load calculation. Each kW/h of lights used in storage adds 865 kcal/h to the cooling load. The equipment load is estimated from the following expression:

$$Q_4 = 865 \cdot \left(t_\mathrm{o}E_\mathrm{w} + t_\mathrm{m} \cdot E_\mathrm{m} + t_\mathrm{p} \cdot E_\mathrm{o}\right) \tag{9.26}$$

where Q_4 is the heat produced by equipment and other reasons (kcal/24 h); E_w is the load of electric lights (kW); E_m = load for motors (kW); E_o is the load due of other items (kW) and t_o, t_m and t_p are the operating time of each component (h).

9.19.5 Convective Heat Gain/Loss

Atmospheric air enters in the cold storage or cold air moves outside through leaks, opening of doors, etc., which adds to the heat load. Such air exchange causes heat loss/gain due to convection, which are on a higher side during loading of the commodity and minimal when the doors are closed. The heat gain or loss due to convection is expressed by

$$Q_5 = (h_o - h_i) \cdot V \cdot N/\rho_a \tag{9.27}$$

where Q_5 is the convective heat gain/loss (kcal/24 h); h_o is the enthalpy of atmospheric air (kcal/kg); h_i is the enthalpy of cold air inside the store (kcal/kg); V is the volume of storage (m^3); N is the number of air exchange/24 h and ρ_a is the average specific volume of outside air (m^3/kg).

9.19.6 Total Cooling Load

Addition of above given loads yields the total refrigeration load due to gain or loss of heat for a cold storage. An additional load of 10–20% is added as a factor of safety (service factor) to the total refrigeration load. This factor takes care of unusually hot weather or unforeseen heat load of short time. The loss of time during defrost of refrigeration system is also taken into account. Defrost of refrigeration system is done 4 times in 24 h during loading of commodity and each defrost cycle is about 30–60 min. Thus, the effective operating time of refrigeration system is 20–22 h in a day in place of 24 h, and hence, a time loss factor of 1.1 to 1.2 is multiplied. Hence, the refrigeration system capacity is calculated by multiplying the total refrigeration load with service and time loss factors.

9.20 Economic Aspects of Storage

Perishable crops are seasonal in nature and their value varies throughout the year. The storage quantity of a commodity depends upon the returns to the storage. It is the sum of the current price relative to the price expected at the time of disposal after deducting the storage cost. The decision of storing a commodity depends upon the expected increase in the commodity prices.

9.20.1 Variable Costs

This cost is incurred only when commodity is stored for certain period. The highest variable cost linked with a storage system is the interest on investment. The cost of interest depends on the storage duration, the existing interest rate and the purchase price of the commodity. The variable costs include the cost of utilities for drying, aeration, conveyance and handling.

9.20.2 Monitoring Costs

The quality of a commodity depends upon temperature, moisture content, insects and molds. Thus, regular monitoring, after 1–2 weeks interval in summer and after every 3–4 weeks in winters, is essential. Monitoring costs cover the cost incurred on workers deployed for taking samples and equipment used for sampling and analysis.

9.20.3 Pest Management Costs

The pest management in grain storage is of two types, i.e. preventive and curative, and the costs incurred on both are the pest management cost. The steps taken to prevent insect damage include sanitation of the structure prior to storage, monitoring for insects during storage period and intermittent fumigation.

9.20.4 Shrinkage

The weight decreases of a commodity due to moisture loss is termed as shrinkage. This loss usually takes place when the commodity is stored at higher-moisture contents. A gain in weight may also be obtained, for example wheat purchased at 9% moisture content in summer.

9.20.5 Quality Deterioration

Grain quality may deteriorate with the storage period, and a poor-quality commodity receives lower prices, unless there is a gap in demand and supply. Such decrease in price due to poor quality is a part of storage cost.

9.20.6 Fixed Costs of Storage

The fixed costs of storage are the capital investment in the facility. It includes investments on storage structure, quality monitoring equipment, handling devices, aeration equipment and accessories, site preparation expenditures, installation of structures and equipment and construction of facility. The annual fixed storage costs of a commodity cover interest, cost of depreciation of facilities and equipment, taxes levied, insurance and maintenance cost.

The amount of interest on the fixed cost is the payable interest on the total investment on creation of storage facility. Depreciation cost is the investment made on the facility and equipment divided by the useful life of the storage facility.

9.20.7 Returns on Investment (ROI) in Storage Structures

The ROI for a storage facility is calculated as:

$$\text{ROI} = \text{Return to Storage} - \text{Cost of Investment}/\text{Cost of Investment} \tag{9.28}$$

Example The following example illustrates the method of calculating cost economics of a storage structure for a farmer:

$$\text{ROI} = P_\text{s} - P_\text{p} - C_\text{s}$$

where

P_s is the cost of purchase at the time of storage (Rs.)
P_p is the selling (market) cost at the time of liquidation (Rs.)
C_s is the storage cost involved (Rs.)

The margin (%) may be calculated as the ratio of ROI and cost involved in purchase and storage ($P_\text{s} + C_\text{s}$).

A farmer gets a price of Rs. 20 per kg for wheat when he sells wheat immediately after harvest in May. When the farmer decides to store the wheat in a warehouse for sale later (e.g. in December), the storage cost is added. The transportation cost of the produce to the warehouse is Rs. 8 per 100 kg. The handling charge is Rs. 2 per 100 kg. The storage charge of the warehouse is Rs. 4 per 100 kg per month. There is likely a loss of 1% grain during loading, unloading and storage. The interest rate is 12% per annum. The total cost of the storage per 100 kg will be as follows:

Transport charge (field to warehouse): Rs. 8.00
Handling charge (field to warehouse): Rs. 2.00
Warehouse charge (8 months): Rs. 32.00
Charge for losses: Rs. 20.00
Interest charge (8 months): Rs. 160.00
Transport charge (warehouse to market): Rs. 8.00
Handling charge (warehouse to market): Rs. 2.00
Total charge: Rs. 232.00

Thus, a farmer will get the benefit of storing wheat only when the market price of wheat is more than Rs. 232.00 per 100 kg.

9.21 Exercise

Q. 1. What is the requirement of storage? How is storage of perishable foods different from non-perishable/durable foods?

Q. 2. Specify the functional requirements of storage of foods. What is the differeence between the requirements of perishable and non-perishable foods?

Q. 3. How do temperature, relative humidity and water activity affect the storage of food materials?

Q. 4. Which destuctive agents are responsible for damage of food during storage? Explain in brief.

Q. 5. Which factors affect the spoilage of food material? Discuss their contributions.

Q. 6. Explain the phenomena of moisture accumulation of grains during cold environmental condition with suitable sketch.

Q. 7. Discuss various traditional storage structures of grains. Explain the constuctional features of *Kothar*-type storage structures.

Q. 8. What are CAP storage structures? Explain in brief.

Q. 9. Wheat stock of 100 tonnes is to be stored in a warehouse. Make a stacking arrangement when wheat is packed into 50 kg bags and each stack can accommodate 1000 bags. Calculate the dimensions of the warehouse and total floor area required for storage. Show the stack arrangement. The length-to-width ratio of a stack should be 1:0.6, height of a stack is 3.0 m, and size of a filled bag can be taken as $1 \times 0.6 \times 0.3$ m.

Q. 10. For a grain storage silo, prove the following expression for estimation of lateral loads:

$$P_1 = \frac{\rho R}{\mu}\left[1 - e^{-\frac{\mu K h}{R}}\right]$$

where h = depth of bin (m); μ = coefficient of friction of the grain on the wall; K = safety factor; P_1 = lateral pressure (kg/m^2); ρ = bulk density of grain (kg/m^3) and R = hydraulic mean radius (m).

Q. 11. Grains are loaded in a smooth sheet metal silo having 2.65 m internal diameter up to a height of 9 m. The bulk density of grains, angle of internal friction and angle of external friction are 900 kg/m^3, 22° and 11°, respectively. Estimate the lateral load at every meter depth from the top to bottom using Janssen's theory if the ratio of horizontal and vertical pressure k is 0.42.

[Ans: 365.5, 670.0, 949.7, 1195.6, 1410.7, 1604.3, 1773.4, 1924.0, 2056.1 kg/m^2]

Q. 12. Grains are loaded in a smooth sheet metal silo having 4.5 m internal diameter up to a height of 9.0 m. The bulk density of grains, angle of internal friction and angle of external friction are 875 kg/m^3, 25° and 19°, respectively. Estimate the lateral load at every meter from the top of silo using Airy's theory.

[Ans: 296.6, 593.2, 889.8, 1186.3, 1482.9, 1779.5, 2076.1, 2372.7, 2669.3 kg/m^2].

Q. 13. Paddy is loaded in a concrete silo having 2.4 m internal diameter up to a height of 6.6 m. The bulk density of paddy, angle of internal friction and angle of external friction are 755 kg/m^3, 25° and 23°, respectively. Calculate the lateral load at the bottom using Airy's theory.

[Ans: 1632.23 kg/m^2].

Q. 14. Grains are loaded in a smooth sheet metal silo having 4.5 m internal diameter up to a height of 9.0 m. The bulk density of grains, angle of internal friction and angle of external friction are 875 kg/m^3, 25° and 19°, respectively. Estimate the lateral load at every meter from the top of silo using Janssen's theory. Assume $k = 0.4$.

[Ans: 329.1, 621.0, 878.5, 1107.4, 1307.7, 1488.0, 1645.4, 1785.6, 1908.7 kg/m^2].

Q. 15. Wheat is loaded in a concrete silo having 3 m internal diameter up to a height of 9 m. The bulk density of wheat, angle of internal friction and angle of external friction are 950 kg/m^3, 24° and 22°, respectively. Calculate the lateral load at every meter using Airy's theory from the top to bottom and plot lateral pressure with depth of grains.

[Ans: 325.2, 650.4, 975.6, 1300.8, 1625.9, 1951.1, 2276.3, 2601.5, 2926.7 kg/m^2].

Q. 16. Wheat is loaded in a smooth sheet metal silo having 4.5 m internal diameter up to a height of 12 m. The bulk density of wheat, angle of internal friction and angle of external friction are 900 kg/m^3, 27° and 12°, respectively. Estimate the lateral load at the middle and at the bottom using Janssen's theory if the ratio of horizontal and vertical pressure k is 0.43.

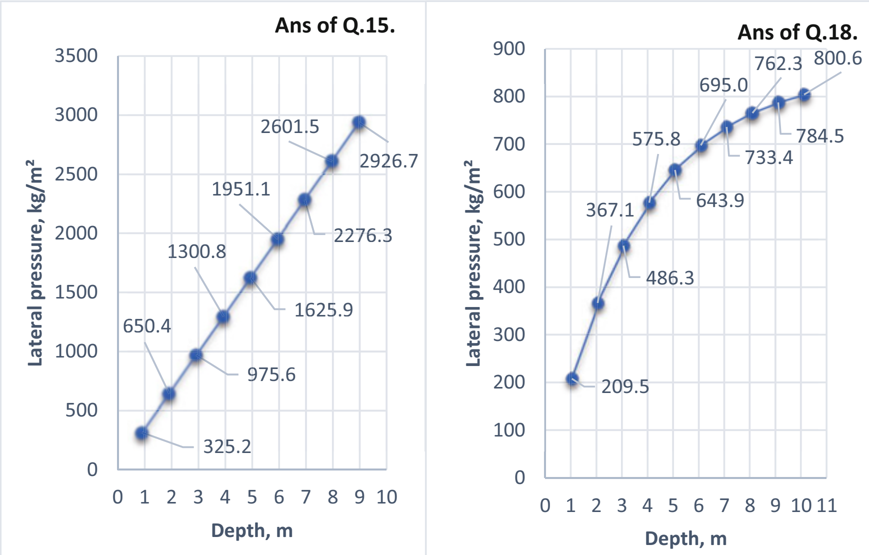
[Ans: 1834.9, 2966.2 kg/m^2].

Q. 17. Paddy is loaded in a smooth sheet metal silo having 2.10 m internal diameter up to a height of 7 m. The bulk density of grains, angle of internal friction and angle of external friction are 566 kg/m^3, 24° and 17°, respectively. Estimate the lateral load at every meter depth from the top using Janssen's theory if the ratio of horizontal and vertical pressure k is 0.39.

[Ans: 197.1, 354.4, 479.7, 579.7, 659.4, 722.5, 773.0 kg/m^2].

Q. 18. Paddy is loaded in a smooth sheet metal silo having 2.0 m internal diameter up to a height of 10 m. The bulk density of grains, angle of internal friction and angle of external friction are 586 kg/m^3, 21° and 19°, respectively. Plot a graph after estimation of the lateral load at every meter depth from the top using Janssen's theory if the ratio of horizontal and vertical pressure k is 0.41.

[Ans: 209.5, 367.1, 486.3, 575.8, 643.9, 695.0, 733.4, 762.3, 784.5, 800.6 kg/m^2].



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Processing of Cereals

10

Pragati Kaushal and Navneet Kumar

Abstract

Cereal processing is one of the essential components of the food chain in context with its volume and consumption all over the world. In this chapter, a detailed insight on the importance of cereals, characteristics, cereal grain structure, properties, nutritional profile, antinutritional factors, quality standards, production, and processing methods with special emphasis on milling techniques is discussed. The effects of various processing techniques on quality of cereals and cereal-based products are explained in detail. Milling plays a vital role in cereal processing so as to convert it into edible products. The parboiling and milling process of rice is explained. The milling of wheat includes cleaning, conditioning, and milling with break and reduction system, and purification is explained along with standard specification of milling products. The different unit operations used in wet and dry milling of corn are also explained using flow diagrams. The important milling equipment like rubber roller, hammer mill, ball mill, and various separators are explained using simple schematic diagrams. The value-added processed products of rice, wheat, and corn are also listed to emphasize the recent trends of cereal processing.

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Keywords

Composition and nutrient potential of cereals · Wheat processing · Rice processing · Corn processing · Milling equipments · Quality standards · Applications

10.1 Introduction

Cereals are the edible grains of *Gramineae* family that fulfills 70–80% day-to-day energy needs especially in South Asia. Cereals are the supreme source of food [1] and cereal-based foods are the chief source of energy, micronutrients (vitamins and minerals), and protein for the global population. In general, cereals are inexpensive, effortlessly preserved, and easily transported and do not deteriorate readily when kept dry. Cereals are considered to have low fat content, which generally varies from 2 to 5%.

The major cereals grown in the world include wheat, rice, barley, maize, oats, sorghum, and rye. Wheat is well-liked across the globe because of its utilization in a number of food products such as bread, cakes, pastries, etc. Rice is the foremost food for nearly half of the global community and constitutes almost as much as 80% of the calories for most of Asia's people. Wheat ranks second to rice in worldwide use and is the principal cereal grain used in European countries. Corn is widely used in Central and South America.

10.2 Importance of Cereals

Cereal constitutes 60–70% starch and supplies energy-rich foods for humans. A perfect nutritious diet plan should provide 20–30 g/day of dietary fiber, which can be attained simply by consuming cereal grain–based products. Wheat and wheat products can comfortably provide the required amount of protein to the humans, but wheat gluten is deficient in essential amino acids, lysine, and threonine and therefore can be fortified with lysine-rich proteins. Rice protein, which is richer in lysine, can be combined. To make a complete protein, it is good to combine cereal and pulses.

Cereals are the prime source of fat-soluble vitamins. Intact cereal kernels fulfill 20–30% of the day-to-day demands of minerals like calcium, zinc, copper, etc. The seed or the kernel of the cereal grain is composed of three main segments or parts, i.e., bran, germ, and endosperm. The greater part of the minerals, iron and phosphorus, and the B-complex vitamins are concentrated specifically in the bran and germ portion of the kernel. Wheat and rice are of utmost importance in context to cereals due to their prime role in human nutrition and constitute about 55% of the overall cereal production.

10.3 Major Popular Cereals

Wheat Wheat is one of the predominant cereals consumed worldwide. The main parts of wheat include bran, germ, and endosperm. Wheat grain is composed of approximately 85% endosperm, 13% husk/bran, and 2% embryo. The outer portion of wheat is known as bran that constitutes 13% of the total portion. Bran further consists of several layers predominantly epidermis, hypodermis, tube cells, cross cells, testa (seed coat), and nuclear tissue. Testa (seed coat) protects the endosperm and is responsible for the color of wheat. Germ or embryo constitutes 2% of the wheat seed and is known as sprouting section of the seed. Germ holds maximum amount of protein, lipids, and sugar. The major portion (85%) of the seed is composed of endosperm (Fig. 10.1), which is the storehouse of nutrients like riboflavin, thiamine, pantothenic acid, niacin, and proteins and is used to make white flour.

Maize It is one of the most important cereals (Fig. 10.2) that is widely consumed all over the world after wheat and rice. Sweet corn is a kind of maize with sweet grain. The three foremost parts of maize grain (Fig. 10.2) are seed coat, endosperm, and germ. Seed coat is the thin layer surrounding the whole grain, whereas endosperm is the bigger portion popularly known as storage tissue of the grain. In maize, the endosperm is nearly two-thirds of the kernel's volume and accounts nearly 86% of its dry weight. In the starch and bound protein, 10% (gluten) is the major component of endosperm [2]. The maize oil is nearly 4% by weight of the grain and germ is the main source of vegetable oil. Mature germ (Fig. 10.2) is composed of central embryo axis and scutellum. Germ consists of a large shield-shaped cotyledon popularly known as scutellum. The axis of the embryo is submerged in the scutellum and it

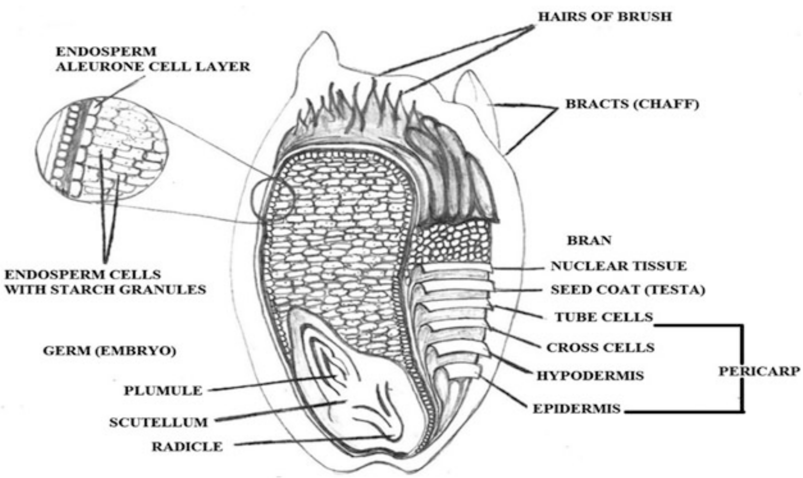


Fig. 10.1 Structure of wheat grain

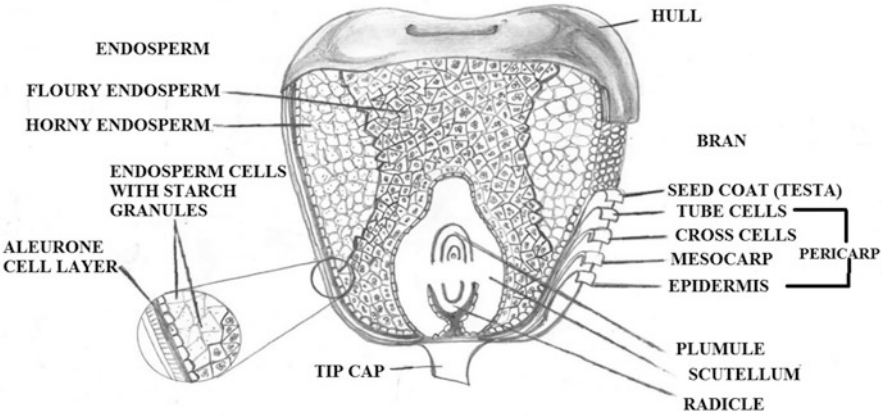


Fig. 10.2 Structure of maize grain

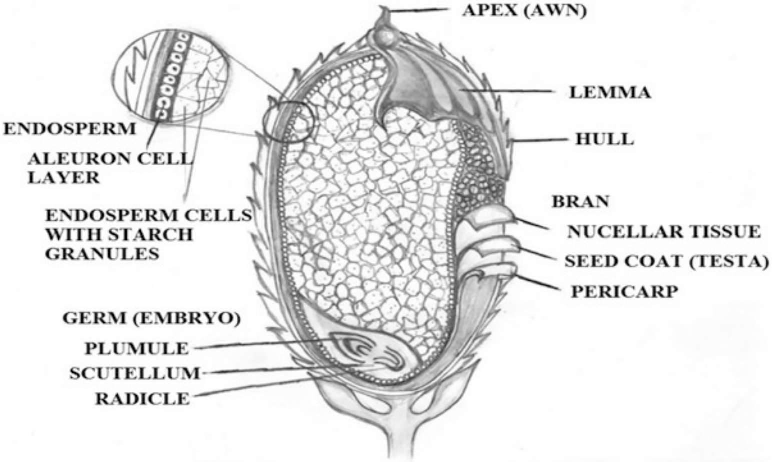


Fig. 10.3 Structure of rice grain

comprises a plumule (at upper end) and radicle (at lower end). Both radicle and plumule are confined in sheath.

Rice Rice (Fig. 10.3) is a distinctive cereal that prefers to grow scarcely in hot and humid climate. Nearly 80% of the rice consumed in world is planted in Asia, specifically in submerged fields known as "paddies." The rice grain (Fig. 10.3) consists of hull (16–28% db) and caryopsis. The detaching hull during the milling process produces brown rice. The brown rice consists of endosperm (90–91%), pericarp (1–2%), aleurone plus nucellus and seed coat (4–6%), germ (1%), and

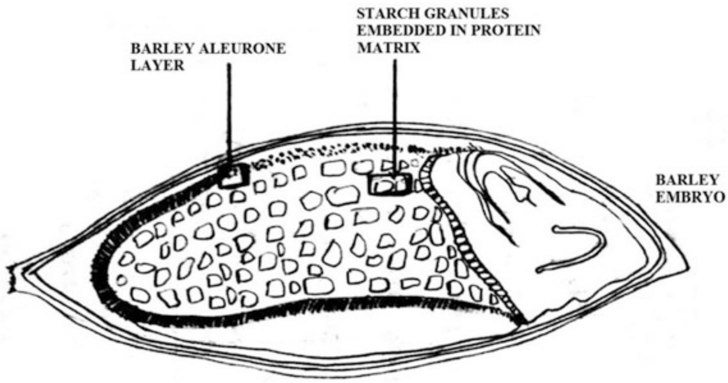


Fig. 10.4 Structure of barley grain

scutellum (2%) [3]. The aleurone layer contains numerous coatings usually 1–5 and is comparatively thicker at the dorsal side.

Barley It is another predominantly consumed cereal after wheat, rice, and corn. Barley grain mainly consists of endosperm, embryo, and covering layers of maternal origin (hull) (Fig. 10.4). The starchy endosperm surrounding the aleurone layer consists of maximum share, 75% of its weight of the barley grain [4]. The hull ranges 7–25% and comprises nearly 13% of grain weight [5]. Barley (low in protein) is specifically used for malting. On the other hand, high-protein barley has wider applications in animal feed especially for pigs and cattle.

Sorghum Sorghum comes under the category of millets. Millets are the group of tiny implanted grasses widely grown around the world as cereal crops. It is well-liked especially in Africa and Asia and is suited best for livestock feed. Sorghum grain is generally used in baking and its syrup is used as a sweetener. The composition of sorghum grain is generally similar to that of corn, except for lower oil content. Sorghum grain is composed of approximately 84% endosperm (storage tissue), 6.5% pericarp (outer layer), and 9.5% embryo.

Oats This cereal is considered as an important one predominantly in American and European countries. It has a blend of nutrients that possess health benefits particularly related to gastrointestinal problems. The main parts of oat include hull, germ, bran, and endosperm. A hull, which contains nearly 90% of the total insoluble fiber, is about 20–30% of the weight of oat kernel. Endosperm is rich in proteins, carbohydrates, and B-complex vitamins. On the other hand, germ/embryo is a very good source of essential fatty acids, trace minerals, and vitamins. Bran is also a good source of fiber, B-complex vitamins, and trace minerals. Oats contain excellent amounts of dietary fibers like β-glucan, lipids, phytochemicals, etc.

Rye It is particularly used for preparing crisp bread and health cereals and has not gained much importance in the market. The main parts of rye kernel are endosperm, hull, and germ. A whole kernel consists of starchy endosperm nearly 80–85%, the germ 2–3%, and hull 10–15% [6]. Rye is also an exceptionally good source of dietary fiber.

Fonio This cereal crop is well-liked in western regions of Africa and even in specific parts of India. This cereal is particularly employed in preparing porridge, bread, and beer. The endosperm comprises the major part of the fonio's kernel weight. The foremost parts of fonio grain are bran, endosperm, scutellum, and germ. Bran constitutes about 23% of fonio's kernel weight [7]. The four structural parts of endosperm are the aleurone layer and the peripheral, corneous, and floury endosperm. The thick cell walls of aleurone cells contain fat/oil, protein, minerals, and enzymes. The peripheral, corneous, and floury endosperms are beneath the aleurone layer and fonio has a single aleurone layer that completely encircles the endosperm. The chemical composition of fonio grains is similar to other cereals and pseudocereals with starch as the major component. The starch content can be over 80% on the dry basis. White fonio contains 7–17% moisture, 4.4–8.5% protein, 1.1–4.7% fat, 0.5–18.2% dietary fiber, and 0.5–3.1% ash [8]. Fonio is a rich source of micronutrients like copper, zinc, iron, and calcium and contains a moderate amount of macronutrients like protein and fiber.

Buckwheat This cereal crop is also very popular and is mainly consumed as flour and flour-based products. It is categorized as a pseudocereal; therefore, it shows both differences and similarities with cereals. It is very rich in nutrients like protein and amino acids and widely used in noodles, porridge, and pancakes. Buckwheat grain mainly consists of endosperm, embryo, and hull (pericarp) and is considered as an excellent source of macronutrients, micronutrients, and bioactive compounds. Buckwheat contains 1.5–3.7% fat and 11–14% protein with a balance of all essential amino acids. It also consists of 0.65–0.76% reducing sugars, 0.79–1.16% oligosaccharides, and 0.1–0.2% long-chain polysaccharides along with a good amount of thiamine, riboflavin, niacin, pantothenic acid, folate, and ascorbic acid [9]. In buckwheat grain, starch reserves are stored in the endosperm, as in common cereals, and the embryo, rich in fat and proteins, extends through the starchy endosperm [10]. The starchy endosperm layer is surrounded by the aleurone layer (rich in protein).

Quinoa It is a very popular pseudocereal and is mainly consumed all over the world due to its well-balanced amino acid profile, which is rare in other cereal grains. The exceptional nutritional value of quinoa relies on its balanced composition of high-quality protein, minerals, fibers, and minor compounds (such as antioxidants and vitamins). Quinoa contains 52–74% starch, 7–9.7% dietary fiber, and 9–17% protein. Oil content ranges from 2 to 9.5% being rich in essential fatty acids such as linoleic and α-linolenic and contains high concentrations of natural antioxidants such as α- and γ-tocopherol [11]. Embryo together with seed coat represents the overall bran fraction present in quinoa. Embryo is a rich source of fat, minerals, and dietary fiber.

Though wheat, rice, and maize simultaneously constitute 87% of the overall worldwide grain production. But there are other noticeable cereals that are consumed in a particular region. "Teff" belongs to such category of cereals, planted chiefly in Ethiopia, but is rarely familiar in other parts of the globe. It contains a very good amount of protein and fiber and is frequently consumed as staple food or occasionally utilized as breakfast cereal.

10.4 Production of Cereals

The enormous demand and supply of cereals in the worldwide trade are creating outstanding platform for the export of cereal-based products. According to the Food and Agriculture Organization, the total world cereal production during 2019 reached 2980 million tons, evincing 2.4% increase as compared to 2018 (Table 10.1). China is the largest producer of cereals in 2019 (615 million tons), followed by the United States of America (422 million tons) and India (324 million tons). The global production of cereals has come down from 2970 million tons in 2017 to 2910 million tons during 2018 (Table 10.1).

10.5 Properties of Cereals

The physical properties of cereal grains play a wide role in designing various equipment related to handling, storage, aeration, etc. The most important properties in this category are 1000 grain weight, sphericity, roundness, etc. These properties differ extensively, depending on density, moisture content of cereal grains, etc.

Table 10.1 World cereal production statistics (million tons) [12]

Year	Countries					World
	Brazil	China	India	Russian Federation	Unites States of America	
2010	75.16	498.00	268.00	59.61	401.00	2460.00
2011	77.58	521.00	288.00	91.78	386.00	2580.00
2012	89.90	541.00	293.00	68.75	356.00	2560.00
2013	101.00	554.00	295.00	90.36	434.00	2760.00
2014	101.00	559.00	296.00	103.00	443.00	2810.00
2015	106.00	620.00	284.00	102.00	432.00	2830.00
2016	84.16	616.00	298.00	118.00	503.00	2920.00
2017	118.00	616.00	311.00	131.00	440.00	2970.00
2018	103.00	611.00	322.00	110.00	440.00	2910.00
2019	121.00	615.00	324.00	118.00	422.00	2980.00

Thousand grain weight is a measure of compactness or dense filling of cereal grains. Basically, this is calculated directly by taking the weight of 1000 grains. This property is important in storage, handling, and processing of cereal grains and depends upon the size of grain and its density.

Sphericity refers to the resemblance of a food with a sphere, and it provides accurate estimation of shape-related parameters, which are important for determining several important properties like drag coefficient, terminal velocity, etc [13, 14].

Bulk density is one of the most important physical properties, which is beneficial in determining the storage requirement and can be calculated by estimating the weight of a cereal of a known volume. Porosity is a salient property of grains that influences various unit operations like milling, drying, etc. and is defined as the ratio of the percentage of void space to the total volume of grain space.

Angle of repose is particularly employed to measure the flow behavior of different grains and is defined as the angle between the conical surface of a grain pile at rest and the horizontal surface. The coefficient of friction is very useful to check the pressure of cereal grain against the silos and bin walls, which is an important factor in designing various harvesting and handling equipment for cereal grains. The coefficient of friction is dependent on various parameters like shape and moisture of cereal kernel, roughness/smoothness of surface, etc. The details of these properties and their estimation methods are discussed earlier in Chap. 2.

10.6 Composition and Nutrient Potential

Cereals are considered a good source of macronutrients and micronutrients. Intact cereal kernels mainly contain bran, endosperm, and germ.

Bran Bran is the hard outer layer of grain and consists of combined aleurone and pericarp. It is the outermost layer of grain, which is rich in micronutrients (vitamins and minerals), omega-3 fatty acids, etc.

Endosperm The huge central part of the cereal grain, which contains high levels of protein and starch and low levels of micronutrients (vitamins and minerals).

Germ This part of the cereal grain is the treasure of nutrients for the seed. This layer contains enormous amounts of micronutrients, fat, and protein content. The embryo (or germ) is a thin-walled structure that is separated by the scutellum from the endosperm.

Aleurone This layer lies just below the bran. This part of the grain is rich in vitamin B_1, phosphorous, protein, and fat. During milling, this layer of the grain is separated as bran from endosperm and germ.

All cereal grains possess high energy values, predominantly from the starch. Apart from moisture content and inedible substances such as cellulose, cereal grains

Table 10.2 Nutritional profile of various cereals[a] [16]

Grain	Moisture (g)	Protein (g)	Ash (g)	Total fat (g)	Total dietary fiber (g)	Carbohydrate (g)	Energy (kJ)
Wheat (whole)	10.58	10.59	1.42	1.47	11.23	64.72	1347
Rice (raw, milled)	9.93	7.94	0.56	0.52	2.81	78.24	1491
Brown rice	9.33	9.16	1.04	1.24	4.43	74.80	1480
Maize (sweet)	74.40	4.16	0.36	1.35	3.30	16.42	405
Barley	9.77	10.94	1.06	1.30	15.64	61.29	1321
Sorghum	9.01	9.97	1.39	1.73	10.22	67.68	1398
Quinoa	10.43	13.11	2.65	5.50	14.66	53.65	1374

[a] All values are expressed per 100 g edible portion

contain 65–75% carbohydrates, 2–6% lipids, and 7–12% protein along with traces of minerals and vitamins [15]. The comparison of nutritional profile of various cereal grains is presented in Table 10.2.

10.6.1 Health Benefits

Cereals provide numerous health benefits, including the supply of requisite nutrients in the daily diet of individual. These health benefits are due to the presence of various micronutrients (vitamins and minerals) and macronutrients.

Whole grains are a good source of phytonutrients (plant compound) that are required for maintaining a healthy human body. The various phytonutrients in whole cereal grains include saponins, lignans, and phenolic compounds that help in lowering the cholesterol level, regulate various metabolic activities, etc. The phytonutrient content varies considerably within and among the major cereal varieties. Cereals like oats are very rich in dietary fiber (soluble), which help in reducing cholesterol level in the human body. Sprouted cereals assist in weight loss.

10.7 Antinutritional Factors

Cereals contain comparatively higher proportions of phytate (phytic acid). Soft wheat contains 1.13% phytate, whereas phytate in oats, corn, and brown rice are 0.77%, 0.89%, and 0.89% on a dry weight basis, respectively [17]. In majority of the cereal grains, the phytate is prevalent in the aleurone layer and less concentrated in germ portion [18]. This clearly depicts that milling can substantially affect the phytic acid content in cereals [19]. Phytate can easily attach with various minerals like iron and zinc and make them unavailable.

The range up to which it influences the nutritional profile of cereals depends on numerous attributes, which includes the concentration of minerals and antinutrients in the food, overall diet plan, and nutritional profile of the consumer. Various antinutrients like tannins, which are generally found in sorghum, can attach with protein and reduce its digestibility. Various methods for improving the nutritional profile of sorghum are sprouting and treatment with ammonium bicarbonate, calcium oxide, etc. The predominant antinutrients that are prevalent in pearl millet are phytic acid, goitrogenic polyphenols, and C-glycosylflavones [20].

Antinutrients like trypsin inhibitors, which can diminish the digestibility of protein, have also been identified in pearl millet, but these can be inactivated by heat treatment [21]. There are numerous antinutritional factors present in rye, but those are of little importance because these can be reduced or eliminated by different treatments during processing and baking.

10.8 Processing of Cereals

10.8.1 Fermentation

The various examples of fermented cereal foods include *idli*, *dosa*, *dhokla*, *appam*, *kanji*, *chilra*, *sinki*, *kenkey* (fermented corn product) in Ghana, *tapéketan* (a rice pudding) in Indonesia, etc. [22]. In the bread making process, fermentation results in generation of carbon dioxide gas, which makes the dough to expand and increase in volume. In the proofing step, there is a breakdown of damaged starch by the action of amylase, which results in producing maltose that plays a very important role in maintaining the activity of yeast in bread making.

Lactic acid bacteria (LAB) are used along with yeast for producing sourdough bread that gives acidic taste to bread. Numerous biologically active compounds are expected to increase during fermentation of dough. Bacteria play a predominant role in making dough stronger by influencing the proteins present in the dough. The bioavailability of minerals in other fermented foods (cereal based) tends to be high. This may be due to the breakdown of phytic acid and other compounds in the whole process. Fermentation provides numerous benefits that include enhancement of the quality of protein and improvement in digestibility. Fermentation significantly increases in vitro starch and protein digestibility of selected cereal flours. Therefore, fermented foods are considered better as compared to unfermented ones due to activation of various endogenous enzymes that destroy the antinutritional factors [23]. As a result, it can significantly influence different physicochemical and functional properties.

10.8.2 Extrusion

It is high-temperature short-time (HTST) technique that requires a screw press with a limited gap to create different fabricated foods. Breakfast cereals and pastas are the common examples of extruded products. This process can affect the amount of soluble fiber, phytate, etc. The severe extrusion conditions can cause depolymerization and damage to the integrity of the cell walls, and it may lead to dissimilarity in density and hardness of the extrudates due to the reduction of molecular weight [24].

10.8.3 Milling

The conventional techniques of milling utilized pestle and mortar, but the product attained from these methods retains the least part of the germ portion. Light milling is alike to home pounding, which produces a product having the maximum nutritional value. On the other hand, heavy milling generates a tremendously refined product but nutritionally inferior.

10.8.4 Milling of Rice: A Case Study

Paddy (*Oryza Sativa* L.) is the most predominant food kernel of the world. Husk accounts around 20–25% of the weight of paddy. The objective of rice milling technique is to detach husk and bran coatings from paddy so as to generate intact rice kernels with minimum broken grains. The yield and grade of milling rely on several factors:

Cleaning
Cleaning of paddy is done so as to remove foreign matter like sand, stones, chaff, dust, etc. Cleaning is important to reduce storage space and to help in further processing and in proper storage of paddy.

Drying
This unit operation is done to reduce the moisture level of paddy from 18 to 25% to a desired value and 14% to ensure good storage life. The most preferable method of drying paddy is still sun drying in developing nations, and the best quality is achieved in a dry weather with comparatively low humidity. The substitute to natural drying technique is mechanical drying, in which hot air is blown through the paddy mass.

Milling
Milling of rice is done to get the maximum benefits from milled rice by reducing breakage to a minimum extent. Traditionally for milling, hand pounding method was the common but became unpopular after introduction of hullers. Commercially,

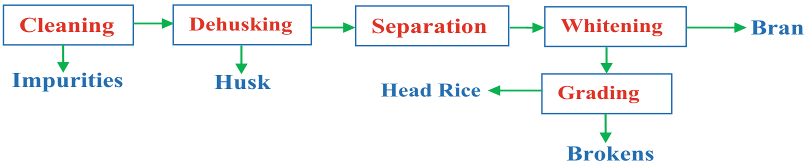


Fig. 10.5 Modern rice milling process

paddy is milled in a number of steps. The main stages of modern rice milling are dehusking, whitening, and grading (Fig. 10.5).

Milling of paddy in modern rice mill is performed in different steps with the purpose of reducing mechanical stress and heat buildup in the kernel, thereby reducing grain breakage and producing uniformly polished grain. In modern rice milling technique (Fig. 10.5), cleaning is the primary step that is done to separate out various impurities (like dust, seeds, stones, light empty grains, etc.) from paddy stock using an aspirator. If these impurities are not removed before dehusking, the efficiency of the huller and milling recovery are greatly affected.

After cleaning, the husk is removed from the paddy by friction and the step is known as dehusking or dehulling. It is achieved by the action of frictional force when paddy is passed in between two abrasive surfaces. Before the brown rice goes to the bran removal stage, husk must be separated. The main objective of using paddy separator is to separate husk from brown rice. The fractions of paddy and brown rice are separated on the basis of weight, physical differences, etc.

In the process of whitening (Fig. 10.5), the bran and germ layer of the brown rice are removed. To minimize the extent of broken grains, rice is generally passed through various whitening instruments that are linked to each other in series, and the surface of the rice is slightly polished to give it a shiny appearance. Polishing removes the remaining bran particles and therefore improves the appearance of milled rice. After polishing, white rice is graded into head rice and large and small rice broken by using oscillating screen sifters.

The milling quality of paddy is judged by means of several factors:

a. Husk content (%): It is calculated as the percentage of weight of husk to the weight of cleaned paddy.
b. Extent of polishing (%): It is defined as the percentage of weight of the bran to the weight of brown rice initially taken for polishing.
c. Overall rice outturn (%): It is calculated as the percentage of weight of milled rice to the weight of paddy sample taken for milling.
d. Whole rice outturn (%): It is defined as the percentage of weight of head rice to the weight of paddy sample taken for milling.

10.8.4.1 Parboiling

Rice is highly prone to breakage due to cracks in rice developed during harvesting and threshing, which cannot be retrieved by any other means except premilling process known as parboiling. Parboiling, literally, means partial boiling. In practice, it means boiling (i.e., cooking) of the rice within the husk (so as to retain its size and shape) after which it is dried. In other words, parboiling (hydrothermal treatment) is nothing but precooking of rice in paddy form. This treatment is given to paddy before milling so as to minimize breakage and to attain maximum recovery of head rice. This technique includes soaking, steaming, and drying the paddy (rice with husk).

About one-fifth of the world production and more than half of the paddy produced in India are reported to be parboiled. Cooking implies hydration and gelatinization of starch. The degree of gelatinization can also be affected by the method of cooking. The water-to-rice ratio can also affect textural parameters and degree of gelatinization. The gelatinization temperature generally lies between 50 and 80 °C. Parboiling with improved soaking methods can enhance the rice quality by reducing its glycemic index. Short- and long-grain varieties may result in loss of different constituents and cooking characteristics during different degrees of milling [25].

The milling characteristics of parboiled rice firmly depend on various drying conditions. While proper drying can, practically, avoid breakage of rice entirely, improper drying could lead to even 100% breakage. Drying, thus, plays the most crucial role in the technology and economics of parboiling. During the process of parboiling, the husk opens slightly due to swelling of the kernel. This makes the dehusking operations easier, thereby increasing the shelling capacity of the mill. As a matter of fact, the improvement in the milling quality sometimes offsets the cost of processing, and often the parboiled rice is sold at a cheaper rate than raw rice.

10.8.4.2 Crucial Steps in Parboiling Process

The three crucial steps in the parboiling are generally adopted as:

1. Soaking of paddy in water to enhance the moisture content
2. Steaming of paddy to attain partial gelatinization
3. Drying of paddy to achieve the desired (14%) moisture content

10.8.4.3 Different Stages of Parboiling

1. Soaking: Soaking of paddy is carried out by dipping in water at or below its gelatinization temperature. Dipping in water at room temperature takes a prolonged time (72 h) for soaking treatment, making paddy susceptible to development of mycotoxins. Hence, soaking at elevated temperature of water is considered better. The soaking duration varies with temperature. The lower the temperature used for soaking paddy, the slow the process for soaking is and vice versa (Table 10.3).

The following time–temperature combination is considered for soaking treatment (Table 10.3):

Table 10.3 Optimal time–temperature conditions for soaking paddy [26]

S. no.	Temperature (°C)	Time (h)
1	60	8
2	65	6
3	70	4
4	72	3.5

2. Steaming: In this operation, soaked paddy is exposed to steam so that the starch present in the rice grain gets gelatinized. Heat for gelatinization of starch is supplied by saturated steam (pressure range of 1–5 kg/cm^2) [27]. The time duration of steaming operation varies as per the quantity of paddy. The longer steaming time and higher temperature may result in harder and dark-colored rice.
3. Drying: After steaming, paddy is dried to 14–16% moisture content to impart hardness to the grains required for milling and subsequent storage. Drying is done to minimize the moisture from 45–50% (db) to 14–16% (db). Parboiled paddy may be sun dried or use hot air. Rapid drying gives high breakage during milling. In a continuous drying system, the breakage starts at moisture, around 18%, and increases rapidly with further drying [28] due to the development of cracks while cooling of grains. Therefore, the paddy is dried to 18–20% moisture content in the first stage and left for 4–8 h for tempering, which is dried further till attaining the moisture of about 14% in the second stage of drying. Afterwards, the dried paddy with 14% moisture is milled using huller or rubber roll sheller to separate the kernels and husk of parboiled paddy.

10.8.4.4 Benefits of Parboiling

Parboiling process provides numerous benefits like:

1. Higher vitamin content than raw milled rice.
2. Extensively employed in the catering industry as it is comparatively less sticky when cooked.
3. Improvement of texture profile of rice, making it firm and less sticky.
4. Nutritionally better as it contains a very good amount of Vitamin B1 and niacin and a moderate amount of zinc and iron. Digestibility of parboiled rice is better.
5. Increase in milling yield and improvement in quality.

10.8.4.5 Drawbacks of Parboiling

Several drawbacks associated with parboiling process are mentioned as under:

1. Rupturing of protein and decrease in solubility.
2. More susceptible to oxidative rancidity leading to deterioration of flavor.
3. Longer milling time is required due to hardening of the grains.
4. Polishing of parboiled brown rice leads to the problem of rice stickiness and clogging of the mill screen.

5. Polishing of parboiled rice requires more power, thereby lowering down the capacity of the polisher.
6. It adds to the cost of drying.

10.8.4.6 Parboiling Methods

A number of methods of parboiling of paddy have been adopted worldwide, but the commonly used methods on a large scale for parboiling of paddy are discussed as under:

Single Boiling Method

In this method, paddy is firstly soaked in cold water in tanks for some days. The prolonged soaking of the paddy results in fermentation that produces a bad odor. Afterwards, steaming is carried out. The soaking time is comparatively more in this method. This process is either performed batchwise or run on a continuous platform. The entire technique of parboiling relies on several parameters like type, quality of paddy, and the attributes of the final product.

Double Boiling Method

This method requires double steaming activity in a series of unit operations. The two steaming kettles made of mild steel equipped with steam pipe are used. In this method, steam is first injected into raw paddy in steaming kettle before soaking. Hot paddy raises the temperature of soaking water to 45–50 °C, which assists to decrease the soaking time to 24 h. The soaked paddy is further raised backward into the steaming kettles for another steaming process. The technique followed for this steaming process is exactly similar as done in earlier step. The parboiled paddy is then released from the kettles and allowed to dry using mechanical drier.

CFTRI Method

This process was created by Central Food Technological Research Institute, Mysore (CFTRI), for improving the grade and yield of rice. In this method, both soaking and steaming operations are performed in similar cylindrical tanks made of mild steel. First, paddy is soaked in hot water (85 °C) in parboiling tank for 3–3.5 h. Afterwards, excess water is drained from parboiling tank and steaming is carried out by maintaining a pressure of 4 kg/cm^2. Then, drying of steamed paddy is done in a number of stages. The demand of water and steam during parboiling operation is approximately 1.25 times the weight of paddy and 200 kg/ton of paddy, respectively.

10.8.4.7 Effect of Parboiling on Milling, Cooking, and Nutritional Quality

Milling and Nutritional Quality

1. Parboiling results in the reduction of breakage.
2. There is an improvement in milling quality of rice due to gelatinization of starch, and as a result, it increases the yield of head rice.
3. Parboiled rice is rich in protein and micronutrients like vitamins and minerals.
4. Parboiled rice contains lesser oil/fat.

5. Bran of parboiled rice contains lesser starch and more oil as compared to raw rice bran.

Cooking Quality

Cooking quality of rice relies on several factors like cooking time, expansion ratio, water absorption capacity (WAC), etc. The effect of parboiling on the cooking quality is summarized as follows:

1. Parboiled rice takes longer cooking time as compared to raw rice to achieve the required softness.
2. The solid gruel loss is lesser in the case of parboiled rice.
3. Parboiled rice cooks flakier than raw rice.
4. Water absorption capacity (WAC) of parboiled rice when fully cooked is more than that of raw rice.

10.8.5 Milling of Wheat: A Case Study

Wheat is the second most predominant cereal grain in South Asia after rice. Wheat is processed to make flour, which additionally acts as a main ingredient for making extruded products, soft wheat flour–based products (cookies, biscuits), hard wheat flour–based products (like bread), etc.

10.8.5.1 Pre-cleaning/First Cleaning

Initially, wheat is weighed, inspected, and graded prior to cleaning. Wheat procured from various sources may contain weed seeds, chaff, shrunken wheat, unripe and broken wheat, sand, stones, mud balls, and seeds of other crops, viz., mustard, maize, barley, or Bengal gram, due to prevalent agricultural and handling practices. The pre-cleaning is performed to remove dust and coarse impurities to avoid choking in further processing. The cleaning of wheat starts with magnetic separator to remove the metallic parts, which is followed by sieving operation to remove bigger impurities like maize, straw, etc. using 7–8 mm sieve and fine impurities like sand, fine brokens, etc. using 0.2 mm sieves. The wheat received from the sieving operation is fed to disc separators to separate the wheat from other produces, based on size. Some weeds are very harmful or even poisonous, which must be eliminated before grinding operation.

10.8.5.2 Conditioning/Dampening of Cleaned Wheat

The cleaned wheat is damped using a washer-whizzer and stored for conditioning in bins to allow water to penetrate deep inside the wheat grains and to maintain uniform moisture content. The appropriate time should be provided for grains to achieve the desired mellowness of the endosperm and toughness of bran. Hard wheat needs more time for conditioning. The water addition in stages renders better results than the water addition in lot at one time.

The desired mellowness causes endosperm to easily reduce in desired particle size and the desired toughness of bran does not allow easier fragmentation [29]. However, over moistening of grains should be avoided as it may create problems during sifting operation. About 8–48 h is required for various wheat varieties to maintain moisture level of 15–17.5% moisture, while it needs only 3–6 h in the case of durum wheat. The good dampener of wheat should be capable of adding appropriate and correct quantity of water up to 5% in a single stage. It should also distribute the moisture evenly around the grain surface and among all the grains in the lot.

10.8.5.3 Second Cleaning

The polishing of outer surface of wheat grains is performed using scourer. The second cleaning does not remove germ, but it facilitates breaking in the first breaker rolls. The scouring due to friction among the grains provides the most ideal operation, which could be achieved holding the grains back in the machine. The dirt generated during scouring is passed through the perforated jacket. The scoured wheat is passed through the aspiration channel. The water is added through atomization at the rate of 0.3–0.5%, which toughens the bran and does not allow bran to be mixed into the powder [30].

10.8.5.4 Milling

The grains are broken during milling operation, and ground endosperm portion is collected as flour. The bran and germ portion should be eliminated from the flour. The roller mills are used in flour milling units, which may consist of various types of rollers, viz., grooved, fluted, striated, and plain rollers based on required operation.

Rollers

Generally, 250 mm diameter and 1000 m length rollers are used in roller mills. Sometimes greater length may also be adopted according to the specific requirement. These rollers are hollow in structure and made of gray cast iron, which is hardened using appropriate chilling method. The hardened surface remains at the surface of roller at about 15 mm, which is reduced in fluted/grooved rollers. The rollers may be classified into two categories, i.e., break rollers/rolls and reduction rollers/rolls.

Break Rolls/Rollers

The serrations/striations are made on the roller surface in inclined directions with respect to the axis of rolls. In the case of fluted/grooved rolls, special care of roller in terms of damage should be taken as it affects the product characteristics. The objective of the grooved rolls is to create the first break and scrap out the bran pieces in subsequent breaking operations. The tensile strength of the break rolls is about1650–1800 N/mm^2 (equivalent to 480–520 Brinell hardness number). The fineness of rollers increases with further subsequent break processes, e.g., the second break roller is smoother than the first break rollers. The grooves/flutes become smaller and are kept 3.2–4.1, 5.1–5.7, 6.4–7.0, 8.6–9.6, and 10.2–10.8 flutes/grooves/cm in the first, second, third, fourth, and fifth break rolls, respectively [30].

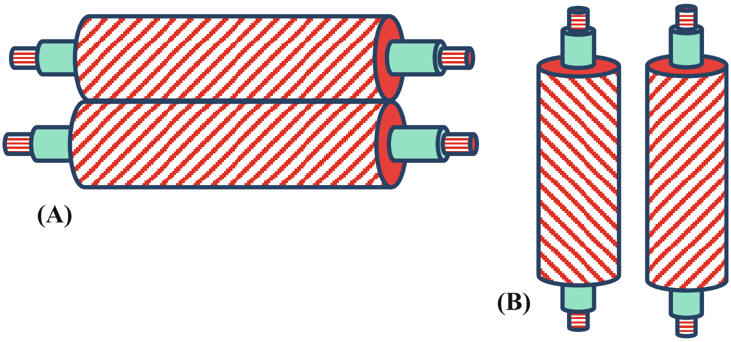


Fig. 10.6 (**a**) Spiral break rollers in arrangement and (**b**) left- and right-hand spirals

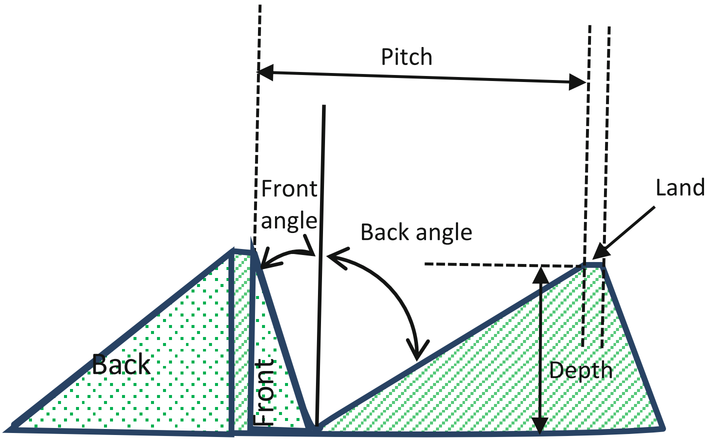


Fig. 10.7 Nomenclature of flutes of break rollers

The top and bottom rollers run at different speeds to provide shearing action for crushing the wheat grains (Fig. 10.6a. The rollers are driven using gears or toothed belt drives. The faster roller runs at 480–550 revolutions/min in break rolls and the slower roller runs at speed ratio of 1:2.5 ratios with the faster roller [30]. Higher shearing and scraping can be attained using a greater difference in speed of both the break rollers.

The break rollers have inclined grooves on its surface, which are termed as spirals. The inclination is usually expressed in terms of percentage. Both the break rollers may have either left-aligned spiral or right-aligned spiral (Fig. 10.6b). Left- and right-aligned spirals are not used together as it does not result in desired breaking operation. The first break roller uses about 4% spirals, which increases up to 10% till the last break rolls. The larger angle of spiral provides more numbers of crossings of the spirals, which results in more cutting action. The flute angle may be expressed in terms of front angle and back angle (Fig. 10.7). The front angle refers to the angle formed in the cutting side, while the back angle represents the depth of the flutes.

Break System

The break system has grooved rollers and is used to open the wheat structure and scrap the endosperm from the bran layer/skin left on the flat outer flakes. The cutting of bran skins should be minimized. The wheat skin, which contains the bran layer, should be left as large as possible for not mixing in the endosperm part. The main function of the break system is to release maximum amount of coarse material, i.e., semolina, middling, and minimum amount of flour. The material received from the break system is fed to plansifter for separating the coarse material/semolina and flour. The coarse material/semolina are fed to the purifier, which separates the branny flakes from pure endosperm. The clean endosperm is fed to the reduction system for converting it into the flour. The effectiveness of the break system depends on the moisture content of wheat, flutes of the rolls, and flute condition [30]. The more numbers of break rolls used in the system minimize the possibility of cutting the bran layer unnecessarily and help in retaining the bran layer as large as possible.

The wheat is broken in the first break, and several fractions are produced, viz., break stock (greater than 1000 μm), semolina (280–1000 μm), middling (180–280μm), dunst (coarse flour, 132–180 μm), and flour [30].These fractions are separated using plansifter, which has a screen of different sizes. The bran finishers are also used to remove endosperm particles from the bran before sending it to the next rollers. The coarsest break stock (greater than 1680 μm) and fine break stock (1000–1680 μm) particles are adhered with bran [30], which are sent to the next break roller for cutting, and similar separation is carried out. The material received after every stage of break rollers is sent to the plansifter before sending it to the next rollers.

The bran portion is the highest in coarse stock and lowest in flour. Every break roller should provide maximum quantity of coarse material, which is separated from the endosperm part from the stock. The semolina and middling proportions contain pure endosperm particles along with particles with attached bran. This stock is sent to the purification process to separate similar-sized material based on their mass. The dunst is sent to the reduction system for grinding into the flour, and the flour received from each break passes is sent to the flour outlet. The break and reduction roller system in wheat milling is presented in Fig. 10.8 as under:

Reduction System

The reduction rollers do not have grooves/flutes and run at different speeds like breaking rollers and are driven using gears or toothed belt drives. These are usually smooth surfaced; however, abrasive surface can also be made to enhance grinding. The tensile strength of the reduction rolls is about 1350–1435 N/mm^2 (equivalents to 400–420 Brinell hardness number). The faster roller runs at about 380–420 revolutions per minute and the slower roller runs at a lower speed ratio of 1:1.25. The higher differential speed generates comparatively higher heats in the rolls and ground material and causes shearing of bran particles, which is not preferred.

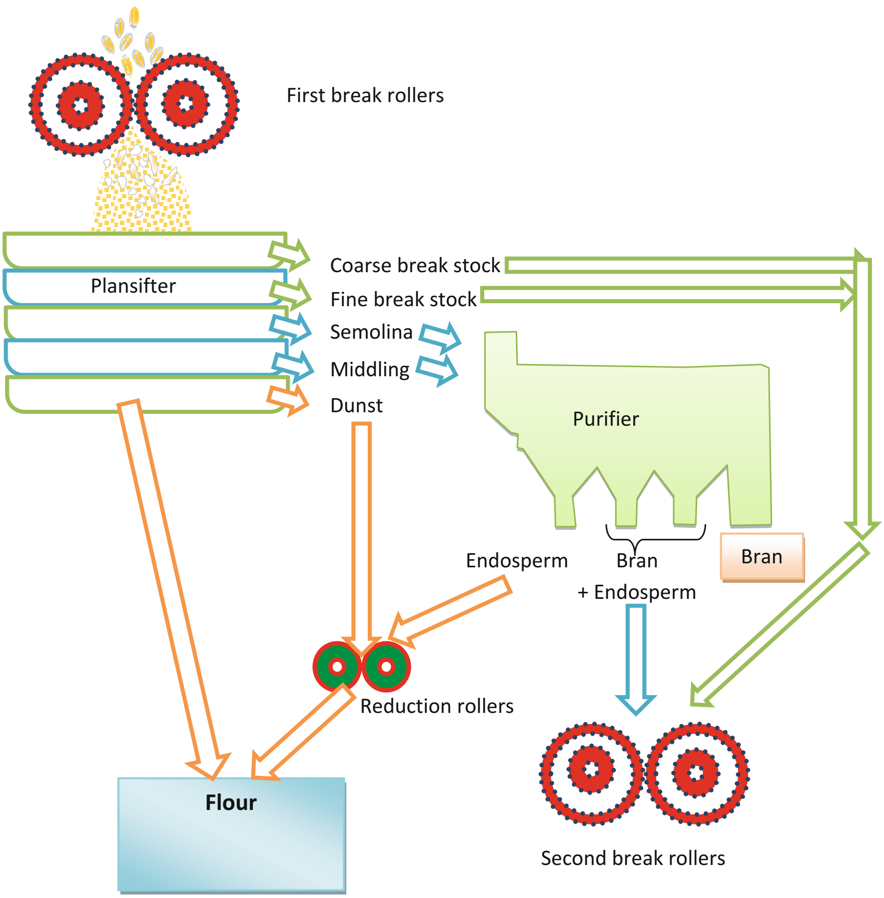


Fig. 10.8 Break and reduction roller system in wheat milling process

The clean endosperm portion of wheat received from plansifter and purifier is fed to the reduction rollers to produce the flour. The reduction system also consists of a series of reduction rollers and plansifters. This system reduces the size to the desired product size. The clean endosperm particle breaks and shattered as flour, while the remaining branny stock is compressed into thin/flat particles. This is being removed using plansifter. The commercial milling of wheat involves 8 to 12 reduction passages to grind endosperm into flour [30].

Purification

The material collected from the sifters may contain bran. Therefore, purification is carried out to separate bran from endosperm particles on the basis of their terminal velocity by the application of air currents. *Semolina (sooji)* of different granulations is handled in the purification system to separate out clean endosperm particles, which are finally ground to flour in the reduction system [30]. Purifiers can remove bran

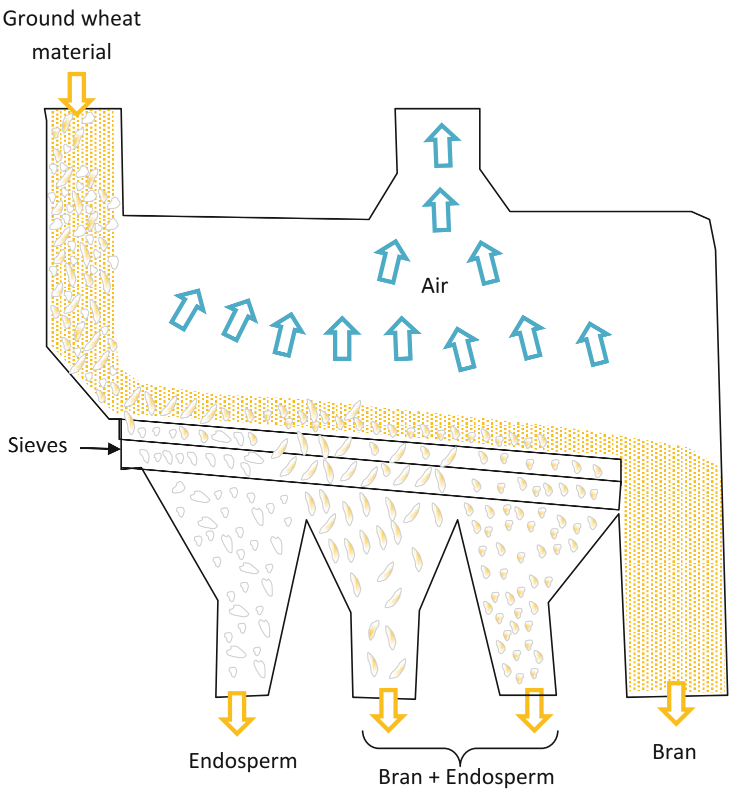


Fig. 10.9 Schematic diagram of a purifier, including the flow of air and product

and produce more refined flours from middling (Fig. 10.9). In a purifier, a controlled circulation of air is used to separate lighter-weighed bran. The separation of coarse fractions on the basis of size is also performed. Purifiers are particularly employed in a flour mill to separate the semolina/middling from bran particles and to classify the semolina/middling to pure and composite stock and send it to their proper destinations. This helps the miller to produce good-quality semolina and mill into flours of low ash content. A portion of purified stock is packed as *Semolina (sooji)*, while the remaining material is reduced to the desired particle size in the reduction system to obtain wheat flour *(maida)*.

The average range of *maida (wheat flour)*, semolina *(sooji)*, *atta* (wheat flour), and bran is 49–55%, 8–10%, 15–18%, and 22–23%, respectively, from the overall wheat milling operation. In case of increasing the extraction rate of *maida* (wheat flour), the reduction of semolina *(sooji)* can also be performed in reduction rollers. Extraction rate is defined as the amount of wheat flour that is extracted from a given weight of clean and conditioned wheat.

The specifications for *atta* (wheat flour), *maida (wheat flour)*, and semolina are presented in Tables 10.4, 10.5, and 10.6. Gluten is the main principal functional

Table 10.4 Specifications for *atta* (wheat flour)

S. no.	Characteristics	Low gluten [31]	High gluten [31]	Coarse ground wheat product [32]	Fortified atta [32]	Protein-rich atta [32]
1.	Moisture, % (max.)	13.00	13.00	14.00	14.00	14.00
2.	Total ash, % (max.)	2.5	2.5	2.00	2.00	2.75
3.	Acid-insoluble ash, % (max.)	0.10	0.10	0.15	0.15	0.10
4.	Gluten, % min	7.0–9.0	Above 9.0	6.0	6.0	
5.	Alcoholic acidity (max.)	0.10	0.10	0.18	0.18	0.12
6.	Granularity	Pass through 99.8% material through 0.600 mm sieve	Pass through 99.8% material through 0.600 mm sieve	–	–	–
7.	Crude fiber, % (max.)	2.5	2.5	–	–	2.5
8.	Total protein, % (max.)	–	–	–	–	12.5
9.	Fortification (max.)	–	–	–	Ca, 1500 mg; iron, 60 mg; sodium iron, 25 mg; zinc, 30 mg; vitamin A, 1500 μg RE; ascorbic acid, 100 mg; thiamine, 3.5 mg; riboflavin, 4.0 mg; niacin, 45 mg; pyridoxine, 5.0 mg; folic acid, 250 μg; vitamin B12, 2.5 μg; vitamin D, 1000 IU	Groundnut flour, soya flour, groundnut–soya flour mix, 10%

Table 10.5 Specifications for *maida* (wheat flour)

S. no.	Characteristics	Maida [33]	Maida [34]	Maida (bakery) [34]	Fortified maida [34]	Protein-rich maida [34]	Durum wheat maida [34]
1.	Moisture, % (max.)	13.00	14.00	14.00	14.00	14.00	13.00
2.	Total ash, % (max.)	0.70	1.0	1.0	1.0	1.4	1.75
3.	Acid-insoluble ash, % (max.)	0.05	0.1	0.1	0.1	0.1	0.15
4.	Gluten, % min	7.5	7.5	7.5	7.5	7.0	–
5.	Alcoholic acidity (max.)	0.10	0.12	0.12	0.12	0.12	0.12
6.	Granularity	Pass material through 100%, 0.18 mm (180 μm IS sieve)	–	–	–	–	Pass material through 315 μ sieve
7.	Uric acid, mg/100 g (max.)	10	–	–	–	–	–
8.	Crude fiber, % (max.)	–	–	–	–	0.53	–
9.	Total protein, % (min.)	–	–	–	–	12.5	11.0

(continued)

Table 10.5 (continued)

S. no.	Characteristics	Maida [33]	Maida [34]	Maida (bakery) [34]	Fortified maida [34]	Protein-rich maida [34]	Durum wheat maida [34]
10.	Fortification (max.)	–	–	Benzoyl peroxide, 40 ppm; potassium bromate, 20 ppm; ascorbic acid, 200 ppm	Ca, 1500 mg; iron, 60 mg; sodium iron, 25 mg; zinc, 30 mg; vitamin A, 1500 μg RE; ascorbic acid, 100 mg; thiamine, 3.5 mg; riboflavin, 4.0 mg; niacin, 45 mg; pyridoxine, 5.0 mg; folic acid, 250 μg; vitamin B12, 2.5 μg; vitamin D, 1000 IU	–	–

Table 10.6 Specifications for semolina (*sooji*)

S. no.	Characteristics	Semolina/sooji/suji [34] Large particle grade	Semolina/sooji/suji [34] Small particle grade	Semolina/sooji/suji/rawa [32]
1.	Moisture, % (max.)	13.50	13.50	14.50
2.	Total ash, % (max.)	1.00	1.00	1.00
3.	Acid-insoluble ash, % (max.)	0.05	0.05	0.10
4.	Gluten, % min.	6.0	6.0	6.0
5.	Alcoholic acidity, max.	0.10	0.10	0.18
6.	Granularity	• 100% pass through, 1.18 mm sieve • 90% retained on 0.73 mm sieve • 98% retained on 0.24 mm sieve	• 100% pass through, 1.18 mm sieve • 10% retained on 0.73 mm sieve • 98% retained on 0.24 mm sieve	–
7.	Uric acid, mg/100 g (max.)	–	–	–
8.	Crude fiber, % (max.)	–	–	–

protein in wheat flour. The amount of gluten in *maida (wheat flour)*, *atta* (wheat flour), and semolina are 7.5, 7–9, and 6%, respectively (Table 10.4). Alcoholic acidity is considered as an index of deterioration of sample during storage. High alcoholic acidity value reflects changes in the sample due to enzymatic hydrolysis.

The wheat flour particle should remain less than 0.600 mm in size [30]. The fortification of various minerals and vitamins is permissible under the category of fortified *atta* (wheat flour). Protein-rich *atta* can also be prepared by adding groundnut flour, soya flour, or the mixture thereof in the ratio of not more than 10%, which may enhance the protein content as high as 12.5%.

The *maida* (wheat flour) particle should remain less than 0.180 mm in size [34]. The fortification of various minerals and vitamins is also permissible. Protein-rich *maida* (wheat flour) can also be prepared by adding protein-rich source, which may enhance the protein content as high as 12.5% and is permissible.

10.8.6 Milling of Corn: A Case Study

10.8.6.1 Wet Milling of Corn

This technique uses plenty of water for steeping of grains so as to separate out the germ fraction. The difference between dry and wet corn milling is that wet corn milling initiates with a squeezed soft pulp, whereas dry corn milling begins with a raw corn seed. The flow sheet representing the wet milling of corn is presented in Fig. 10.10.

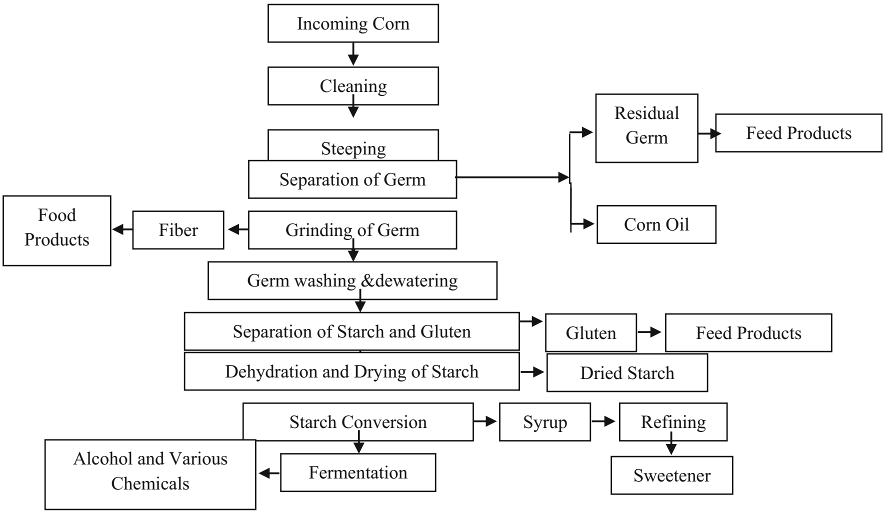


Fig. 10.10 Wet milling of corn

1. Cleaning: The incoming corn is first cleaned so as to remove dust and various other objects that can cause trouble in the further milling operations. It can be achieved with the help of various screens and by the use of compressed air that helps in removing the impurities.
2. Steeping: The prime objective of this step is to soften corn kernels. Additionally, steeping (Fig. 10.10) is achieved by hydration of kernels that results in softening of germ portion and disruption/formation of various internal bonds and interactions. In this step, cleaned corn kernels are treated with lukewarm water for a specific period of time. The temperature of water should be in between 54 and 58 °C.
3. Germ separation and grinding: The softened corn is ground in mills to disintegrate the grain and extract germ out of the corn. The separation of germ (low density) from the slurry is achieved by the application of cyclone separators. The different extraction techniques can be applied to withdraw oil from the germ. The germ residue is considered as an additional convenient ingredient for animal feed.
4. Germ washing and dewatering: The starch slurry is removed through a germ washing stage (Fig. 10.10). Generally, germ is rinsed in few steps to detach the leftover starch in the fluid from germ cyclones and to prepare the germ to pass through germ dewatering press.
5. Starch and gluten separation: The separation of gluten from the starch is achieved by centrifugation process that relies on density differences between starch and protein.
6. Dehydration and drying: Starch can be modified into specialty starches or transformed into corn syrups and glucose. The refined starch is further dehydrated by employing centrifugation technique and then dried using a flash dryer.

7. Conversion of starch into syrup: Corn starch can further be modified into other products like corn sweeteners, corn syrups, etc. Corn starch is liquified with acid and/or enzymes to a resultant product (dextrose solution), which can be purified using filters, centrifuges, and ion-exchange columns. The surplus amount of water is evaporated. Syrups are either used as such or further processed to prepare high-fructose corn syrups (HFCS).
8. Fermentation: In this stage, glucose is transformed into alcohol or other products by fermentation technique (Fig. 10.10) by the action of yeast and other bioproducts through either yeast or bacterial fermentation. After fermentation, distillation is carried out to recover alcohol from the resulting broth through various techniques.

10.8.6.2 Dry Milling of Corn

Dry milling of corn is a lesser-capital-oriented technique that targets to produce grain ethanol. This technique is preferably done to utilize corn by converting it into breakfast cereals; animal feed, additional feed ingredients (e.g., corn meal), etc. The flow sheet representing the dry milling of corn is presented in Fig. 10.11.

The dry milling of corn accompanies the following stages:

1. Cleaning: This step involves screening of particles on the basis of shape and density so as to remove ferromagnetic metals and other unwanted materials.
2. Conditioning: After the cleaning step, conditioning (Fig. 10.11) is done for equilibrating the moisture within the grains. The optimum moisture content of grains should be 20% at this stage, and moistened corn is allowed to equilibrate for 1–3 h. The aim of this operation is to loosen the germ and toughen the bran.
3. Degermination: The aim of this operation is to detach hull, tip cap, and germ by leaving the endosperm into large grits. This can be achieved by either roller mills and sifters/degerminator or impact machines.
4. Drying: The degermed product is further dried so as to achieve the required moisture content (15–18%) for effective grinding and screening operations. Drying is done by employing conventional rotary dryers (50 °C).
5. Cooling: In this step, rotary coolers (cross and counter flow) are employed for subsequent cooling of dried products.
6. Aspiration: After cooling, aspiration (Fig. 10.11) is done to separate the bran from the mixture of germ and endosperm. The separation of bran is achieved on the basis of terminal velocity, which in turn relies on shape, density, and particle size.
7. Gravity separator: After aspiration, the particles of a mixture with different specific weights are separated using gravity separation. The specific gravity separation is done using gravity separators so as to separate endosperm from the germ.
8. Milling: The milling operation consists of a number of steps like grinding, classifying, sifting, and purification. Grinding of endosperm fractions is done by means of roller mills. Different endosperm fractions are first passed to break rolls and then to reduction rolls so as to attain the required particle size. Then,

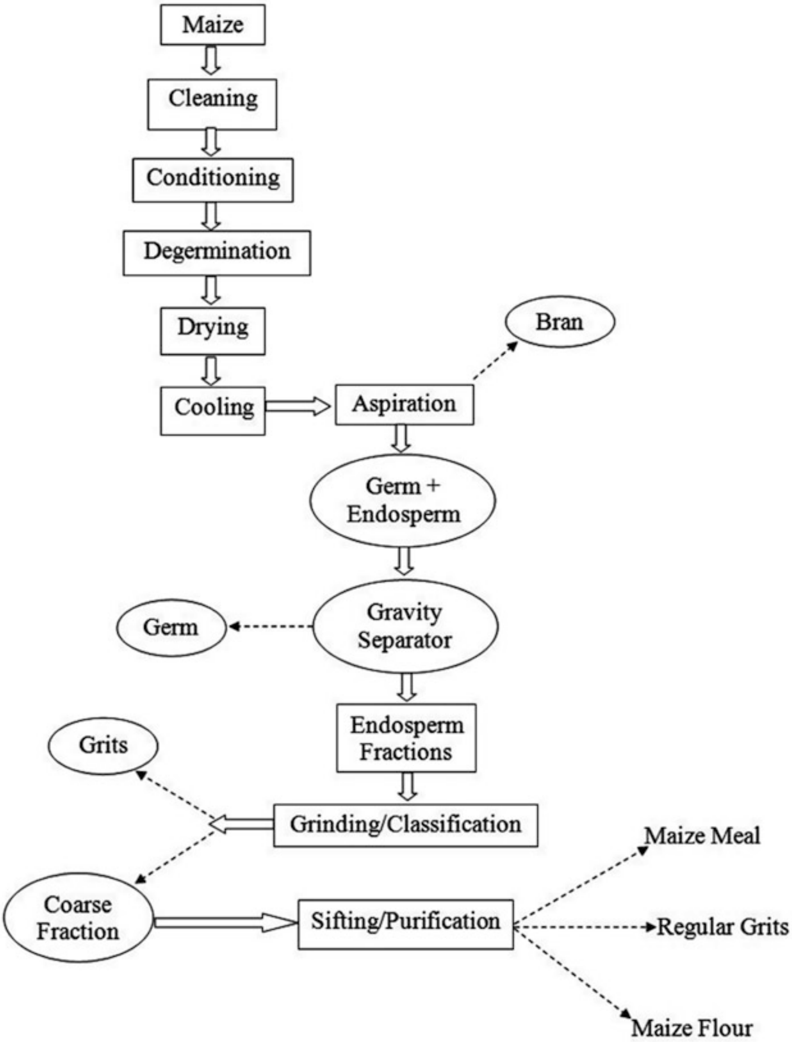


Fig. 10.11 Dry milling of corn

different fractions are passed through the sifters and purifier to get different products like maize meal, regular grits, maize flour, etc. (Fig. 10.11).

10.9 Equipment Involved in Handling and Processing of Cereals

Various equipment are involved in processing of cereals. Milling operations require dehusker, pearler, grinder/size reduction equipment, mixer, polisher, etc. However, several other equipment are also used in processing of cereals. Most of the equipment used for milling are made up of mild steel. Some of the important equipment are described as under:

10.9.1 Hullers/Grinders

Dehulling is the technique of detaching hulls from seeds/grains by passing the grains in between two abrasive surfaces that are rotating at different speeds. Following dehusking, the husk is separated by suction and conveyed to a preservation damp outside the mill.

10.9.1.1 Rice Dehuller

This equipment operates at a very high speed performing both dehulling and cleaning operations simultaneously in one operation. The equipment, being light in weight, can be easily moved to the operation sight by means of wheels provided on its frame. The dehulled rice grains are automatically conveyed to the sieves of the separator attached with the dehuller for removing the bran and other dust particles.

10.9.1.2 Rice Huller Polisher

In this equipment, paddy is fed into the hulling unit via hopper. The hulling unit consists of an enclosed cylinder in which a special rotor having helical and longitudinal ribs operates [35]. The polishing unit is positioned just below the huller and comprises of emery rollers to obtain clean and polished rice. The clearance between the rotor and cylinder is adjusted to obtain high hulling efficiency and prevent grain breakage. This equipment is specifically used to remove hulls from paddy and to polish the rice grain in a single unit/operation.

10.9.1.3 Rubber Roller/Rubber Roll Sheller

Numerous designs of rubber roller are extensively used in industries. These machines are made in several forms.

The rubber roller shell comprises of two rubber rollers having the same diameter and rotates at different speeds in opposite direction (Fig. 10.12). The space between rubber rollers is adjusted by keeping in mind the excessive wear and tear of the equipment, intensive heat liberation, etc. The circumferential speed variation pushes the paddy grains to strike in between the two rubber rollers that result in shearing operation and detach the husk from the grain.

The rubber rollers are then further cooled or refreshed by air blast around the surface of rollers. The rate of dehusking using rubber roller shell is nearly sustained around 85%. The longevity of the rubber rollers differs with various conditions like type and moisture of paddy, quality of rolls and pressure applied to rolls, etc. The rubber roller dehusker has an advantage of getting negligible breakage.

10.9.1.4 Hammer Mill

Hammer mill is employed for crushing a wide range of materials into small particles having free-flowing properties by the application of impact force. The crushing of

Fig. 10.12 Rubber roller

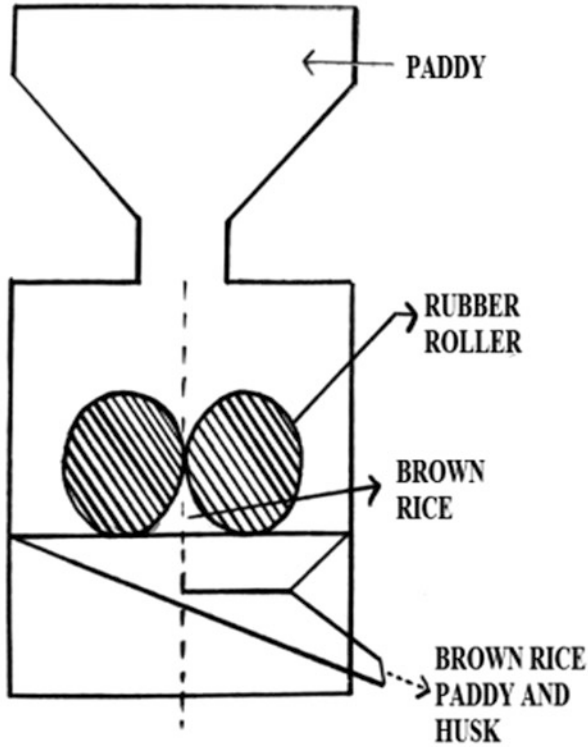
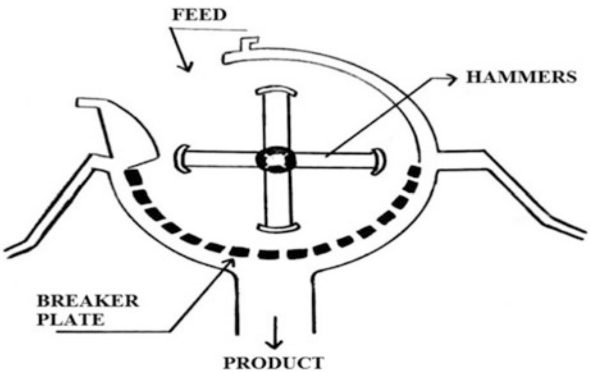


Fig. 10.13 Hammer mill



materials further depends upon the speed of the mill that varies between 1000 and 2500 rpm for comminuting large size particles. The foremost mechanism involved is the pulverization of the material.

Hammer mill consists of series of hammers (normally fabricated with hardened steel) confined within a metal shell and mounted on a central shaft (Fig. 10.13). It comprises of high speed rotor revolving inside a cylindrical metal shell. The basic principle behind working of hammer mill is the impact force. The feed material is put into the hopper that is coupled with the drum (Fig. 10.13). The material is crushed to the desired size by accelerated rotating hammers by the action of impact force and accumulated on screen. Breaker plate or screen is fitted at the bottom of the hammer mill, which retains coarse material while permitting appropriate sized materials to pass as final finished product (Fig. 10.13). One of the best advantages of hammer mill is its continuity due to which jamming is minimized. The mill produces coarse to moderately fine powder. Its accelerated speed of working sometimes creates damage to the mill if foreign matter such as stones or metal is present in feed.

10.9.1.5 Ball Mill

Ball mill (or pebble mill) consists of a hollow cylindrical shell that regularly rotates around its own axis (Fig. 10.14). The balls are considered as the milling elements, and drive rollers assist to rotate the milling chamber. The comminution in ball mill is achieved by the action of impact and attrition. More than half of the bulk is covered with steel balls. Whenever the cylindrical shell rotates, balls are lifted up and down. Centrifugal force plays a predominating role by keeping the ball in contact with the mill wall and with one another during the upward movement. In the process, the solid particles in between the steel balls and ground are comminuted by impact force.

The extent of milling using ball mill is affected by numerous factors like size, nature, and the quantity of balls, residence time of material in the mill, rotating speed of mill, etc. One of the best advantages of ball mill is its continuity, wide applications, ability of producing very fine particle, etc. The major disadvantages associated with ball mill are contamination of the product, long time of milling, difficulty of cleaning the mill after usage, etc. Ball mill is suitable for dry or wet grinding and widely used for crushing of various materials, producing superfine food powders, wheat flour, fruit powders, etc.

10.9.2 Separators

Grains are always mixed with various impurities such as pod, pebble, and sand grass during harvesting, transportation, and storage. Before processing, grains are to be cleaned.

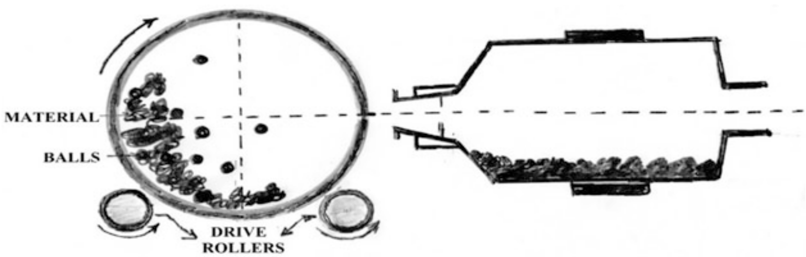


Fig. 10.14 Ball mill

10.9.2.1 Cyclone Separators

This type of equipment is cylindrical or conical in shape in which a high-speed rotating airflow in a helical pattern is entrenched. A fan sucks flour from the mill via screen and conveys to the cyclone separator.

It is necessary to draft the cyclone separator in a proper manner so as to ignore the losing product into the air. The distinct drafts/designs for conveying flour are presented in Fig. 10.15. The finer the fan suction is , the faster the separation of flour from the mill is, and the finest will be the pipe draft/design (Fig. 10.15).

In evaluating the design of a cyclone separator, pressure drop is a primary factor that depends on the cyclone design and its operating parameters such as inlet velocity. The best design is chosen for proper conveying of the flour using cyclone separators as it results in higher inlet velocity, less kinetic energy loss, and frictional loss due to minimum pipe bends (Fig. 10.15). The extent of suction relies on the various components like diameter of the air intake, smooth corners to ducting and pipes, etc.

10.9.2.2 Magnetic Separators

The magnetic separators are not complex in operation and their working is simple as compared to other seed cleaners as few settlements are required for its fabrication. The separation of cereal grains using magnetic separator is done on the basis of stickiness and textural properties of cereal grains. The grains must be pretreated with a magnetic material such as finely ground iron powder. The grain mixture is fed to a screw conveyor that tumbles and mixes the grains with a required amount of water to

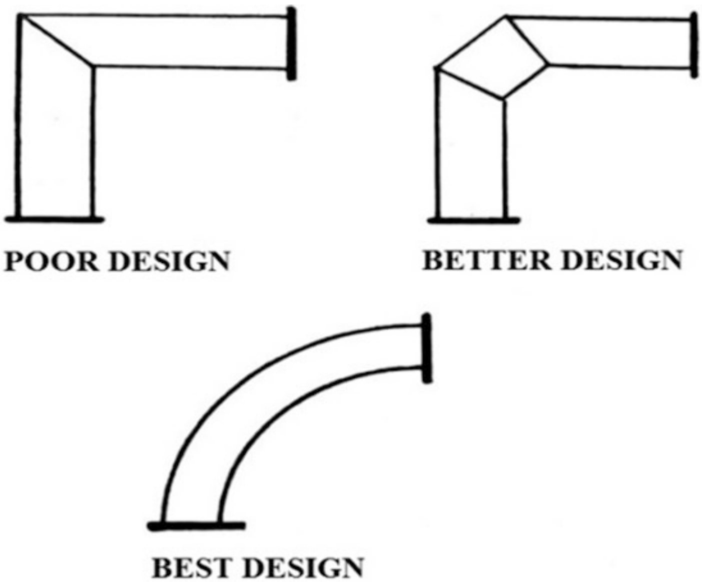


Fig. 10.15 Different bend designs

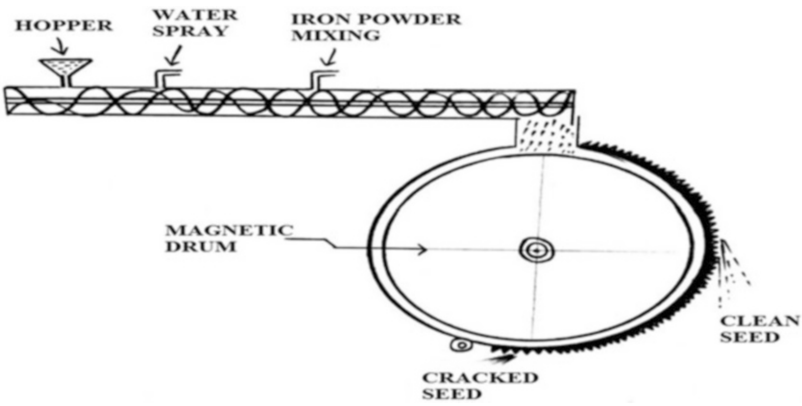


Fig. 10.16 Magnetic separators

adhere iron particles (Fig. 10.16). If the iron powder can be made to cling on inert material and other unacceptable components present in the seed mixture, then these materials will respond to a magnetic field. For this purpose, the mixture of cereal grains preconditioned with water is fed to the top of revolving magnetic drum through hopper (Fig. 10.16). The smooth grains that do not contain iron powder fall along the sides of the drum by the impact of gravity. Further, grains/particles that contain iron powder are attracted by magnetic drum and are further taken away by rotary brush. The magnetic separator is illustrated in Fig. 10.16.

10.9.2.3 Specific Gravity Separator (SGS)

Specific gravity separator (SGS) separates on the basis of variation in density of the materials. This operates on the attributes of grains to run over an inclined plane and movement of particles due to upward motion of the air.

The triangular-shaped perforated deck is the foremost portion of the SGS. The mixture of cereal grains is fed into the hopper where air is blown up through the deck surface and bed of cereal grains by a fan to such an extent that material is substantially lifted in association with the deck surface. The air is adjusted so that only the lightweight seeds are lifted up off the desk surface. Therefore, lighter materials are lifted to the top of the stratified stack that proceeds with the direction of conveyance due to vibrating movement of the deck and released from the left corner of the deck. On the other hand, the heavier seeds having velocity greater than that of the air column will not be lifted and lie on the deck surface.

10.9.2.4 Inclined Draper

The inclined draper separates cereal grains in context with their potential to roll or slip. Separation is done on the basis of difference in texture and shape of the material. These attributes are further dependent on the shape and texture of the cereal grains and by the frictional behavior of the surface of draper they are contacting. The mixture of the cereal grains is put on the center of the belt in ascending direction

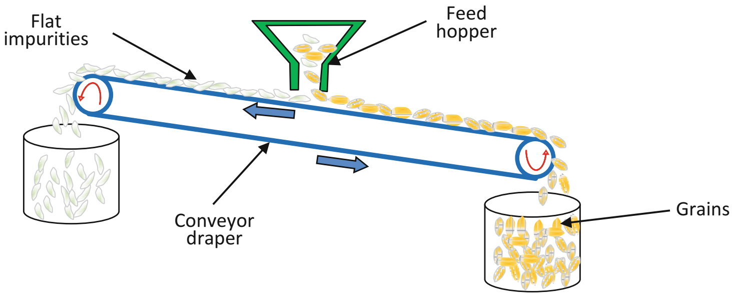


Fig. 10.17 Inclined draper

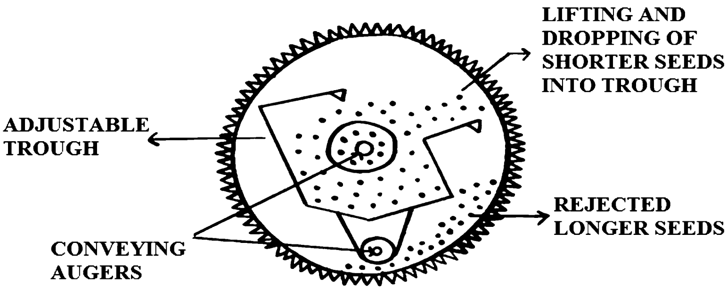


Fig. 10.18 Indented cylinder separator

(Fig. 10.17). The smooth-shaped cereal grains easily slip down at a comparatively accelerated rate than the upward movement of the belt, and then these required cereal grains are released at the other end. The flat-shaped cereal grains are conveyed to the top of the inclined draper, which further slide into another hopper (Fig. 10.17). It is very important to keep the feed rate slow for the effective separation of each grain. The inclined draper is presented in Fig. 10.17.

10.9.2.5 Indented Cylinder Separator

As per the required grading criteria, the incoming cereal grains are separated according to roundness or length. The mixture of cereal grains is put into one end of the horizontal rotating cylinder, which has indents on its interior surface (Fig. 10.18). The indents are in close proximity and hemispherical in configuration. Short cereal grains are collected by the collaborative consequence of fitting into the indents and by the action of centrifugal force. Grains are released into adaptable trough inside of the cylinder near the apex of rotation (Fig. 10.18). Conveying auger is provided in the bottom of the trough, which conveys the material. The cereal grains, which are larger in size than the indents, will persist inside the cylinder and conveyed to the outlet where the shell unloads into the outlet casing. The indented cylinder separator is illustrated in Fig. 10.18.

10.10 Quality Standards

1. Quality of raw materials: Poor quality of grains is one of the most common problems and is associated with improper post-harvest practices and storage facilities in the mill. Generally, millers purchase grains from farmers and do a check on the practices associated with plantation, harvesting, storage, and transportation. Agreements with the farmers in the beginning can render quality raw materials and finished products.
2. Moisture content: The important step in storage is to remove excess moisture from the cereal grains. The Codex standards for maximum moisture contents to secure storage with good shelf life of cereal grains are presented in Table 10.7.
3. Quality checks on flours: The tests most commonly employed to authenticate the wheat flour quality are moisture content, protein, ash, minerals, fat content, water absorption, dough resistance, gluten quality, flour starch viscosity, diastatic activity, maltose value, damage starch, flour color grade value, particle size estimation, etc. These tests are carried out under strict control and regulations approved by the American Association of Cereal Chemists, (AACC), International Association for Cereal Science and Technology (ICC), FSSAI, etc. These quality checks are important to predict the quality and authenticity of the products. Besides, the weight packed into sacks is not below the weight declared on the label or listed on the sack.

10.11 Applications

10.11.1 Processed Rice Products

The different rice processed products and by-products along with their uses are presented in Table 10.8 as under:

Table 10.7 Maximum moisture (%) of main selected cereals

Grain	Moisture content[a] (%, max)	Codex standards
Wheat	14.5	199-1995
Rice	15.5	198-1995
Maize	15.5	153-1995
Oats	14.0	201-1995
Durum wheat	14.5	
Whole and decorticated pearl millet grains	13.0	169-1989b

[a] Lower moisture range essential in context with environmental conditions, transportation, and good shelf life [36–41]

Table 10.8 Processed rice products, by-products, and uses

Processed products	Popular uses
Rice flour	Preparation of *papad*, vermicelli, and other products
Puffed rice	As breakfast cereal or snack food and as an ingredient of *bhelpuri*
Flaked rice (beaten rice)	To make *poha*, weaning food, etc.
Quick cooking rice	Vegetable pulao
Polished rice	Rice pudding, breakfast cereals
Parched rice	Consumed as such or utilize with milk/buttermilk
Extruded products	*Murukku* instant mix, *vadagam*, *idiappam* mix
Rice beverages	Rice milk, rice water, black vinegar
Rice starch	In puddings, custard powders, ice creams, etc.
Rice broken	To make *idli*, *upma*, *dosa*, snack mix, and brewery and in cattle feed
Rice bran	Source of vegetable oil, animal feed, and dietary fiber
Husk	As fuel, feed, and in production of white ash
Rice hulls	As packaging material during shipping and as a fuel in power plants
Rice straw	As animal feed, fuel, and mushroom bed and in preparation of paper and compost

10.11.2 Processed Wheat Products

The different processed wheat products and by-products of wheat processing along with their utilization are summarized in Table 10.9:

10.11.3 Processed Corn Products

The different processed corn products and by-products of corn processing along with their utilization are summarized in Table 10.10:

10.12 Exercise

1. If 300 g of paddy was dehusked in a rubber roller, 75 g of husk and 35 g of rice broken were acquired. Enumerate the husk content (%). [Answer: 25%]
2. In the above numerical problem, after dehusking of paddy, head rice was polished for 2 min, out of which 20 g of bran and 25 g of rice broken came out of the polisher. Calculate the overall rice outturn, whole rice outturn, and extent of polishing. [Answer: 68.3%, 48.33%, 10.53%]
3. Give generalized flow sheet for processing of wheat. How is wheat turned into flour step by step?
4. How thermal properties of cereal grains are beneficial for designing equipment for various heat transfer operations?
5. How different by-products of wheat, rice, and corn processing are utilized?

Table 10.9 Processed wheat products, by-products, and their uses

Processed products	Uses
Whole wheat flour	*Chapatti*, cookies, biscuits, bakery products like bread, pastries, cakes
Refined wheat flour	Cakes, pancakes, wafers, bread, pizza, breakfast cereals, etc.
Wheat gluten	Used as a binding ingredient and source of protein in pet foods, production of leavened products, useful ingredient in pasta and meat products
Puffed wheat (golden crisp)	Used as breakfast cereal/snacks
Wheat starch	Used in bakery products, ethanol production, thickening agent (soups, sauces, and gravies)
Semolina	Used for formulating extruded snacks like breakfast cereals, pasta products (spaghetti and macaroni)
Noodles	Extended and fine strip of pasta or alike flour paste
Porridge	Particularly consumed as weaning foods
Roasted wheat kernels	Consumed as such
Wheat bran	To produce alkaline protease and in the production of value-added product, gamma-aminobutyric acid (GABA)
Wheat germ	Used in extraction of oil, binder in meat loaf, etc.
Wheat germ oil	Used in salad dressings, substitute for other oils
Chaff	As animal feed

6. What is the impact of milling on various antinutrients present in cereals?
7. Give flow sheet of rice milling. Briefly discuss the various steps of modern rice milling technology.
8. Differentiate wet milling from dry milling in context with corn. Explain the technique of corn flour production by wet milling.
9. What are the crucial steps in parboiling of rice? What are the dominant physico-chemical and nutritional changes prevailed after parboiling of rice? How double boiling method is different from single boiling method in context with parboiled rice?
10. What is the principle of specific gravity separators (SGS)? How do they work?

Table 10.10 Main processed corn products and uses

Processed products	Uses
Corn flakes	As breakfast cereal, making *upma,* butter crunch biscuits, crusted fried chicken, etc.
Popcorns	Consumed as such
Corn nuts (toasted corn) and tortilla chips	Snack food
Maize flour	In confectionery, wheat flour additive, thickening agent, etc.
Corn syrup	As sweetener in hard candies, cold drinks, fruit drinks, etc.
Ogi	In preparation of *pap* (similar to custard) and puddings
Corn starch	As a thickener for sauces, gravies, fruit pie fillings, etc.
Corn gluten meal	As livestock feed
Corn germ meal	Valuable in poultry and swine rations
Nixtamalized maize	To make ready-to-eat finished *masa* products (*masa* is a maize dough from ground nixtamalized corn) and sold as shelf-stable product
Corn steep liquor	Feed ingredient, pellet binder, etc.
Corn fiber (maize coarse bran)	As animal feed and in manufacturing of ethanol
Maize fine bran	As animal feed
Corn germ	To extract oil and as animal feed
Maize oil	In cooking, used in soap salve, paints, ink textiles, insecticides, etc. and in pharmaceutical industry
Cobs	Used as a biofuel, animal feed, and in charcoal production
Maize hulls	Used as animal feed

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Processing of Pulses

11

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Abstract

Pulses or grain legumes are dry edible seed with the pod. Pulses contain essential micronutrients, complex carbohydrates, and dietary fiber and are commonly referred as poor man's meat because of the rich source of protein at low cost. This chapter discusses the nutrient potential of pulses and the various unit operations involved in processing. The chapter summarizes the major factors that can affect the milling efficiency, and also the effect of milling on the composition, functional properties, cooking quality, etc. of pulses. Case studies of important pulses like chickpea, pigeon pea, and black gram are also explained with process flow diagrams. The estimation of milling efficiency in terms of dehulling index (DI), dehulling efficiency (DE), split yield, and percentage of brokens is worked out using examples. The quality characteristics and functional properties of pulses are also discussed.

Keywords

Nutrient potential of pulses · Unit operations in pulse processing · Milling · Grinding · Milling calculations · Value addition of pulses · Quality standards

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11.1 Pulses: Importance

Pulses are among one of the important food sources in the world next to cereals. These are edible seeds from species of plants belonging to the family Fabaceae (Leguminosae) and are often referred as grain legumes, legumes, or dhal/dal. Pulses in general may be defined as the edible seeds of leguminous plants. According to FAO classification of commodities, the pulses include only the crops that are harvested solely for dry grain. The pulses exclude the crops harvested for oil extraction (groundnut) and vegetable purposes (green peas and green beans). This covers eleven primary pulses as per Table 11.1. Table 11.1 enlists the vernacular name (common name) and its corresponding botanical name of pulses as per updated taxonomic database published by FAO in 1994.

India is the world leader in the production of pulses where legumes have been categorized into three types: grain legumes, peas, and beans [2]. The whole legumes are called as legume grains, whereas the dehusked and split part are called as dhals. Production of the top 10 countries in the world is shown in Fig. 11.1.

Realizing the importance of pulses, United Nations (UN) General Assembly declared 2016 as the International Year of Pulses. Pulses have different formats of consumption. The products such as noodles and baked and canned beans are part of the value chain, whereas other Asiatic splits/dhal types are eaten in raw or cooked form in regular diet. Pulses are known to have a distinct significance of improving the fertility of the soil as nitrogen-fixing crops, and the taproot system in pulse crop

Table 11.1 Primary pulses considered as per FAO classification[a] [1]

Class	Common pulses/legumes	Botanical names
Dry beans	Bean/wild bean	*Phaseolus* species as per FAO, but some countries include other beans also from *Vigna* genus
Dry broad beans	Horse bean, broad bean, field bean faba bean	Mainly *Vicia faba*
Dry peas,	Garden and field peas	*Pisum sativum* and *P. arvense*
Chickpeas	Chickpea, Bengal gram, garbanzos	*Cicer arietinum*
Dry cowpeas	Cowpea/black eye pea/bean	*Vigna unguiculata*
Pigeon peas	Pigeon pea, cajan pea, Congo bean	*Cajanus cajan*
Lentils	Lentils	*Lens esculenta*, *Ervum lens*
Bambara Beans	Bambara groundnut, earth pea	*Voandzeia subterranea*
Vetches	Spring/common vetch	*Vicia sativa*
Lupins	Lupins	*Lupinus* spp.
Pulses nes	Lablab or hyacinth bean, jack or sword bean, winged bean	*Dolichos* spp., *Canavalia* spp., *Psophocarpus tetragonolobus*

[a] All species listed in this table come under the category of pulses, but some also fall under the category of vegetables when harvested unripe

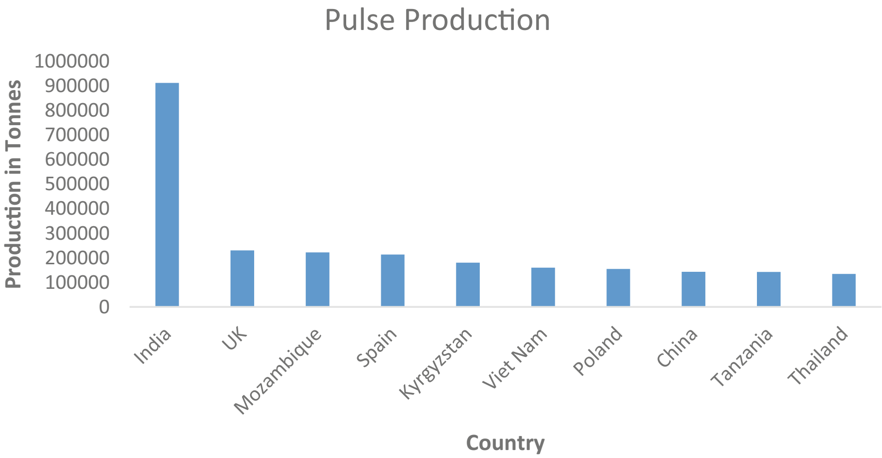


Fig. 11.1 Production statistics of pulse

makes the soil porous thereby improving physical health of soil. They can grow on relatively poor soils even without the application of fertilizer under rainfed conditions. Being short-durational crop, farmers can take two crops of pulses in the same year. In India, people found to have some organoleptic preference also among the pulses grown in different seasons. Pulses are considered as a source of protein and can be used as a tool to eradicate malnutrition.

11.2 Nutrient Potential of Pulses

Pulses are generally called poor man's meat as they are widely consumed by people from developing countries, due to high-quality proteins. They are a very important source of complex carbohydrates, protein, and dietary fibers along with vitamins and minerals. Carbohydrate is observed as the highest among other nutrients found in pulses, with an average range of 60–65%. A maximum portion of carbohydrate occurs in the form of starch. Content of oligosaccharides and dietary fiber may vary depending on the degree of removal of husk. A higher percentage of amylose and complex carbohydrates in pulses makes them rich in resistant starch content, which makes pulses a low-GI foods. The presence of oligosaccharides in pulses is linked with anti-colon-cancer potential by promoting the growth of bifidobacteria in the gut [3]. Dietary fiber present in legumes may play a role in reducing the incidence of occurrence of various diseases like diabetes, cancer, diverticulitis, etc. Both edible and non-digestible carbohydrates are found in pulses: flavonoids and isoflavanones. Stachyose is the main oligosaccharide in lentils, exceeding 50 mg/g, whereas raffinose is 39.9 mg/g in chickpea [4].

Legume seeds or pulses store the protein in the membrane-bound organelle of cotyledon, which makes them rich sources of protein (18–35%) with essential amino acids and bioactive peptides. Globulin is the most abundant storage protein present in pulses. The protein in pulses is twice than that of cereals, and it is also superior in qualitative terms. Apart from storage protein, legumes also contain minor proteins like trypsin inhibitors, lipo-oxygenase, urease, lectins, etc. Pulse proteins are rich in lysine, leucine, aspartic acid, glutamic acid, and arginine but devoid of sulfur-containing amino acids, methionine, cysteine, and tryptophan. This deficiency is complemented as pulses are consumed with cereals like rice or wheat. Pulses as the source of protein have a potential to partly replace wheat flour in products like crackers, cookies, bread, pizza, noodles, cakes, etc. Pulses are low in fat, particularly if consumed as splits. In contrast to many pulses, chickpeas are reported to have a relatively higher fat content. Fat in pulses is mainly composed of polyunsaturated fatty acids [5].

Legumes are good sources of micronutrients and vitamins B and K, in general. Potassium is the main macronutrient in pulses. Calcium is highly variable, ranging from 0.92 to 0.28 g/kg in pea and yellow lentil, respectively [5]. The bioavailability of these vitamins will change depending upon the method of cooking and form of consumption. In addition to vitamin B, other vitamins like thiamin, riboflavin, pyridoxine, and folic acid are also reported in pulses [6]. Other than potassium, calcium and iron are important minerals that are present in a good concentration. Chickpeas are a rich source of iron, while lentils and chickpeas have the highest concentration of folate [5]. Beyond nutritional importance, pulses are important components in diets and cropping systems. An overall nutritive profile of some legumes and pulses is shown in Table 11.2.

Nutritional and functional potential of pulses showed that snacks with lower levels of flatulence factors and higher amounts of dietary fiber can be formulated successfully by extrusion techniques based on dry pea, lentil, or chickpea and may provide an alternative to the traditional cereal-based snacks. Though some anti-nutritional factors like trypsin inhibitors, lectins, phytic acid, saponins, cyanogens, α- amylase inhibitor, etc. may be present in pulses, but they can be eliminated by appropriate heating and processing during preparation. Pulses also help to lower cholesterol and triglycerides and the proteins from pulses are easily available [5].

11.3 Antinutrients in Pulses and Effect of Processing

Antinutritional compounds are present in human food or animal feed, which interfere in assimilation of nutrients and affect nutrient absorption [8]. The antinutrients are widely present in the case of plant and animal foods, for example, solanine in tomatoes and potatoes, which is a glycol-alkaloid poison retarding mitochondrial functions, and avidin in raw egg that inhibits biotin absorption. In the case of pulses, antinutrients are relatively present in higher quantities and can be categorized as protein antinutritional compounds (ANCs) like lectins and trypsin and non-protein antinutritional compounds (non-protein ANCs), which include phytic acid, saponins, tannins, etc.

Table 11.2 Nutritive value of pulses [7]

	Energy (kcal)	Moisture (g)	Protein (g)	Fat (g)	Minerals (g)	Carbohydrate (g)	Fiber (g)
Bengal gram dhal	372	10	21	6	3	60	1
Black gram dhal	347	11	24	1	3	60	1
Cowpea	323	13	24	1	3	54	3
Field bean	347	10	25	1	3	60	1
Green gram dhal	348	10	24	1	3	60	1
Horse gram dhal	321	12	22	0	3	57	5
Khesari dhal	345	10	28	1	2	57	2
Lentil	343	12	25	1	2	59	1
Moth bean	330	11	24	1	3	56	4
Green peas	93	73	7	0	1	16	4
Kidney beans	346	12	23	1	3	61	5
Red gram dhal	335	13	22	2	3	58	1
Soybean	432	8	43	20	5	21	4

Several other antinutritional compounds, which include oxalate, lathyrogen, oligosaccharides, goitrogens, etc. are also present in several pulses. The most common and important antinutritional compounds in various pulses are listed in Table 11.3.

The processing methods significantly affect the physicochemical and nutritional properties of raw pulses. The effect of some of the processing methods is discussed:

11.3.1 Soaking

Soaking is a common process before cooking. It helps in the reduction of antinutrients and improves the cooking quality and digestibility of raw pulses. Extrusion after soaking in water (30 °C) for 16 h yielded the following results for peas, chickpeas, faba beans, and kidney beans (Table 11.4).

Extrusion is carried out at feed moisture and barrel temperature of 18% and 140 °C, respectively. From the data, it is evident that soaking also helps in reducing the amount of antinutrients in raw pulses.

Table 11.3 The different antinutrients present in pulses, effect, and elimination approaches

Antinutritional compounds	Occurrence	Effect on nutrient assimilation	Elimination ways	Reference
Trypsin inhibitors	Kidney beans, cowpea, pigeon pea	Inhibits the activity of proteolytic enzymes and therefore decreases the nutritional quality of proteins and intake of amino acids.	Moist heat, germination, autoclaving, extrusion cooking	[9]
Lectins	Castor beans (*Ricinus communis L.*), soybeans, kidney beans, faba beans, and lupin seeds	Lectins can influence hydrolysis and absorption of carbohydrates in the gut because of the bindings.	Aqueous heat treatment like soaking and cooking	[10]
Tannins	Pigeon pea, urdbean, cowpea, chickpea, mung bean and pea	Lower protein digestibility/ decreases amino acid availability	Dehulling, soaking overnight, germination	[11, 12]
Lathyrogen	Seeds of lathyrus, commonly known as khesari or teora	A toxic amino acid known as β-N-Oxalyl-amino-L-alanine (BOAA) in the seeds causes paralysis of the legs	Soaking, parboiling, roasting, and degerming	[13, 14]
Oxalate	Pink bean, black bean, navy bean, soybean, small red bean, small white bean, and anasazi bean and also in nuts and grains	Oxalic acid forms water-soluble salts with Na^{+}, K^{+}, and NH^{4+} ions. It also binds with Ca^{2+}, Fe^{2+}, and Mg^{2+}, rendering these minerals unavailable for absorption and causing diseases like osteomalacia and rickets	Blanching and sprouting	[15]
Phytate	China's legumes, pea, faba pea, dry bean, lentils, black bean, whole grains, oilseeds, nuts	Phytate may bind with dietary minerals including proteins and starch to reduce the bioavailability	Germination, soaking, cooking, autoclaving, roasting	[15–17]
Saponins	Soybeans, peas, potato, yams, asparagus, alliums, oats, sugar beet, tea, ginseng	Inhibiting enzymes (metabolic and digestive) and bind with nutrients such as zinc	Soaking, germination, cooking	[12, 18]

Table 11.4 Effect of soaking and extrusion on tannins and phytic acid [19]

Antinutrient	Unsoaked and extruded	Soaked and extruded
1. Phytic acid (mg/g)		
(a) Faba beans	6.4	6.1
(b) Peas	8.97	8.5
(c) Chickpeas	8.21	8.00
(d) Kidney beans	11.03	9.95
2. Tannins (mg/100 g)		
(a) Faba beans	492	485
(b) Peas	330	269
(c) Chickpeas	260	210
(d) Kidney beans	233	229

11.3.2 Dehydration

Dehydration helps in bringing down the antinutrient levels of pulses. Dehydration results in a general decline of phytic acid in lentils, white beans, and pink mottled beans and reduces the levels of enzyme inhibitors and lectins. Dehydration also helps in improving protein digestibility, thus making dehydrated pulse flours a suitable raw material for the development of ready-to-use special meals.

11.3.3 Cooking

Cooking not only improves the palatability, nutrition, and digestibility but also reduces the antinutritional compounds present in raw pulses. A significant reduction in tannin has been reported in cooked samples of beans and chickpeas [20].

11.3.4 Extrusion

Extrusion is one of the oldest techniques for the production of ready-to-eat and convenience foods like puffed snacks, pasta, noodles, etc. Pulse flours can be used either directly or in combination with other cereal and legume flours for production of healthy snacks and convenience foods. Extrusion significantly affects the nutrient and antinutrient compounds in pulses, and the process variables like barrel temperature, feed moisture, pressure, screw speed, etc. play a decisive role. Extrusion of legume flours has potential for the production of extruded ready-to-eat foods by partially or totally replacing cereals for starch and proteins modification, improving digestibility, and reduces the content of trypsin inhibitors, lectins, phytic acid, and tannins [21]. Table 11.5 describes the effect of extrusion of pea seed and lentil seed and its effect on nutrients and antinutrients. Extrusion at 148 °C temperature, 100 rpm screw speed, and 25% feed moisture for pea seed (cv. Ballet) shows reduction in antinutritional factors [17].

Table 11.5 Effect of extrusion on nutrients and antinutrients present in pea seed (cv. ballet) [17]

Nutrient/anti nutrient	Raw pea seed [16]	Extruded pulse product (pea seed) [16]
Protein (g/100 g DM)	21.6	21.8
Phytic acid (g/100 g DM)	1.19	1.12
Condensed tannins (mg eq cat/100 g DM)	23.8	2.34
Polyphenols (mg/100 g DM)	50	23
Trypsin inhibitor (IU/mg DM)	6.32	0.34
Chymotrypsin inhibitor (IU/mg DM)	4.85	1.68
Hemagglutinins (IU/mg DM)	6.0	0.1

11.4 Unit Operations in Pulse Processing

Major unit operations, other than milling, involved in pulse processing are described below:

11.4.1 Cleaning and Grading

Raw pulses are harvested and received contaminated with a foreign matter like pod walls, weeds, soil, diseased and deformed seeds, and stones. Scalpers and air screens are used to get rid of such unwanted material. After cleaning, grading is done to achieve uniform-sized grains for further processing. The cleaning and grading equipment include [22]:

a. Scalpers, for removing trash and fines. A rotating or reciprocating screen may be used for cleaning operations.
b. The separation is based on size and weight. Aspiration removes the lighter materials and large materials are removed by passing through screens. A secondary screen is used to separate fine seeds from the desired size of seeds.
c. Width and thickness separators consist of rotating, cylindrical, perforated shells. Width and thickness are adjusted in a way so that the large unwanted material is unable to pass through and gets discharged.
d. Gravity-based separators are used to separate grains based on specific gravity and surface characteristics. Fluidizing apparatus is used to fluidize the seeds before feeding onto an oscillating deck. The mixture gets stratified, i.e., light seeds stay up and heavy seeds go in the lower layer, which results in the separation of seeds at the discharge end.
e. Spiral separator exploits the relationship between grain size and its rolling rate. Based on the pulse variety, an angle of the spiral can be adjusted to different values.
f. The color sorter is effective and convenient grading equipment but demands good capital investment.

11.4.2 Pitting

Pitting is the process in which abrasive roller machines are used for scratching and cracking the husk of whole pulses. The purpose of pitting is to facilitate the penetration of oil/water in subsequent steps.

11.4.3 Premilling Treatments

Oil treatment: In wet milling, pulse grains are soaked in water for few hours to overnight, while in dry milling, pulses are subjected to pitting and then oil treatment, and 0.7–1.0% edible oil like linseed oil is applied. Screw conveyor is used for oil treatment of scratched/pitted pulses. Pitted pulses are mixed with edible oil and then passed through a screw conveyor for effective oil penetration [23]

Conditioning: Conditioning is the term used for alternate wetting and drying of pitted and oil-treated pulses. The purpose of conditioning is to further loosen the husk so that dehusking and splitting can be carried out effectively with a minimum breakage. During conditioning, pulse grains are sun dried for a certain period, and then 3–5% moisture is added and left for tempering for about 8 h and then again dried in the sun [23]. This whole process is repeated for 2–4 days until the pulses are conditioned properly.

Drying: Sun drying is usually practiced. Pulses are dried to a final moisture content of about 8–10%. For commercial milling plants, batch- and continuous-type mechanical driers are used. Forced hot air drying and dehumidified air drying are the artificial drying techniques commonly used where the conditions are not suitable for natural drying. In forced hot air drying, the artificially heated air is forced through the grains in bulk to absorb the released moisture. In dehumidified air drying, the grains are dried by circulating the unheated dehumidified air, until the desired moisture content is reached.

11.4.4 Dehusking and Splitting

Conditioned pulses are dehusked using emery rollers, which are also known as Gota machines. In one pass, around 50% of grains are dehusked. Dehusking is followed by the splitting of pulse grains into two. The aspirator is used to remove the husk and sieving is done to obtain split pulses. The process is repeated twice or thrice until the complete dehusking and splitting are done. Roller mill tangential abrasive dehulling device (TADD) [24] is one of the several dehusking devices available in the market. Roller mills are generally used for the splitting of dehusked pulses. Roller mills consist of two discs in which one stays stationary while the other one rotates. A rubbing action is produced, which splits the dehusked whole pulses into two. The size and speed of the disc determine the capacity of the roller mill. Roller mills are used for the splitting of pulses like urad bean, lentil, chickpea, soybean, and mung bean.

11.4.5 Polishing

A small quantity of oil or water may be used for polishing of dehusked and split pulses. Rubber rollers, leather belts, or emery cone polisher can be used for polishing of pulses. In operation, polishing equipment are similar to oil/water treatment equipment.

11.5 Milling

The processing of pulses aimed for dehusking and splitting is also popularly called in the region as milling of pulses. It contributes in increased digestibility and improved sensory characteristics like aroma and texture, to the pulses. This processing step mainly aims to remove hulls as cleanly as possible. Traditional methods of pulse milling may broadly be classified as wet milling and dry milling. The process flow chart involved in the wet and dry milling process is shown in Figs. 11.2 and 11.3, respectively.

The major difference between dry and wet milling is in the premilling treatment. In wet milling, after pitting/scratching, soaking in water is done followed by mixing with red earth. The grains are mixed completely with the red earth paste after soaking in water and heaping for about 16 h followed by final drying. Whereas in dry milling,

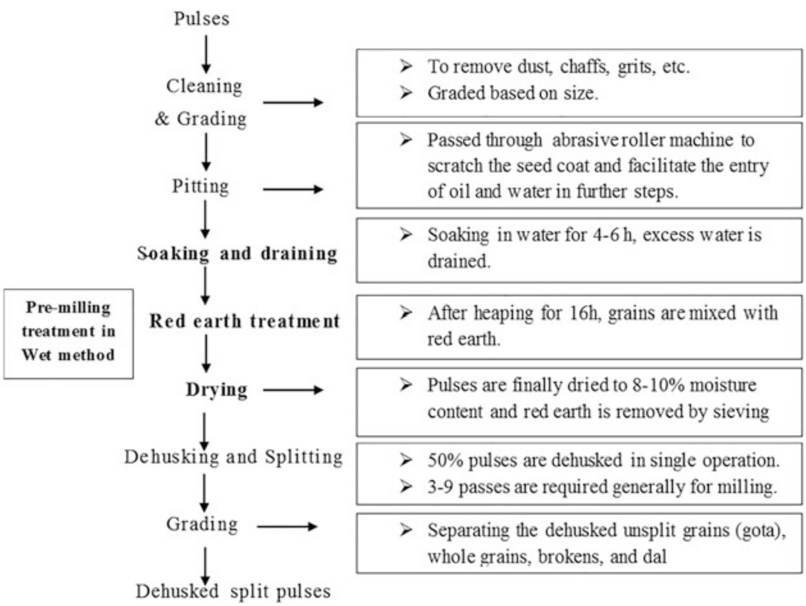


Fig. 11.2 Flow chart of wet milling (illustrated as per [25, 26])

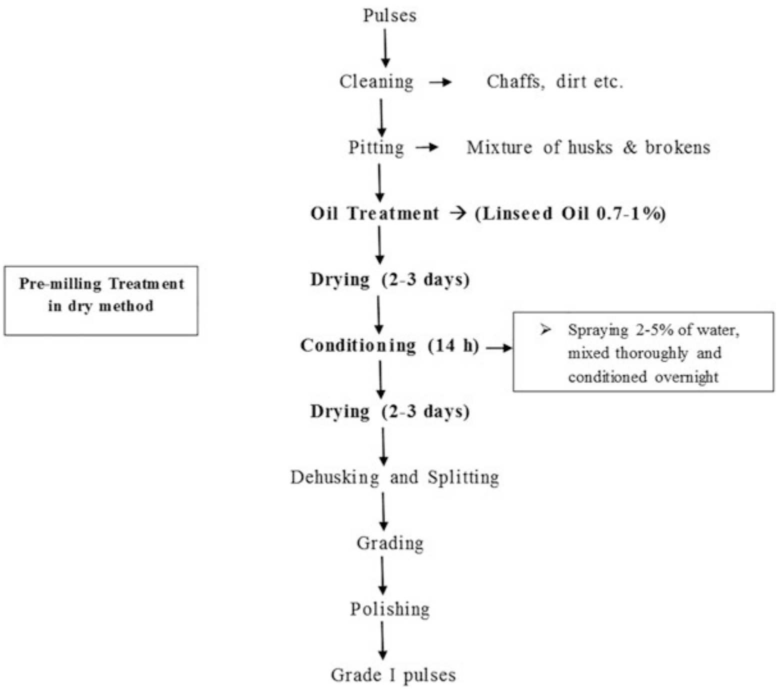


Fig. 11.3 Flow chart of dry milling (illustrated as per [22, 23])

emery roller machines are used for pitting followed by oil/water treatment, whereby linseed oil is used generally at the rate of 1%, which is mixed thoroughly with grains followed by drying for 2–3 days. At the end of drying, conditioning is carried out overnight by 2–5% water application. Dry milling (as shown in Fig. 11.3) also includes an extra step of polishing after dehusking and splitting.

These milling methods are mostly used in Indian subcontinents. Various organizations and research institutions, particularly in India, have made a significant contribution in the development of methods and machinery to process the pulses with higher efficiency and in an economical way. However, the designs vary in terms of capacity, efficiency, ease in use, pulse specificity vs multi-pulse milling, economic viability, and power consumption. A mini-dhal-mill model is shown in Fig. 11.4. This mini dal mill can be used for dehusking and splitting of all type of preconditioned pulses with the capacity of 50 kg/h with the recovery of 78–80% of head pulses and 1–3% of broken. The mill consists of a hopper and a vibratory sieve of different sizes, placed in an inclined position for cleaning and grading as per the type of pulse to be milled, which are operated using a motor-driven shaft. It performs the function of an emery roller machine for pitting of pulses and dehusking followed by an aspirator for removal of husk. The setup also consists of polisher through common shaft arrangement for conditioning of pulse with oil.

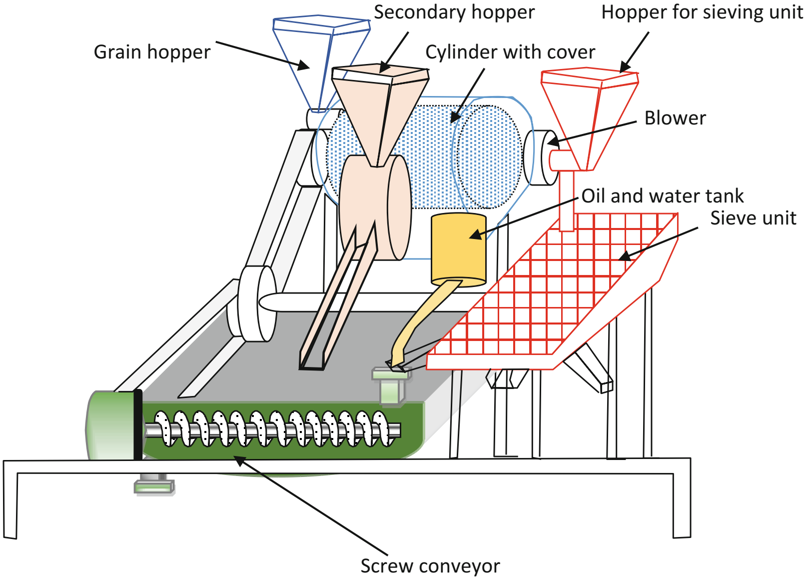


Fig. 11.4 Mini dal mill for dehusking and splitting of grain legume

11.6 Grinding

The pulse flour is produced using various grinders, which reduces the size of pulses. The milling operation produces different particle sizes, which affects the functional properties of flour, viz., water absorption, texture and porosity of flours, etc. Generally, two types of milling techniques are used for the size reduction process:

1. Impact milling process: This technique is used to mill the hard materials by striking and producing fractures. These usually consist of rotating hammers or hammer-type blades. These are preferred in pulse milling due to good control over the size of particles through the size of the opening at the outlet.
2. Attrition milling process: These mills consist of horizontal rotating vessels with a hardened rough surface. The material has to pass through between the place, which provides shear force, and crushing of cotyledons of pulses takes place.

11.7 Major Factors Affecting Milling Efficiency

The properties of pulses play a vital role in the milling process and affect the dhal yield. The milling of pulses depends upon the variety due to variation in thickness, waxiness of husk, size, shape, hardness, and storage conditions. The main factors that affect milling efficiency are:

11.7.1 Seed Size

The bigger diameter grains provide higher recovery due to the advantage of bigger cotyledons. The abrasive rolls provide the required forces to detach the husk from the grains.

11.7.2 Legume Type

Some pulses contain thin-layered seed coat of about 5–10% of seed mass, viz., cowpeas and green gram, whereas chickpeas and pigeon peas have a higher amount of about 14–18% of the grains. A layer of gum also decides the binding of the kernels with the husk, which also varies in texture, nature, and hydration level.

11.7.3 Variety

Variety and agro-climatic conditions affect milling quality of pulses. Milling yield ranges 64–75% in traditional milling as compared to 79–84% by improved milling methods/process.

11.7.4 Moisture

Moisture reduction accelerates the splitting, while the addition of moisture helps in dehusking. Scouring losses can be reduced by separating, dehusking, and splitting operations against simultaneous dehusking and splitting.

11.8 Effect of Milling

Milling can influence various parameters, some of the important ones are described as follows:

1. Composition: The seed coat fraction accounts for 7–15% of whole kernels. The major portion of protein, fat, phosphorus, and iron is present in cotyledons. An appreciable amount of crude fiber and calcium content is available in the seed coat, which remains available in a limited amount due to the removal of husk during the milling of kernels.
2. Antinutritional factors: The removal of the seed coat is expected to reduce the tannin as it is mainly located in the seed coat of beans, while a marginal increase in phytic acid, trypsin, chymotrypsin, and amylase inhibitory activities may be seen as these are found in cotyledons.
3. Protein digestibility: Tannins present in the seed coat form complexes with proteins; therefore, it is associated with poor digestibility of proteins. Dehulling

decreases the tannin content significantly and thus improves the digestibility of legume proteins.

4. Functional properties: The oil and water absorption ability of pulse is improved after dehulling, which remains lower due to the seed coat in the whole seed. This may be due to probable interactions between the endosperm protein components and seed coat materials. The process of milling also affects the functional properties. The ground pulses using the hammer mill produces maximum antioxidant capacity, phenolic content, and resistant starch contents due to the production of finer particles.
5. Cooking quality: The permeability of water during cooking in pulses is improved due to the removal of the seed coat, and hence, faster cooking time is observed. It reduces about 40–70% cooking time by removal of the seed coat.
6. Consumer acceptance: Consumer acceptance has various considerations of taste, cooking quality, cooking time, pre-treatments, etc. The consumers generally accept (a) freshly milled pulses because it tastes better, (b) red pigeon pea over the white pigeon pea due to taste and cooking quality, (c) late-maturing cultivars due to good cooking quality and shorter cooking time, and (d) specific pre-treatment of oil/water/salt.

11.9 Milling of Pulses: A Case Study

11.9.1 Black Gram: A Case Study

Black gram kernels (Fig. 11.5) have seed coat, cotyledons, and embryos in the proportion of 12–14%, 83–85%, and 3%, respectively. The protein, lipid, and ash are contained in cotyledons, whereas crude fiber and calcium are available in an embryo. It contains about 18.1–24.6% oil. The protein is present in the form of about 80% of globulins, 13% albumin, 4% prolamin, and 2% glutelin.

Black gram is found rich in thiamin, niacin, and pantothenic acids along with calcium, phosphorus, and iron. It contains antinutritional factors like protease

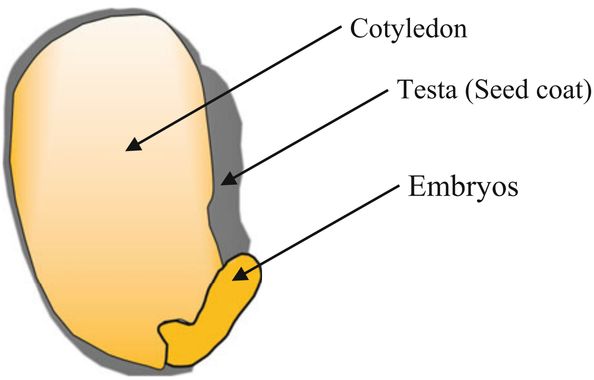


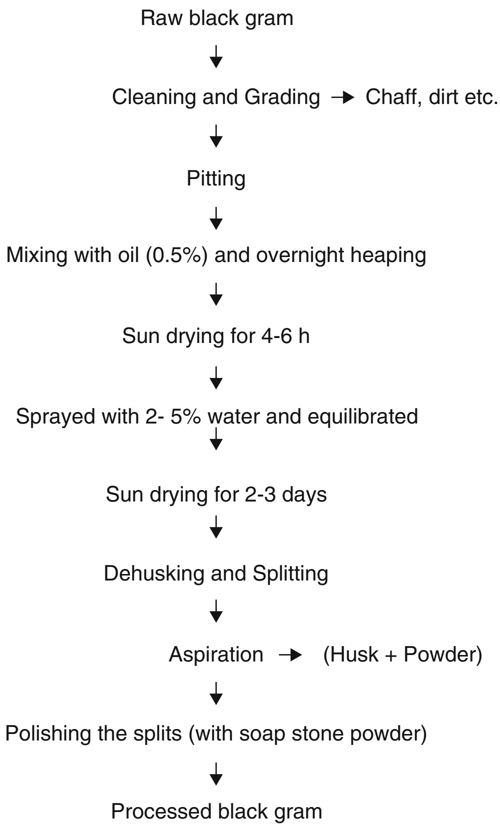
Fig. 11.5 Structure of black gram

inhibitors in the form of trypsin and chymotrypsin, which can be reduced using heat treatment. Steam at 5 psi and 108 °C can reduce inhibiting activity by 33%. Black gram also contains 1.46–1.70% phytic acid. Phytates make insoluble complexes and reduce the bioavailability of proteins, minerals, and vitamins.

The seed coat also contains 1.1% tannin but remains negligible in cotyledons. It also produces flatus after intake due to the presence of oligosaccharides, viz., raffinose, stachyose, verbascose, etc. Flatus can be reduced by germination and fermentation, but roasting enhances the flatus. Interestingly, methionine content of black gram and rice blend is increased in traditional fermentation while reducing inhibitors. Cooking inactivates trypsin and chymotrypsin inhibitor activity.

The typical flow chart for dry milling of black gram is shown in Fig. 11.6. The black gram selected must be sound, whole, and free from insects because the quality of the final product is proportional to the quality of raw material. Selected pulses are cleaned for the removal of unwanted impurities like dirt, chaffs, stones, soil, etc. They are graded for uniformity in size and quality. Graded black gram is prickled/pitted through a rough roller mill to scrape the surface for oil adsorption and to remove the waxy layer on black grams. The pitted grains are treated with 1–0.5% oil

Fig. 11.6 Flow chart of dry milling of black gram [23]



and are heaped overnight for sufficient oil penetration into grams. Followed by oil treatment, the black gram is spread in the drying surface to employ sun drying for 4–6 h for partial dehydration. The partially dehydrated grams are sprayed with 2–5% water and equilibrated overnight. The wetted black gram is thoroughly dried for 2–3 days and can be dehusked in an abrasive, carborundum roller machine for several passes. Around 40–50% pulses are dehusked in the first milling operation, and then husked and unhusked pulses are separated. Unhusked pulses are dried again and the same process is repeated until complete milling is achieved. The average yield of black gram is 70–71%. Dehusked split/whole dhal are polished using soapstone powder to improve the glow and enhance market value.

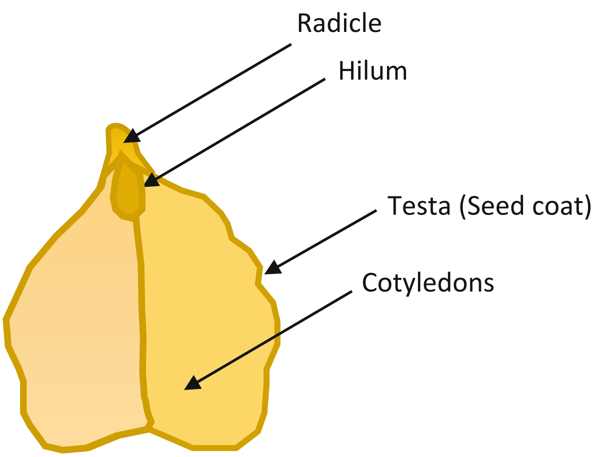
11.9.2 Chickpeas, Lentils, and Bengal Gram: A Case Study

The cotyledons of chickpeas (Fig. 11.7) contribute to 82.9–84%, whereas the remaining 14.5–16.4% is contributed by the seed coat and 1.2–1.5% by the germ. The crude protein and starch content of seed vary between 18 and 30.6% and 37.2 and 50.8%, respectively. The amylase present is about 31.8–45.8% of the total starch, while the remaining is present in the form of amylopectin. The distribution of protein is more in the outer part.

Non-protein nitrogen and glutelin of pulses are mainly found in the seed coat of chickpea. The crude fiber, 7.1–13.5%, mainly with cellulose and hemicelluloses is also found in chickpea. Lipid content in the chickpea ranges from 3.1 to 6.9%. Linoleic and oleic acids are 67.13% of the unsaturated fatty acid fraction found in this legume [27]. The chickpea also provides minerals such as calcium, phosphorus, magnesium, iron, and potassium in diet.

It is the richest source for iron availability as compared to other legumes. A considerable amount of ascorbic acid makes chickpea good for germination of seeds.

Fig. 11.7 Diagram of chickpea



Vitamins like thiamine, riboflavin, niacin, pyridoxine, and folic acid are also present in chickpea. Most of the seed calcium may go off if seed coat is removed, but vitamin contents of whole seed and dhal do not differ significantly. The presence of non-digestible short-chain carbohydrates or oligosaccharides like raffinose, stachyose, and verbascose may give flatulence effect. Due to the higher amount of unavailable carbohydrates, the digestibility of chickpea carbohydrates is lowest as compared to commonly consumed Indian pulses.

Two inhibitors, namely, chymotrypsin and trypsin, are present in the chickpeas, which can be eliminated/reduced using germination, heating, and fermentation. The processing methods also reduce the flatus producing oligosaccharides. The pancreatic amylase inhibitor can be controlled by boiling the chickpea for at least 10 min. The number of tannins in the whole seed and cotyledons is 70–272 mg and 16–38 mg per 100 g, respectively, which reduces the bioavailability of vitamins and minerals [27]. Pressure cooking and open pan cooking can lead to significant reduction in beneficial flavonoids and isoflavanones present in chickpea and lentils [28].

Unlike black gram, Bengal gram, chickpeas, and lentils could be dehusked easily as the husk is comparatively loose. However, the preconditioning is done for a short period of time after pitting. For conditioning, Bengal gram is uniformly treated with water (1:3) by a mixer and is heaped for few hours for sufficient diffusion for water into pulses. The wet pulses are dried for 1–2 days with overnight tempering for complete removal of moisture before milling. The first milling is carried out, whereby 60–70% of pulses are dehusked and split to obtain dhal. The split, dehusked, and unhusked pulses are separated by aspiration and sieving. The remaining unhusked pulses are again treated with water, dried, and tempered followed by milling, and the same process is repeated until maximum pulses are converted to dhal. The complete process takes 3–5 days. The typical flow chart for milling of chickpeas, lentils, and Bengal gram is shown in Fig. 11.8.

11.9.3 Pigeon Pea: A Case Study

Pigeon pea is a rich source of nutrients and is also known as*tur*, *tuver*, *arhar*, red gram, *adhaki*, etc. Pigeon pea seeds contain starch-dominating carbohydrates ranging 57.3–62.9%. The starch content in pigeon pea seeds varies from 39.0 to 58.9%. The amylose is about 26.5–38.6%, while amylopectin constitutes 70–73% of the total starch in pigeon pea. Crude fiber, mainly cellulose and hemicelluloses and some amounts of lignin and pectic substances, ranges from 1.2 to 8.1%. The pectic substances may affect the cooking quality of beans. The pigeon pea seeds also contain some amounts of raffinose, stachyose, and verbascose. Supplementation of pigeon pea in diets with limiting methionine and/or tryptophan can improve its protein quality and protein efficiency ratio [27].

Total lipid content in pigeon pea ranges from 0.6 to 3.8%, of which 95% of the total lipids are present in cotyledons. Unsaturated fatty acids dominate (71.8%) oversaturated fatty acids (20.5%). The linoleic and oleic acid among the unsaturated

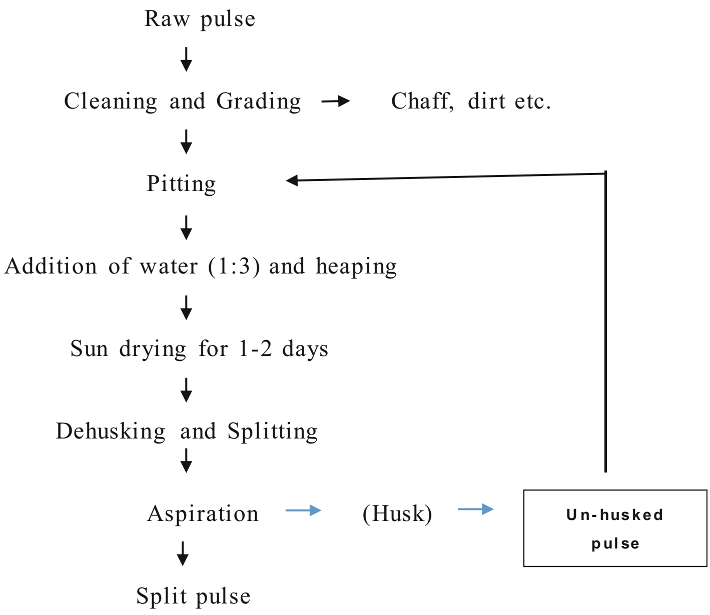


Fig. 11.8 Flow chart of dry milling of lentils, chickpeas, and Bengal gram [23]

fatty acids and palmitic acid in the saturated fatty acids are the major fatty acids. It is reasonably a good source of calcium, phosphorus, magnesium, iron, sulfur, and potassium. Phosphorus is mainly present as phytic acid. Vitamins of B group particularly thiamine, riboflavin, niacin, and choline are also present in this legume.

Pigeon pea seeds contain trypsin and chymotrypsin inhibitors (protease inhibitors), phenolic compounds, cyanogenic compounds, phytate, lectins, and saponins. It also consists of polyphenols, 0.37–1.51%. The amount of the polyphenols in the seeds depends upon the variety, color, and other factors. The lesser content of polyphenols is reported in white seeds than the dark-red to light-red seeds. The polyphenols are mainly located in the seed coat, which can be easily dehulled [27].

Most of the pigeon peas are consumed in the form of *dhal* in northern India and *sambhar curry* in southern India. Immature green seeds may also be used as a vegetable. To reduce long cooking time, it is preferred to soak the splits, but solid loss up to 5% may occur during soaking [29]. Thus, cooking in pressure cookers without soaking can serve a better option. The canning of green seeds of pigeon pea is a common practice in African countries including the West Indies and the Dominican Republic. Green pigeon peas are nutritionally superior to mature seeds of dhal because the seeds are harvested at a stage, where the concentration of desirable nutrients, such as sulfur-containing amino acids, is higher.

Pigeon pea is milled by both dry and wet milling method. In contrast to Bengal gram, black gram, lentil, and chickpeas, pigeon peas are considered a difficult kind of pulses to mill as the husk is tightly attached to the seed coat making the process

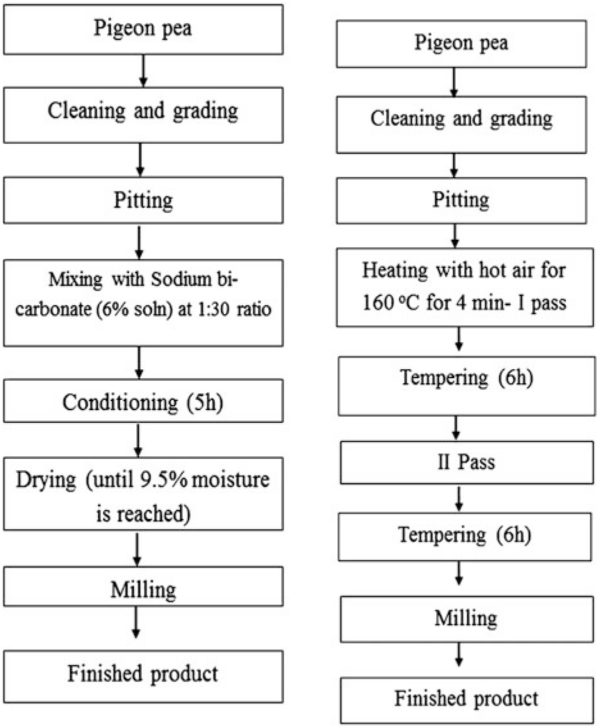


Fig. 11.9 Flow chart for chemical and thermal treatment of pigeon pea milling (Pantnagar process and CFTRI process)

complicated. As already discussed, the dry milling uses oil and conditioning in the process aiding in a loosening of husk. Whereas red earth treatment loosens husk in wet milling treatment. Only 50% of pulses are milled in the first pass in dry milling, whereas 95% is dehusked in wet milling. However, the recovery of is 68–75%, depending on the variety milled and the method used. Apart from wet and dry milling, several premilling treatments like heat, chemicals, and enzymes are used specifically for pigeon pea. Due to crucial milling needs of pigeon pea, various organizations have come up with different methods of pigeon pea milling as shown in Fig. 11.9.

The cleaned and graded pulses are pitted to scrape off the outer seed surface. The common objective of the process is to loosen the husk and aid milling. In the CFTRI process, hot air is used as a medium to loosen the husk, making it fragile and brittle providing an average yield of 80%. This method has been developed to overcome the problem observed due to the weather. However, high electrical consumption and high cost of machinery are the limiting factors. In the Pantnagar process, sodium bicarbonate is employed for loosening the husk with the recovery of dhal up to 80%. Even though this method eliminates the use of oil, the application of chemicals during this process results in the husk with chemical residues limiting its use as animal feed. CIAE method has also been developed to eliminate the use of oil in the milling of peas. Here, pitted grains are soaked in water to attain 35% moisture followed by drying to 10% moisture content, which gives a recovery of 75% [27].

11.10 Milling Calculations

Some important milling calculations are summarized as follows:

11.10.1 Dehulling Efficiency (DE)

Dehulling efficiency is the yield of dehulled whole seed as a percentage of whole unhusked pulse seeds [30] and also called as the degree of dehulling, and it is expressed as

$$\text{DE}\ (\%) = \frac{(\text{DWS} + D) \times 100}{\text{Wt}}$$

where total dehulled fraction = DWS (mass of dehulled whole seeds) + D (mass of dehulled dhal), Wt = original weight.

11.10.2 Dehulling Index (DI)

It is also called pearling index and ranges from +1 (maximum) to −1 (minimum) [31]:

$$n = \frac{(M\text{c} + M\text{h}) - (M\text{uh} + M\text{f})}{Mg}$$

where M_c, M_h, M_{uh}, M_f, and M_g are the mass of cotyledons and broken cotyledons, mass of removed hulls, mass of kernels that remained undehulled, mass of fines in the final product, and total mass of original grain fed into the dehuller, respectively.

However, dehulling index (DI) can also be expressed as [32]

$$\text{DI} = \frac{100 \times \text{SR}}{\text{AF}}$$

where

$$SR\ (\text{Seed coat removed}) = 100 - \left(\frac{W_3}{W_4} \times 100\right)$$

$$\text{AF (Abraded fines)} = \frac{W_1 - W_2}{W_1} \times 100$$

W_1, W_2, W_3, and W_4 are the weight of the original sample, weight of partially dehulled seed, weight of dried seed coat, and weight of dried fully dehulled seed, respectively.

11.10.3 Splits Yield (SY)

Also known as *dhal* yield is the yield of split product material (*dhal*) as a percentage of original whole seeds [30, 33], and it can be expressed as

$$\text{SY (\%)} = \frac{D \times 100}{\text{Wt}}$$

where D = mass of dehulled splits and Wt = original weight.

11.10.4 Percentage Kibble or Brokens

Percentage kibble or brokens are the yield of brokens as a percentage of the original seed weight [30, 33], and it can be expressed as

$$\text{Kibble (\%)} = \frac{K \times 100}{Wt}$$

where K = mass of brokens and Wt = original weight.

Problem 11.1 A mill receives 500 kg of pulses for processing. The cleaning operation separates about 15 kg of chaffs, dirt, sand, stones, twigs, etc. from the raw material. The whole seeds obtained from the cleaners are subjected to dehuller and about 100 kg of whole kernels remained and 300 kg of split dhal is obtained. Calculate the dehulling efficiency.

Solution:

Total dehulled fraction = DWS (mass of dehulled whole seeds) + D (mass of dehulled dhal) = 100 + 300 = 400 kg

Wt = original weight = 500 kg

$$\text{DE (\%)} = \frac{(\text{DWS} + D) \times 100}{\text{Wt}} = \frac{400}{500} \times 100 = 80\%$$

Table 11.6 FCI quality standards for procurement of pulses [34]

Pulse	Quality parameters
Tur, urd, and moong dhal (split)	• Foreign material: 2% max. including sand, dust, etc. • Kachri (damaged grains that included colored, immature, shriveled grains, etc.): 3% max • Retention on 4 mm sieve: 2% max • Red seeds: 95% max • Moisture: 12% max • Weevilled pulses: 4 % max • The material shall be tested on a 4 mm sieve • No live infestations should be there
Bengal gram (whole)	• Foreign matter: 3% max. of which 0.5% max. shall belong to the mineral or animal origin • Other edible grains: max. 2.0% by weight • Damaged/slightly damaged grains: max. 3% by weight • Immature, shriveled, and broken grains: 5% max • Admixture: max. 2% by weight • Weevilled pulses: max. 5% by count • Moisture: max. 12% by weight
Lentils (masoor whole)	• Foreign matter: 3% max. of which 0.5% max. shall belong to the mineral or animal origin • Other edible grains: max. 2.0% by weight • Damaged/slightly damaged grains: max. 3% by weight • Immature, shriveled, and broken grains: 3% max • Admixture: max. 2% by weight • Weevilled pulses: max. 3% by count • Moisture: max. 12% by weight

11.11 Quality Specifications for Pulses

In the interest of both the buyers and sellers, practical legal standards need to be adopted in order to ensure quality of the product. Table 11.6 summarizes the quality standards adopted by Food Corporation of India (FCI) for procurement of some pulses.

As per Food Safety and Standard Regulations (2010), the standards for food commodities are described under various categories. The standards laid down for the quality of pulses are shown in Table 11.7.

11.12 Value Addition of Pulses

Value addition may be defined as adding value to a product by means of processing, cooking, fortification, etc. to make it more marketable and appealing to consumers. Post-harvest operations are either aimed at value addition of raw material or reduction of wastage. Every stage of processing adds some value to the product, and it is estimated that primary processing adds 75% value to raw materials, and secondary/tertiary processing methods add 25% value, respectively. Thus, the role of primary processing in uplifting the income of farmers can’t be neglected. Development of the

Table 11.7 Quality standards for pulses [35]

Parameter	Standard
Moisture	• Not more than 14% by weight for masoor whole and split, urd whole and split, and moong whole and split • Not more than 14% by weight for channa whole and split channa dhal
Foreign matter[a]	• Not more than 1% by weight
Other edible grains[a]	• Not more than 3% by weight for masoor whole and urd whole • Not more than 4% for moong whole dhal, split moong dhal, and split pulse urd dhal and channa dhal • Not more than 2% by weight in split dhal channa and split pulse masoor dhal • Not more than 0.5% by weight for split arhar dhal
Damaged grains[a]	• Not more than 5% by weight for all split and whole dhal
Weevilled grains	• Not more than 6% by count for masoor whole, urd whole, and moong whole • Not more than 10% by count for channa whole and split channa dhal • Not more than 3% by count for split arhar, urd, channa dhal and split masoor and moong dhal
Uric acid	• Not more than 100 mg/kg for all split and whole dhal
Mycotoxin including aflatoxin	• Not more than 30 mg/kg for all split and whole dhal

[a] Provided that the total of foreign matter, other edible grains, and damaged grains shall not exceed 8% by weight

following category of foods from pulses through secondary/tertiary processing can be considered an effective way of adding value to pulses:

11.12.1 Baby Foods

Baby foods can be supplemented with pulse powders in order to increase the protein content and overall nutritive value. Pulse protein extract or specific bioactive peptides can also be used for fortification of baby foods. Boiled mung bean along with rice soup has been reported to be an effective protein supplement for babies [7]. Traditional processing practices like soaking, germination, malting, roasting, etc. can be employed for the development of nutritionally balanced, readily available, affordable source of weaning foods for infants [36].

11.12.2 Imitation Milks

Imitation milk is manufactured as a substitute of original milk and contains plant-based fats, proteins, water, and stabilizers like gums or alginates. Soy proteins are known to be the most effective plant-based proteins for use in imitation milks. The use of pea and lentil protein extracts has also been reported. Lentil protein extract gives intermediate-quality imitation milk as compared to soy protein isolates and the pea protein extract. A study on chickpea- and lupin-based legume beverage as an alternative to milk resulted in protein contents varying from 1 to 1.5 and 1.8 to 2.4%, respectively. Chickpea beverage with cooking water showed best results in terms of sensory quality with the yield of 1221 g/100 g of seed [37].

11.12.3 Bean Curd

Tofu is one of the most popular soy foods, which is made from soy milk and resembles the texture of cottage cheese. With a protein concentration of 2.3–3% and the use of 1.5% $CaSO_4$ as coagulant, pulses like chickpea, lentil, smooth pea, mung bean, faba bean, and winged bean yield a good-quality bean curd.

11.12.4 Meat Products

Pulse flours can be used as an ingredient in the meat products like burgers, sausages, nuggets, etc. [30]. Black-eyed bean flour, lentil flour, and chickpea flour have been successfully used as ingredients in meatballs at a 10% supplementation level.

11.12.5 Baked Goods, Glazers, Frosting, and Pastes

Pulse flours can be used to dilute wheat flour to improve the nutritional potential of baked goods. Protein, ash, fiber, and the amino acid scores can be increased by replacing wheat flour with chickpea or soybean flour.

11.12.6 Extruded Products

Pulse flours can be incorporated into extruded products like pasta, noodles, puffed snacks, etc., which will enhance the nutrient value of such products.

11.13 Quality Standards

Pulses may be marketed as raw whole or dehusked split. Quality plays an important role in marketing of pulses. Clean and properly graded pulses usually fetch higher prices in the market. Proper packaging also plays an important role in increasing consumer acceptability and reducing post-harvest losses.

11.14 Exercise

Q.1. 25 kg of pigeon pea is received in a commercial milling plant, which is subjected to processing. Preliminary operations like cleaning and grading are carried out to remove chaffs, dirt, sand, stones, twigs, etc. After cleaning and grading, the seeds are dehulled using advanced pigeon pea dehuller. After dehulling, 14.5 kg of whole seeds and 8.5 kg of split dhals are obtained. Calculate the DE (%). [Answer: 92]

Q.2 50 kg of black gram is subjected to cleaning and grading. The cleaned gram is then subjected to dehulling by high-speed gram dehuller and splitting machine resulting in 37.6 kg of dehulled split dhal. Now calculate the split yield (%). [Answer: 75]

Q.3. 100 g of sambar made from tur and moong dhal contain protein content of 22 g. Considering the nitrogen intake as grams of protein divided by 6.25. During the process of assimilation, it is observed that 1.26 g of nitrogen is lost. Calculate the biological value (BV). [Answer: 64]

Q.4. 100 kg of chickpea seed is milled to obtain 70 kg of dehusked whole dhal, 10 kg of broken dhal, 15 kg of removed hulls, 2 kg of underhulled seeds, and 3 kg of fines in the final product. Calculate the following:

a. Dehulling index [Answer: 1.2]
b. Kibble (%) [Answer: 14]

Q.5. Freeda weighs 40 kg with the height of 5 ft, 2 in. She is motivated to follow vegan protein-rich diet for her weight gain plan. If she consumes 400 g of pea-based menu containing 100 g of protein for 7 days, she can increase her weight to 42.5 kg, and then calculate the protein efficiency ratio of proteins present in her diet. [Answer: 3.5]

Q.7. Draw the process flow for wet milling process and indicate the critical process parameters.

Q.8. Elaborate the importance of premilling operations.

Q.9. Define dry milling of pulses and enlist the types of pulses that are dry milled.

Q.10. Discuss in brief about two milling techniques commonly employed in size reduction.

Q.11. Describe the effect of milling on nutritional, cooking, and functional quality of pulses.

Q.12. List the antinutritional factors in pulses and their effect on nutrient assimilation.

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Processing of Oilseeds

12

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Abstract

Edible oils are among essential commodities of the world. In this chapter, the information regarding the status of oilseed production, composition of oilseeds, properties of fats and oils, processing methods of oilseeds, their packaging, FSSAI standards and utilization of by products is covered. The physical properties, thermal, electrical and optical properties of fats and oils are also discussed. Understanding of various processing techniques of oilseeds is very important. Pre-treatments like cleaning, dehulling, decortications, flaking and heat treatments assist to enhance the recovery and quality of oil during processing. Oil extraction methods including ghanies, hydraulic press, screw press and solvent extraction are discussed in detail. The crude oil after extraction contains various impurities, waxes, gums, free fatty acids, phosphatides, etc., which may impart off odour and colour to the oil. Due to the presence of these components, the crude oil obtained needs to be refined by either physical or chemical refining process. Therefore, refining techniques are discussed in detail including the factors influencing these steps. In hydrogenation process, hydrogen gas is used to convert unsaturated fatty acids into saturated form, which is more stable. This process and factors influencing this process are also explained. This chapter also includes case studies for individual oilseeds processing techniques

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like rapeseed, soyabean, groundnut, sunflower oil, cottonseed oil and castor seed oil. Important parameters for different refined oil are given as per FSSAI guidelines. Huge amount of oil cake is obtained after processing of various oilseeds. These oil cakes are very good source of protein, fibre, acid insoluble ash, etc.; hence, these cakes can be used for food supplementation or important antibiotics, vitamins, etc.

Keywords

Composition of oils · Properties of oils · Oilseed processing · Oil extraction · Physical and solvent extraction · Refining · Hydrogenation · Packaging · Case studies (rapeseed, soybean, groundnut, sunflower, cottonseed and castor seed processing) · Quality standards, by-product(cake) utilization

12.1 Introduction

Oils/fats are important part of human diet along with other components including carbohydrates, protein, minerals and vitamins. One gram of fat supplies about 9 kcal of energy, which is more than double the number of calories provided by carbohydrates and proteins. The fat-soluble vitamins required by our body, i.e. vitamin A, D, E, K, are also supplied by oils and fats. Oils consumed in diet play various roles in our body; (1) these are stored in the form of fat in adipose tissue for future usage; (2) fatty acids are involved in the formation of cell membranes, protoplasm, as they combine with proteins. (3) The fats are oxidized to carbon dioxide and water and the energy produced during this process is useful for doing work and to maintain the body temperature. Major sources of oils and fats are oilseeds and animals.

At global level, India is among the major oil-producing countries. Processing of oilseeds has an important position in Indian economy since India is a major producer and consumer of oilseeds like rapeseed, peanuts, sunflower seed, soybeans, cottonseed, and their derived products. On the basis of consumer tastes and diversity, consumption of cooking oils vary from region to region.

As per the latest USDA report (June 2019), oilseed production across the globe has seen the steady rise during the last few years (Fig. 12.1). On the other hand, oilseed consumption at global level is forecasted to rise since the demand for protein feeds is growing, and it continues to drive the market.

India exports various oilseeds and is ranked seventh in world production. Indian peanuts find great demand in countries such as Philippines, Malaysia, Thailand, Ukraine, Indonesia, Algeria, Vietnam, Russia and neighbours. The countries producing groundnut in major amount are India, China, USA, Argentina and some tropical African countries. Indian soybeans find markets in Canada, Sri Lanka, Spain, Belgium and the United States. Whereas copra has demand in the UK, Nepal, Canada, the United States and Australia.

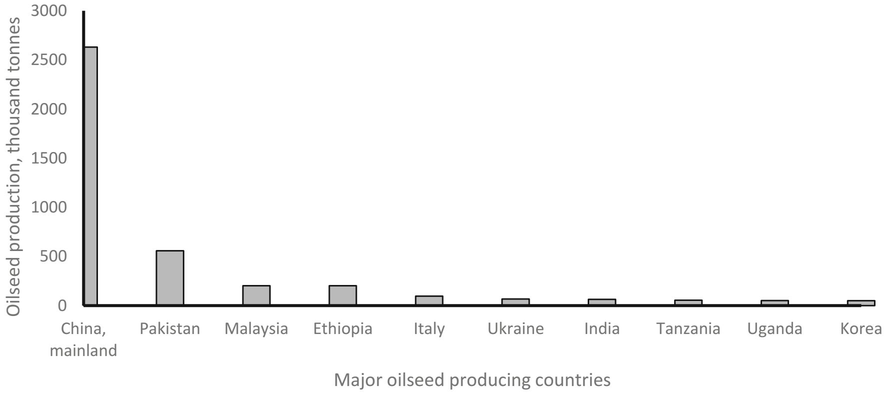


Fig. 12.1 Oilseed production from major oil-producing countries during 2018 (FAOSTAT)

12.2 Composition of Oils

Vegetable oils are composed mostly of triacylglycerols and very small amounts of di and mono acylglycerols, tocopherols/tocotrienols and phytosterols. The vegetable oils are characterized by the type of triacylglycerols and other minor components present, which decide the use in various formulations and manufacturing of foods. The colour of oils is dependent on the presence of fat-soluble pigments, e.g. chlorophyll, carotenoids, which may be affected by oxidation or polymerization during processing.

Fatty acids are hydrocarbon chains with methyl group at one end and carboxylic functional group at the other. A number of fatty acids are present in vegetable oils characterized by the length of chain, degree of saturation and presence of functional groups. The important fatty acids are saturated, monounsaturated and polyunsaturated fatty acids (PUFA). In saturated fatty acids (SFA), carbon atoms are linked by a single bond, whereas in unsaturated fatty acids, one or more carbon atoms are joined by double/triple bonds in the chain. In the present scenario, demand of nutrition has attained prime focus; presence of unsaturated fatty acids in diet has become important. The importance of n-3 α-Linolenic acid (ALA) and n-6 linoleic acid (LA) among PUFA is well established. The n-3 fatty acid provides anti-inflammatory, anti-thrombotic, anti-hypertensive and anti-arrhythmic derivatives, whereas n-6 fatty acid provides inflammatory, thrombotic, hypertensive and arrhythmic metabolite. Inflammatory metabolites are helpful in case of infections or wounds too, which necessitate a balance in n-6/n-3 to avoid immune deficiency in human body. These fatty acids can be determined and separated by gas chromatography, nuclear magnetic resonance techniques and mass spectrometry. A comparison of fatty acids present in vegetable oils is shown in Table 12.1.

Oil usually contains about 95% triglycerols before refining and after refining this value reaches nearby 99%. Presence of some haze after refining in some oils may

Table 12.1 Fatty acid composition of vegetable oils

Name	Soybean	Oil palm	Rapeseed	Cotton seed	Coconut	Sunflower	Groundnut	Palm kernel	Others: Olive	Others: Mustard seeds	Others: Rice bran
	Glycine max	*Elaeis guineensis*	*Brassica napus*	*Gossypium hirsutum*	*Cocos nucifera*	*Helianthus annuus*	*Arachis hypogea*	*Elaeis guineensis*	*Olea europaea*	*Brassica alba*	*Oryza sativa*
8:00	–	0.1	–	–	7.6	–	–	4.1	–	–	–
10:00	–	0.1	–	–	6.5	–	–	3.7	–	–	–
12:00	–	0.4	–	–	48.2	0.5	–	46.0	–	–	–
14:00	0.1	1.1	0.1	0.8	18.5	0.1	0.1	17.8	0.0	–	0.4
16:00	10.8	43.8	5.1	24.2	8.7	6.4	10.4	8.4	12.1	–	18.2
18:00	3.9	4.4	1.7	2.3	2.7	4.5	3.0	1.6	2.6	–	1.9
20:00	0.3	0.3	0.6	0.2	0.1	0.3	1.2	–	0.4	1.6	0.7
22:00	0.2	0.1	0.3	0.1	–	0.8	2.3	–	0.1	1.2	0.2
24:00:00	0.3	0.1	0.2	0.1	–	0.2	1.4	–	0.1	0.6	–
Total SFA	15.7	50.4	8.0	27.8	92.6	12.8	18.3	81.9	15.3	3.4	21.3
16:1 n-7	0.2	0.2	0.2	0.7	–	0.1	0.2	–	0.8	–	0.2
16:1 n-9	–	–	–	–	–	–	–	–	–	–	–
17:1 n-7	–	–	–	–	–	–	0.1	–	0.2	–	–
18:1 n-9	23.9	39.1	60.1	17.4	6.0	22.1	47.9	16.4	72.5	23.2	41.7
18:1 n-7	–	–	–	–	–	–	–	–	–	–	–
20:1 n-9	0.1	0.1	1.4	0.1	0.1	0.2	1.3	–	0.3	8.8	–
20:1 n-7	–	–	–	–	–	–	–	–	–	–	0.5
22:1 n-9	–	–	0.4	0.0	–	0.1	0.1	–	–	36.5	–
24:1 n-9	–	–	0.3	–	–	–	–	–	–	–	–
Total MUFA	24.2	39.4	62.4	18.2	6.1	22.4	49.6	16.4	73.8	68.5	42.4
18:2 n-6	52.1	10.2	21.5	53.2	1.8	65.6	30.3	3.1	9.4	8.9	34.6

18:3 n-3	7.8	0.3	9.9	0.2	0.1	0.5	0.4	–	0.6	12.5	1.2
18:3 n-6	–	–	–	–	–	–	–	–	–	–	–
18:4 n-3	–	–	–	–	–	–	–	–	–	–	–
20:2 n-6	–	–	0.1	–	–	–	–	–	–	–	–
20:3 n-6	–	–	–	–	–	–	–	–	–	–	–
20:4 n-6	–	–	–	–	–	–	–	–	–	–	–
20:5 n-3	–	–	–	–	–	–	–	–	–	–	–
22:2 n-6	–	–	–	–	–	–	–	–	–	–	–
22:4 n-6	–	–	–	–	–	–	–	–	–	–	–
Total PUFA	59.8	10.5	31.5	53.4	1.9	66	30.8	3.1	10.0	21.4	35.9
Total n-6	52.1	10.2	21.6	53.2	1.8	65.6	30.3	3.1	9.4	8.9	34.6
Total n-3	7.8	0.3	9.9	0.2	0.1	0.5	0.4	–	0.6	12.5	1.2
Ratio n-6/n-3	6.7	34	2.2	266	18	131	76	–	16	0.7	29
References	[1–7]	[1, 2, 8–10]	[3, 5, 6, 11]	[1, 2, 4, 6, 7, 12, 13]	[1, 2, 14–16]	[1, 2, 4, 7, 8, 17, 18]	[1, 4, 7, 19–21]	[1, 16]	[1–3, 22–25]	[1, 2, 4]	[1, 3, 26–28]

indicate the presence of wax esters, monoacylglycerols and sterol glucosides. Phospholipids are present in crude oils, which are removed during refining process. Soybean oil contains 1.5–2.5% phospholipids, whereas this percentage is approximately 1% in sunflower oil and less than or equal to 2.5% in rapeseed oil. This is the reason for considering soybean as a major source of lecithin. Another major component of fats and oils is sterol. It is present in rapeseed oil in quantity of about 7.5 g sterol per kg of oil. The presence of cholesterol in vegetable oils is not very significant (20–50 ppm) as compared to fats from animals (up to 1000 ppm), fish (nearly 700 ppm) and egg yolk (12,500 ppm).

12.3 Properties of Oils/Fats

The important characteristics of oilseeds for designing equipment, transportation, storage bins are density, specific gravity, porosity, angle of repose, refractive index, coefficient of friction, etc. The physical properties generally depend upon the molecule's organization, structure and interaction between molecules and their packing.

12.3.1 Density

The density of liquid is the mass of oil per unit volume. Factors affecting density are fatty acid composition of oil, other minor components and temperature. The information is very important for designing storage tanks and pipes. The density of oil generally ranges between 910 and 930 kg/m^3 at ambient temperature [29], whereas densities of completely solid fat ranges between 1000 and 1060 kg/m^3 [30]. The density decreases with increase in temperature and increases with increase in solid fat content (SFC). The density of oils remains higher with the presence of saturated fatty acids or lower density is evident due to the presence of unsaturated fatty acids in oil [31]. This remains the reason for higher density of solid fat; however, lower density of solid fat may be sometimes observed due to incorporation of air inside the solid mass.

$$\text{Density of oil}\left(\text{kg/m}^3\right) = \frac{\text{Mass of oil (kg)}}{\text{Volume of oil}\left(\text{m}^3\right)} \tag{12.1}$$

$$\text{Relative density of oil}\left(4^{\circ}\text{C}\right) = \frac{\text{Mass of any volume of oil}}{\text{Mass ofequal volume of water}} \tag{12.2}$$

12.3.2 Rheological Properties

Oil follows Newtonian behaviour at room temperature (25 °C) between 30 and 60 mPa. The viscosity of liquid oil decreases with increase in temperature and follows logarithmic relationship. Rheological properties are dependent on the concentration, interactions and morphology of fat. The solid fat demonstrates plastic behaviour, and the force required to flow the material is known as yield stress. The rheological behaviour can be expressed by the following equation:

Case I: Shear stress is less than yield stress:

$$\text{Shear stress } (\tau) = \text{Shear modulus } (G) \times \text{Shear strain } (\gamma) \tag{12.3}$$

Case II: Shear stress is equal or greater than yield stress:

$$\text{Shear stress } (\tau) - \text{Yield stress } (\tau_0) = \text{Viscosity } (\eta) \times \text{Shear strain rate } (\acute{\gamma}) \tag{12.4}$$

Normally, fat does not behave like an ideal solid and also exhibits flow characteristics to show plastic behaviour. Above the yield stress, non-Newtonian behaviour is exhibited by solid fats. Yield stress increases with the increase in solid fat content. The structure formation of solid fat is possible due to the ability of fat crystals to form three dimensional networks through bonding.

12.3.3 Thermal Properties

The main thermal properties of oils are specific heat, thermal conductivity, melting point and latent heat. The specific heat of most of the liquid oils is about 2 kJ/kg K at ambient conditions, which increases with the increase in temperature. The conductivity of oil, 0.170 W/mK, is lesser than the water, 0.60 W/mK. The melting point of saturated fatty acids is higher due to more stable structure. The smoke, flash and fire points are also important characteristics of oil and can be defined as the temperatures at which generation of smoke, initiation of volatile oil production and initiation of thermal decomposition respectively take place under continuous combustion [32].

12.3.4 Electrical Properties

Fats have relatively low dielectric constants, high electrical resistances and are poor conductor of electricity. The dielectric constant of pure triacylgycerols increases with the increase in chain length. The value of dielectric constant for oil is about 3 as compared to 80 for water.

12.3.5 Optical Properties

These properties can be used to monitor the compositional quality and overall appearance of oils which can be related to molecular arrangements within the liquids. The refractive index determines amount of scattering of light. Refractive index is used to determine the quality of oil. The refractive index usually increases with the increase in chain length, double bonds and conjugation of double bonds. Refined triglyceride is nearly colourless and does not absorb any light in visible spectrum. The impurity of pigment can also be adjudged by optical properties.

12.3.6 Solid Fat Index

Solid fat index (SFI) is defined as the percentage of solid fat in a total mixture of liquid and solid fat. SFI is an important parameter for establishing parameters for process control and formulations in oil and fat industry. SFI can be measured by various techniques like volumetric (dilatometric) technique, DSC, NMR, etc. In dilatometric technique, samples are loaded into dilatometer and immersed into water bath at different temperatures so that the samples can be tempered which causes the crystallization of samples under controlled conditions for comparative purpose. Volumes of the tempered samples at increasing temperatures are measured. Volumes versus temperature responses give the SFI values at different temperatures. Dilatometric techniques takes approximately 5 h. Therefore, advanced techniques like DSC and NMR can be applied. DSC measures heat flow into a sample and from a sample when it is heated, cooled or held at a temperature isothermally. The samples can be cycled through a heat, cool and reheat cycle and the melting endotherms can be used to analyse the SFI values. As the hydrogenation increases, the melting transition shifts to higher temperatures.

12.4 Oilseed Processing

Several post-harvest practices and unit operations are involved for minimizing losses during handling, extraction and purification of oil. Selection of appropriate technology not only enhances the oil yield but also reduces the cost of processing.

Some of the important post-harvest unit operations are described as follows:

12.4.1 Handling and Storage

The oilseeds undergo losses due to animals, birds, insects, deteriorative autocatalytic reactions, enzymatic action and microbial spoilage. The presence of immature seeds may increase the rate of deterioration due to active enzymes; therefore, it is necessary to separate such seeds during the initial stage of processing. The dirt, sand, dust, leaves, stems, stones, weed or metal may also be separated for saving additional cost in further processing; however, it may be performed after drying in case of very high moisture content of raw oilseeds received for processing.

The moisture content of seeds is usually high and is improper for safe storage. The oilseeds can be dried up to a temperature of 105–110 °C to shorten the drying period. This also helps in the retention of nutritional value of the oil and by-products. Usually, traditional sun drying practices may also be adopted according to the availability of time, space and labour requirement. After attaining the appropriate moisture content (7–11%) after drying, damaged and immature seeds can be screened again to reduce the respiration rates. Oilseeds are generally stored for some time to minimize the effect of chlorophyll content in oil for restricting the induction of greenish colour and enhancing the oil recovery. Most of the oilseeds are stored in heaps, bags, bins or silos.

12.4.2 Sorting/Grading

The stored oilseeds are checked for soundness, impurities, moisture content and other milling characteristics. The parameters such as type and quality of impurities/foreign material, moisture content, quality of shrivelled/immature seeds, oil content, colour and acid/iodine value of extracted oil are considered for sorting.

12.4.3 Pretreatments

Pretreatments assist to enhance the recovery and quality of oil. Some important pretreatments are:

a. Cleaning: The oilseeds from field/storage are obtained with different contaminants, viz. stones, stalks, sand, weed seeds, etc. and retained during harvesting, handling, transportation and storage. Larger impurities such as stones, metal/wooden pieces can damage the machinery involved in different unit operations. Proper cleaning enhances the crushing efficiency, quality of oil and cake and reduces plant maintenance.
b. Dehulling/decortications: As oilseeds contain appreciable amount of hull, which do not contribute to the extraction of oil; therefore, the oilseeds should be dehulled before further processing.
c. Size reduction/flaking: The size of oilseeds is reduced by mechanical expression through grinding or rolling. Large amounts of oil-bearing cells are disintegrated, and cells lose oils through their wall by the action of appropriate heat and pressure. The efficiency in the reduction of size of oilseeds affects the oil recovery. The size reduction in *ghani* takes place due to the action of pestle, sometimes small amount of water is added to provide grip for shearing due to smooth and slippery surfaces of oilseeds.

   Primary milling is required for hydraulic press; however, it can be avoided in screw press due to creation of thin flakes by shearing stress generated in the barrel of expeller. Flaking is inevitable for the extraction of oil through solvent extraction through rolling operation. About 0.20–0.25 mm size of flakes are preferable for solvent extraction. The moisture content of oilseeds should be adjusted to about 10–11% and heated up to 75 °C temperature; else seeds may be steamed prior to oil extraction.

d. Heat treatment: Oilseeds release oil more easily after heating prior to mechanical/solvent extraction due to coagulation of protein and creation of coalescence of oil droplets. This reduces the affinity of oil from the solid surface and also destroys moulds and bacteria. The rupture of oil cell wall takes place due to volumetric expansion of oil droplets, which makes it easier to ooze out the oil from the cells. Generally, the temperature 105–130 °C for 30–120 min is sufficient for heat treatment. However, optimization of process conditions is dependent on the type of oilseeds, initial moisture content, chemical and biochemical characteristics, heat treatment method, equipment used and oil extraction method. The moisture content of oilseeds should remain about 9–15% during heat treatment for efficient crushing operation. Over-heating/cooking produces oil with dark colour and low nutritive values. The moisture content remains critical for extraction of oil.

12.4.4 Oil Extraction

The extraction of oil from oilseeds is performed using ghanies, rotary oil mills, mechanical expellers and solvent extraction units.

12.4.4.1 Ghanies

Raw oilseeds are directly fed into ghanies without any pretreatments. The ghanies have power-driven rotating metallic mortar with a wooden pestle. The heat is generated while crushing of oilseeds between mortar and pestle, which remains insufficient for efficient extraction of oil (Fig. 12.2). Water is also added for hydration of protein and release of oil. The oil cake obtained from the ghanies are left with about 12–14% oil.

12.4.4.2 Hydraulic Press

The hydraulic press has higher efficiency and easiness in operation. It operates on physical extraction process and provides high yield from high oil-bearing seeds, viz. almonds, peanuts, sesame, walnut, flaxseeds, etc. The temperature of oil-bearing material is kept constant while processing for maximum retention of organic compounds. The extraction in hydraulic press can be performed either using cold processing of various oil-bearing crops, viz. almond, flaxseeds, walnut, etc. or hot processing of other oil-bearing crops such as peanut, sunflower, sesame, corn/wheat germ, etc. The quality of oil in terms of original flavour, purity, freshness, health and nutritional attributes are excellent due to extraction through physical process and remain popular amongst consumers. The cold pressing provides better quality of oil and cake due to minimal loss of nutrients and lesser impurity.

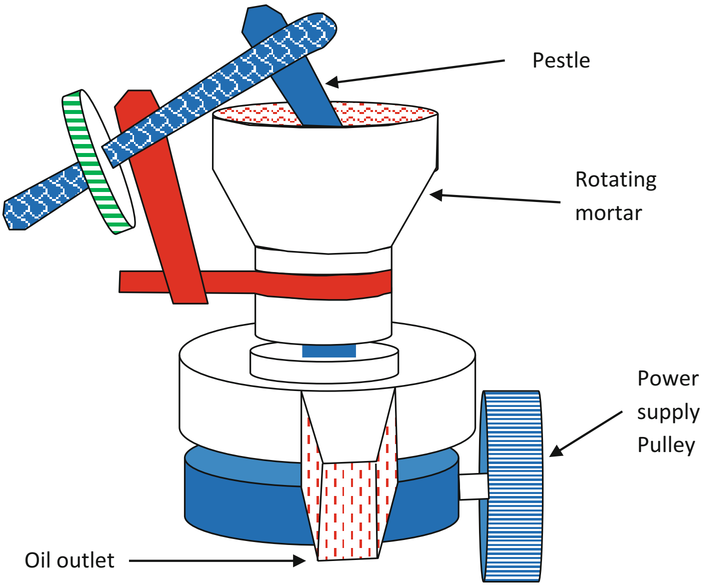


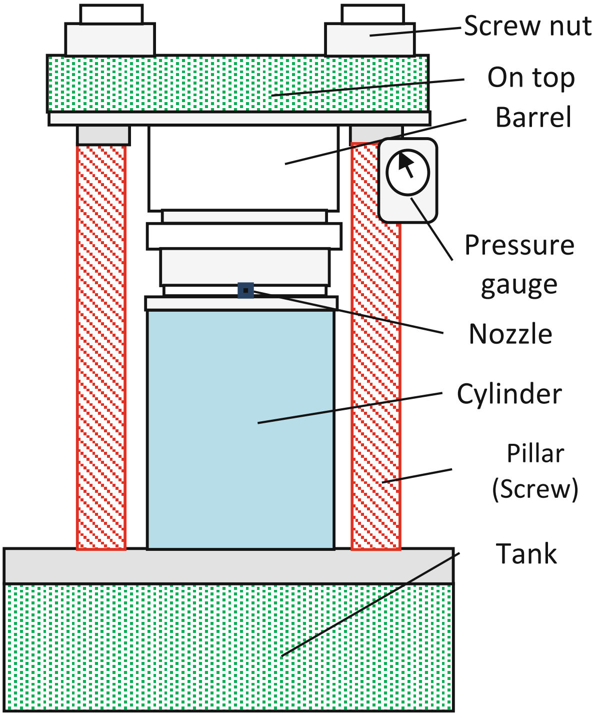
Fig. 12.2 Traditional oil expression using Ghani

The hydraulic press works on hydraulic transmission systems, which provides higher performance and lower failure rates (Fig. 12.3). The field press uses higher degree of automation using integration of mechanical and electrical mechanism. The feed cylinders are fabricated according to the crop for maximum oil extraction. The line cylinders, which have very small gaps between the metallic bars, are used for the extraction of oil from peanut, mustard, sesame, sunflower, while circular perforated cylinders are used for walnut, almond and flaxseeds.

12.4.4.3 Screw Oil Press/Expellers

Screw press is used to extract the oil through exerting pressure through dynamic extrusion by pushing the feed through a tightly packed barrel with a screw. The pressure generated through screw or worm also generates heats, which results in oozing out of oil from the oilseeds (Fig. 12.4). These are capable of producing higher yield through continuous operation and are robust in nature. An efficient expeller can extract almost 94% of oil. Sometimes, double pass is required, which is carried out on the basis of economy, oilseed type, end use of cake and acceptable quality. It extracts oil from a number of oil-bearing seeds, viz. rapeseed, peanut, vegetable seeds, cotton seeds, sunflower seeds, soybean, palm seeds, etc. High-grade material is used in the fabrication of screw press to achieve greater performance, durability, easier operation and lower maintenance. In case oil left is more than 8% in screw press, the cake may be subjected to solvent extraction. About 44% energy can be saved using mechanical expellers as compared to conventional ghanies.

Fig. 12.3 Hydraulic press



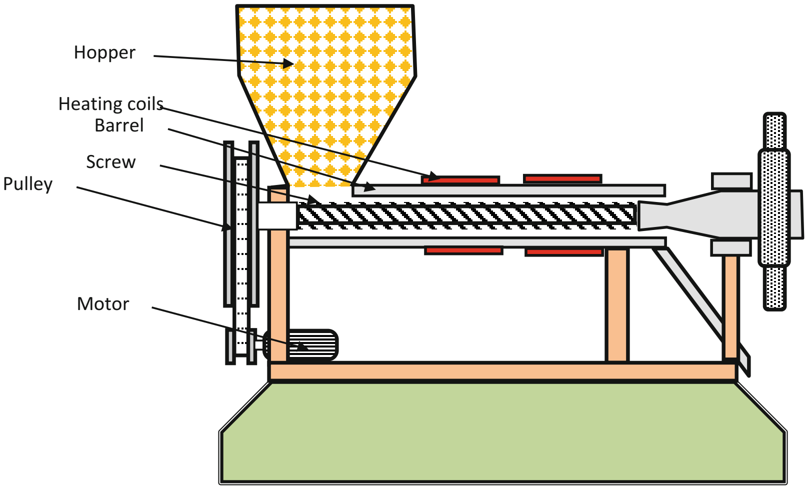


Fig. 12.4 Oil expeller

An oil expeller mainly consists of:

a. Frame: It provides housing to all the parts of oil expeller including hopper, barrel, main shaft, motor, pulley/gear, etc. It is usually made of heavy cast iron to ensure the stability to the expeller parts. It is also fabricated with heavy welded angle iron (MS angles of L-shaped structural steel). A motor is fitted on the frame to provide power to the expeller.
b. Hopper: It is used to feed the cleaned oilseeds to the screw press. It is designed to maintain consistent supply of oilseed by providing smooth flow and holding considerable amount of oilseeds for feeding.
c. Bed: It is provided to support the oil expeller to ensure balancing and alignment of various parts of the machine. It also helps to absorb vibration created during the working of expeller.
d. Main shaft: It consists of worm gear, cone, collar, gear, etc. It gains power from the motor through pulley and gear. The pulley is made through casting; however, the gears are made of alloy steel with proper quenching to increase hardness. The gears are usually fitted with oil bath case for smooth operation. The worms are provided on the shaft to exert compression on the oil-bearing material.
e. Barrel: A hollow and strong cylindrical barrel provides caging to the oil expeller. It is usually made from mild steel assembly with caging bars and frames. Sometimes heating coils along the barrels are provided for optimum recovery of oil.

The diameter of screw and barrel is designed with decrease in volumetric space that there is forward travel of oilseeds and the oil is expelled. The compression ratio in screw press is estimated by the volume moved in one revolution at feeding side to the volume moved at discharge end. The pressure and volume curves have three sections namely feed section, ram section and plug section (Fig. 12.5). The pressure increases in the feed section and reaches to a maximum. Thereafter, material moves to the ram section, and the pressure is reduced. In the plug section, pressure is released at the discharge end.

Various models based on capacities are prevalent in the commercial market such as:

Small Screw Oil Press

These are preferred to be installed in medium or small oil processing units. Their advantage of being simpler in structure, higher production rate and continuous seamless operation makes them popular in oil processing units. The high temperature and pressure generated through the process are effectively handled by high carbon steel or heat-treated steel.

Large Screw Oil Press

The large screw press can be used alone in oil plant or may be used as pre-pressing machine in bigger capacity plant. The automation is the need of the hour to provide consistent quality and minimum human interaction, which can also arrest the labour cost. The temperature of barrel can be controlled using online data acquisition and control systems. The vacuum filtering system can also be added to the system to enhance production efficiency and oil yield.

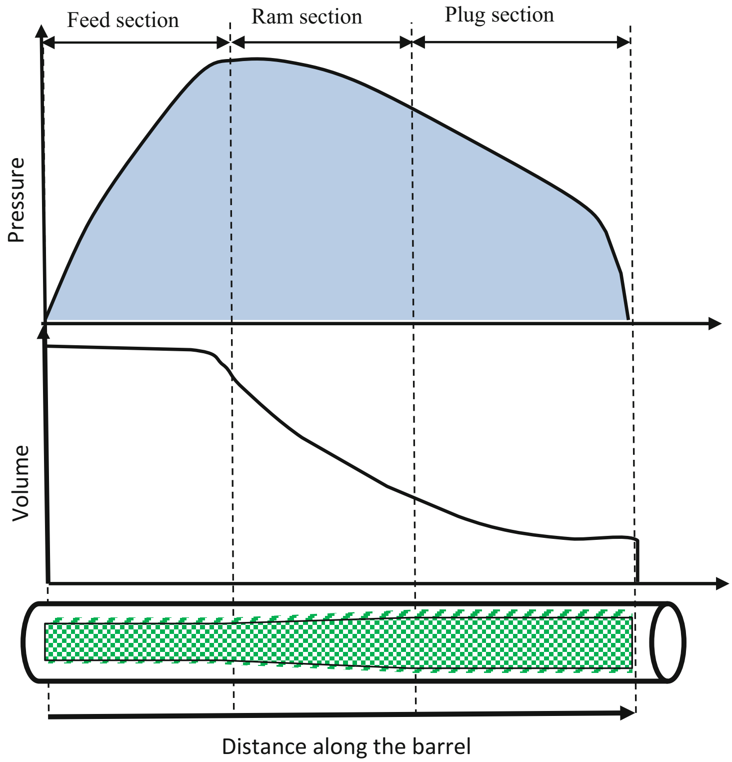


Fig. 12.5 Volume and pressure diagram along the length of barrel in screw press

12.4.5 Filtration of Oil

The crude oil obtained from hydraulic press and screw press needs filtration, which is performed using filter press (Fig. 12.6). The filter press contains papers or cloth as filter, which is supported by vertical plates and fixed on frames. The edible oil containing insoluble particles is pumped into the press, which allows liquid to pass through the filters and move to the drain provided as an outlet from each plate separately. The deoiled cake is deposited between the limited space provided between the plates, which continues till complete filling of space. The pressure is applied to build up to certain defined value for maintaining the flow of liquid. Plates are dismantled on complete deposition of cake in the space provided, which is removed and then filter press starts operating for next filtration process.

Centrifugal filter press uses centrifugal force to extract the oil at higher rotation velocity and separates impurities present in oil (Fig. 12.7). It has simpler operation in comparison to filter press. The oil enters the centrifuge under pressure, which is escaped through nozzles provided in tangential direction, and the speed of centrifuges is kept about 800 revolutions per minutes. The dirt and insoluble solids

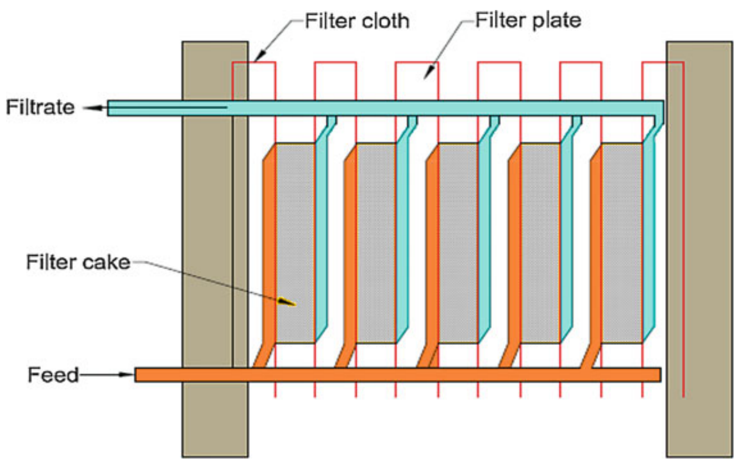


Fig. 12.6 Filter press

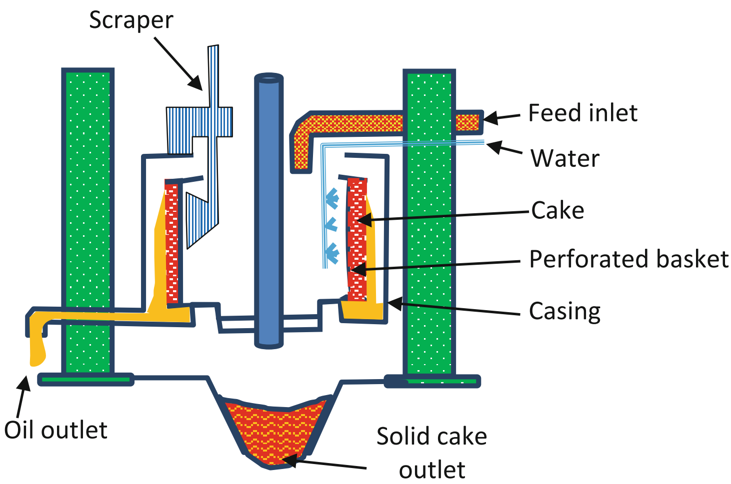


Fig. 12.7 Centrifugal filter press

are deposited on inner wall of rotor, which is collected through scratching by unloader knife and allowed to pass from the bottom opening.

Q1: Rape seeds contain about 48% oil and 8% moisture, and 500 kg is fed to a hydraulic press for extraction of oil. The moisture and oil content of the cake, received from the filter press, is 12% and 6%, respectively. Estimate the amount of oil extracted, oil recovery and moisture present in oil received through outlet in the hydraulic press extraction and filtration process.

Solution: The mass balance flow diagram of oil extraction considering steady state condition is presented in Fig. 12.8.

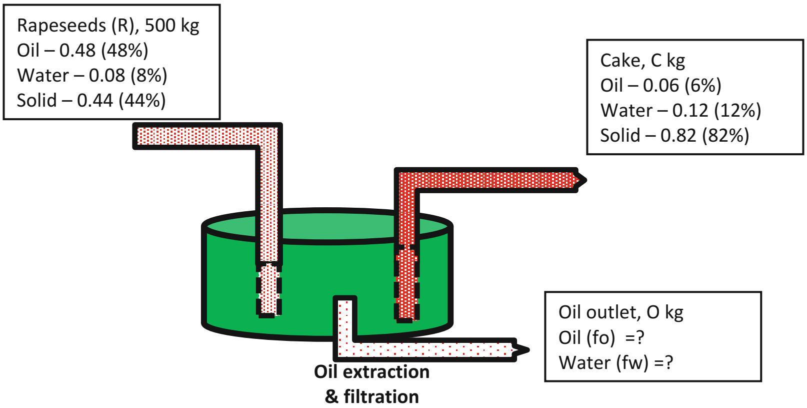


Fig. 12.8 Process flowchart

Applying total mass balance equation,

$$R = C + O$$

Applying component mass balance for solid, the solid is present in rapeseeds and cake produced

$$R \times 0.44 = C \times 0.82$$

$$500 \times 0.44 = C \times 0.82$$

$$C = 268.29 \text{ kg}$$

By putting the value of C in total mass balance equation,

$$O = R - C$$

$$O = 500 - 268.29$$

$$O = 231.71 \text{ kg}$$

Considering the oil balance equation,

$$R \times 0.48 = C \times 0.06 + O \times \text{fo}$$

$$500 \times 0.48 = 268.29 \times 0.06 + 231.71 \times \text{fo}$$

$$\text{fo} = (500 \times 0.48) - (268.29 \times 0.06)/231.71 = 0.9663 \text{ OR } 96.63\%$$

$$\text{Actual amount of oil recovered in oil outlet :}$$

$$\text{Actual Oil } (O_{act}) = fo \times O = 0.9663 \times 231.71 = 223.90 \text{ kg}$$

$$\text{Oil recovery } (\%) = \frac{\text{Actual amount of oil received from oil outlet}}{\text{Total amount of oil present in oilseeds}} \times 100$$

$$= \frac{223.90}{(0.48 \times 500)} \times 100$$

$$= 93.29\%$$

Amount of water in oil received from oil outlet can be calculated by deducting the amount of oil received by amount of actual oil received:

$$\text{Amount of water in oil} = O - O_{act} = 231.71 - 223.90 = 7.81 \text{ kg}$$

$$\text{Moisture content of oil received } (\%) = \frac{7.81}{231.71} \times 100 = 3.37\%$$

12.4.6 Solvent Extraction

The solvent extraction is also termed as liquid extraction method. In this, solute is separated based on the different solubility. In the extraction, mixture is allowed for phase separation, wherein the solvent-rich product is referred as extract and the residual liquid from which solute is removed is termed as raffinate (Fig. 12.9). The dissolved material is recovered, and the solvent is reused in the extraction process.

Solvent extraction is used as a final separation process of oil from oil-bearing (oleaginous) materials. The oil-bearing material is processed mechanically, if the material contains more than 30% oil, e.g. rapeseeds, groundnut, sunflowers, copra. While in case of less oil containing material (<30%), e.g. rice bran, corn germ, the oilseed material can be processed and directly used in solvent extraction for separation of oil. The capacity of solvent extraction plants varies from 1500 to 5000 tons/day.

A number of solvents are used in the extraction process, viz. alcohols, pentane, carbon disulphide, benzene, hexane. Commercial hexane is generally prepared using 65% normal hexane and remaining 35% of cyclopentane and hexane isomers. It has

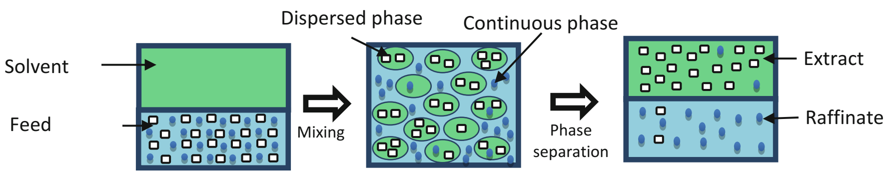


Fig. 12.9 Process flowchart of solvent extraction

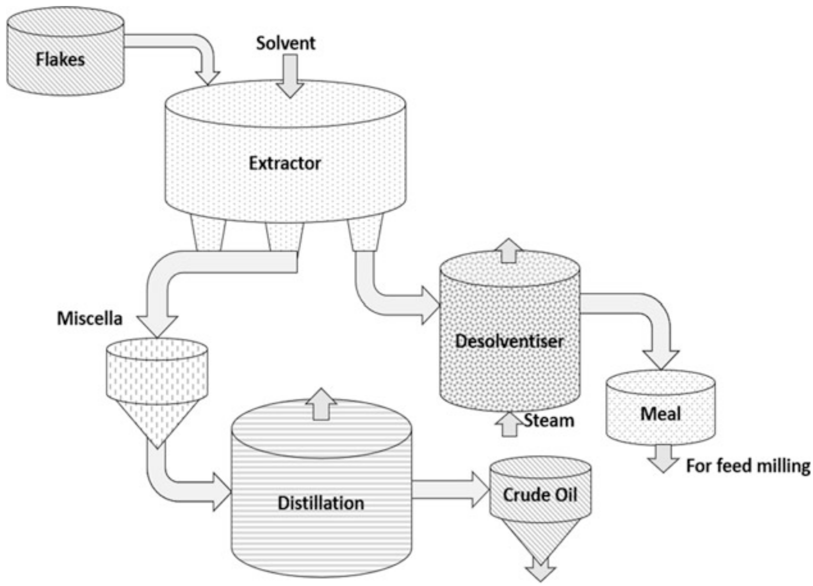


Fig. 12.10 Solvent extraction process

high solubility with edible oils, excellent diffusivity through oilseed cell walls, low solubility with water, relatively low cost, low specific heat, low latent heat of vaporization and moderate boiling range. However, hexane is to be recovered completely to avoid environmental problems and for the economic viability. Usually, solvent extraction process structure is installed at a distance from other sections, viz. seed preparation process, oil refining process and other facilities. Schematic diagram for solvent extraction process is given in Fig. 12.10.

Solvent extraction units have five main key sub-units, viz. solvent extractor, desolventizer, dryer/cooler for meal, miscella distillation and solvent recovery.

12.4.6.1 Solvent Extractor

The oil-bearing material is primarily processed into flakes for increasing the surface area and then fed into the solvent extractor (Fig. 12.11). The solvent extraction is used to dissolve oil fraction from oil-bearing material in the solvent. It takes about 30–120 min residence time and miscella is generated. The miscella (oil + solvent) is washed several times (4–10 times) to extract edible oil and last wash is performed using fresh solvent to complete the extraction process.

The extraction process starts with diffusion of miscella at the surface followed by movement into oil-bearing material and quickly goes into the solution with oil. The internal pressure increases within cell due to continuous entering of miscella, and therefore, concentrated miscella moves back into the solution. The concentrated miscella diffuses with adjacent cell wall and finally reaches at the surface of the particle. As concentrated miscella meets with the miscella, it goes into the solution

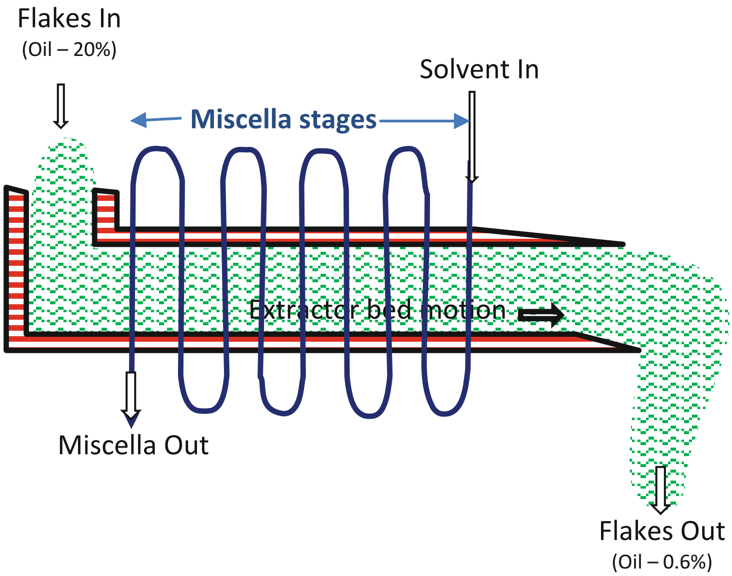


Fig. 12.11 Solvent extractor

and thus increases the concentration of the solution. The process continues till material maintains equilibrium with miscella outside the material.

The extractor with higher bed depth requires smaller surface area, which uses immersion of oil bearing material in miscella. The sufficient flow rate is provided to ensure good contact of oil bearing material and miscella. The extractor with low bed depth requires larger surface area, which provides flow of miscella percolating down through oil bearing material. About 40–50% surface is usually covered with material, and the material is surrounded with miscella liquids and solvent vapours.

The performance of extraction process depends on the following process parameters:

Contact Time

Total time in the extraction process is termed as residence time, wherein it can be divided into wash time (time during oil bearing material remain under washing nozzles) and drain time (time from last nozzle to the discharge outlet). The wash time again can be subdivided into contact time and dormant time. Thus, contact time is the duration spent in contact of oil-bearing material with miscella in washing zone of extractor, which remain actual time for extraction process. While dormant time is considered as the remaining non-contact time of oil-bearing material with miscella. The ratio of contact and dormant time remains important and may vary according to the system. The deep bed depth extractors have very high ratio of contact time to dormant time, which remain lower in case of low bed depth extractors. The variation of contact, dormant and drain times can be observed in Table 12.2, which shows that

Table 12.2 Residence time in extractors

<table>
<tr><th>Time, min</th><th colspan="3">Deep bed extractor</th><th colspan="3">Shallow bed extractor</th></tr>
<tr><td>0</td><td rowspan="11">Residence time</td><td rowspan="7">Wash time</td><td rowspan="6">Contact time</td><td rowspan="11">Residence time</td><td rowspan="10">Wash time</td><td rowspan="6">Contact time</td></tr>
<tr><td>6</td></tr>
<tr><td>12</td></tr>
<tr><td>18</td></tr>
<tr><td>24</td></tr>
<tr><td>30</td></tr>
<tr><td>36</td><td>Dormant time</td><td rowspan="4">Dormant time</td></tr>
<tr><td>42</td><td colspan="2" rowspan="4">Drain time</td></tr>
<tr><td>48</td></tr>
<tr><td>54</td></tr>
<tr><td>60</td><td colspan="2">Drain time</td></tr>
<tr><td>Contact time: Dormant time ratio</td><td colspan="3">5:1</td><td colspan="3">5: 4</td></tr>
</table>

for similar contact and residence time, the dormant and drain times vary in the different extraction processes for 1 h extraction process.

It is always desirable to provide adequate contact time for getting the maximum extraction efficiency and minimum loss of oil in the oil-bearing material. The increase in contact time increases the efficiency, whereas it limits the capacity of the extraction unit. Therefore, optimization of process parameters is of prime importance for deciding the contact time.

Particle Thickness

The thickness of the oil-bearing material is reduced using flaking process, which reduces the distance between miscella and oil in material for easier diffusion of oil. It also reduces the time to attain equilibrium between material and miscella, which eventually results in less processing time. The least possible thickness is desirable for extraction of oil; however, the power consumption in flaking remains a major controlling factor as more power is required for creating thinner flakes.

Extraction Temperature

The temperature increases the diffusivity of miscella through the oil-bearing material and therefore improves the efficiency of extraction. Usually processed flaked/cake attains the temperature of approximately 60 °C, which eliminates the requirement of preheating of oil-bearing material to heat further. Boiling point of commercial hexane remains 64–69 °C, indicating 63 °C is the limiting temperature for solvent extraction process. Which can further be brought to about 60 °C to provide safety margin for boiling. Insulator conveyors are good option for conveying the oil-bearing material to the extractor.

Miscella Flux Rate

The miscella flux rate is defined as maximum volumetric flow rate through the bed of material per unit surface area of bed or downward velocity of material through the bed (m/min or m/h). The material has about 40–50% of area covered with solids, and remaining area 50–60% is set free for the movement of miscella. The flow rate of miscella is restricted by perforated screen (30% in case of shallow bed and 10% in case of deep bed) and entire oil-bearing material is immersed in the miscella, which is termed as flooding of the material bed.

The hexane is not soluble in water, and hence, repulsive forces exist, and therefore, it reduces difficulty in penetrating through the oil-bearing material. The deposited moisture on the surface of screen also narrows down the perforation and thus decreases in miscella flux rates, which can be controlled using brushes on the screen surface.

Q2: The deep bed extractor with 2.8 m bed thickness is used for solvent extraction. The forward flow velocity of the material is 0.32 m/min. The downward velocity of miscella is 0.30 m/min (Fig. 12.12). Calculate the distance of washing nozzle till miscella collection vessel.

Solution:

$$\text{Downward velocity of miscella} = 0.30\ \text{m/ min}$$

$$\text{Forward velocity} = 0.32\ \text{m/ min}$$

$$\text{Depth of bed} = 2.8\text{m}$$

$$\text{Distance of washing nozzle to collecting vessel} = ?$$

$$\text{The downward movement is restricted by pores, assuming 55\%pores space available}$$

$$= 0.30/0.55 = 0.545\ \text{m/ min}$$

$$\text{Time for miscella to pass through bed} = 2.8/0.545 = 5.14\ \text{min}$$

$$\text{Distance between washing nozzle to miscella unit} = 5.14 \times 0.32 = 1.65\ \text{m}$$

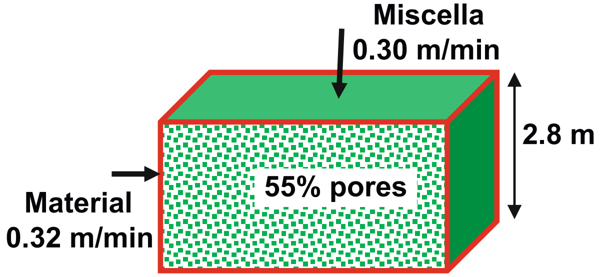


Fig. 12.12 Deep bed extraction of oil

Number of Miscella Stages

The single stage extraction of oil from 20% to 0.5% concentration needs about 17 times more solvent. Therefore, multi-stages are required to extract the oil, which need lesser solvent. Usually for energy efficient distillation systems, the ratio of solvent and material should be maintained as 1:1. The number of stages required for 20% to 0.5% concentration oil in material is kept as 4. However, increase in stage increases the extraction efficiency, but it also increases the cost in terms of more pumping energy and processing time. Commercially, the stages may be limited between 5 and 9.

Solvent Retention

The oil-bearing material is drained in the range of 5 min in low depth extractor to 20 min in deep bed extractor. The drained material has about 25–32% of solvent. The solvent retention is also defined as weak miscella retention, which has about 1% of oil in the drained material. The efficient extraction drain line should minimize weak miscella retention, which can be attained using appropriate miscella flux rate, maintaining proper flake thickness, minimizing fine materials and surface moisture in the material bed.

12.4.6.2 Meal Desolventizer Toaster (DT)

The meal desolventizer toaster is used to remove the solvent from the meal fraction (Fig. 12.13). It receives material from the extractor at about 60 °C with 25–35% solvent by weight. Desolventizer is cylindrical in shape and installed vertically with a number of horizontal trays. The extracted material enters from the top tray, which is conveyed downward tray to tray by agitating anchor attached to the rotating shaft. The meal is heated by steam to evaporate the solvent. The desolventizer has different trays, viz. predesolventizing trays, counter current trays and sparge tray.

Predesolventizing Trays

The steam is generally held at a pressure of 10.5 kg/m^2, which increases surface temperature of tray to 185 °C. The material is spread in a shallow layer of 150–300 mm over the trays. These trays may be placed in numbers and allow vapours to pass around the material and exit from the top. Some trays allow vapours through the annular gap between tray outer perimeter and cylinder and other provides concentric hollow disc-shaped trays having opening at the centre. A larger tray is also preferred in some case to avoid number of trays. The temperature of the material is increased up to 68°C and about 10–25% solvent is evaporated in these trays.

Counter Current Trays

These trays provide conductive heat transfer through their upper surface for keeping the material warm and provide convective heat transfer through lower surface of trays by swirling of steam. A desolventizer may have 1–4 counter current trays. These are placed just below the predesolventizing trays. The apertures provided in these trays have 1–10% of open area, which allows steam to pass through the meal.

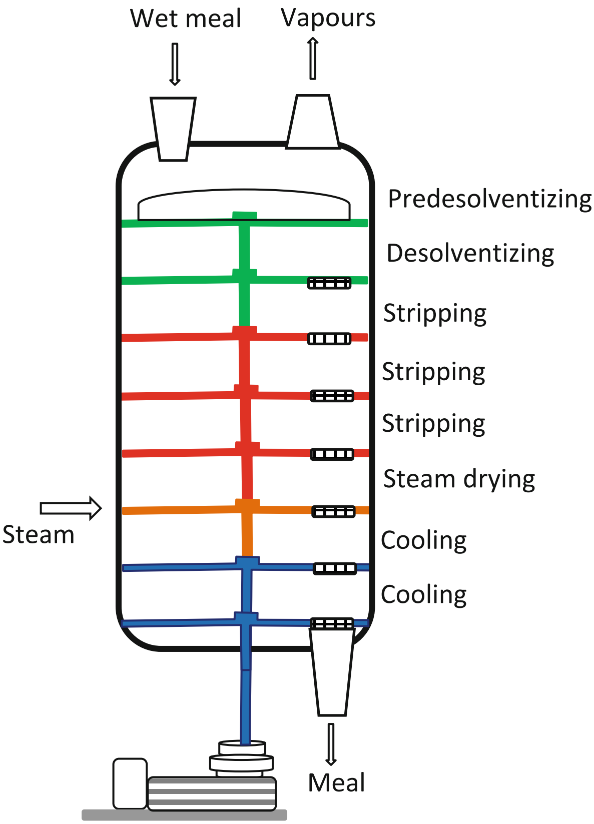


Fig. 12.13 Desolventizer toaster

A deep layer of about 1000–1200 mm is held above these trays, and the material is stirred using rotating sweeps. The condensation of steam adds 17–21% moisture in these trays. The wet meal obtained after top counter currents tray loses 99% of the solvent, while 1000 mm deep layer may be used to provide residence time to allow stripping and toasting of solvent.

Sparge Tray

These trays provide uniform induction of steam into a meal layer and provide conductive heat transfer in the material placed onto it. The upper surface temperature is maintained at about 100–110 °C and may reduce moisture content as low as 1%. More than 99% of the solvent is removed in the first counter current tray, while other counter current and sparge trays are used to provide sufficient solvent stripping and toasting. This reduces the residual solvent to 100–500 ppm level.

12.4.6.3 Meal Dryer Cooler

The meal obtained from desolventizer is fed to the meal dryer cooler (DC). The meal received from desolventizer is at about 108 °C, and it may contain 18–20% moisture.

The meal dryer cooler is used to reduce the moisture to a predetermined level according to the commercial values prior to storage. It is also a cylindrical vessel installed vertically with a multiple of horizontal trays. Sometimes, combined chamber for desolventizer and meal dryer cooler may be installed. It may have different types of trays, viz. steam drying trays, air drying trays and air cooling trays.

Steam Drying Trays
These trays are designed to hold pressurized steam between upper and lower plates, which provides conductive heat transfer to wet meal. These trays may be limited to five in numbers. The steam is held at 10.5 kg/m^2 pressure and 185 °C for drying purposes.

Air Drying Trays
These trays are designed to hold low pressure air, which is evenly distributed into the meal. The size and numbers of apertures are calculated according to the designed air flow rates. The air flows in the upward direction with a nominal velocity of 14–21 m/min to attain fluidization of meal. The temperature of meals drops from 108 to 38 °C, and the moisture content is reduced to 6.5%. The cold air has lower moisture-carrying capacity due to higher relative humidity. In case of higher relative humidity of ambient air, it needs to be heated to evaporate the moisture.

Air Cooling Trays
These trays are designed to hold low pressure air and cool the meal. The cool and damp air exits at the top of meal layer and moves through the side wall of meal cooling trays to cyclone separator in order to remove fine particles and to discharge air into the ambience. The material received from the cooling trays may be fed into size reduction unit to enhance the flowability and reduction of solidification for transport and storage.

12.4.6.4 Miscella Distillation System

The miscella received from the extractor contains about 1% of meal particles. Initially, the meal particles are separated. The larger meal particles above 80 mesh size should be separated using filtration or centrifugation for restricting settling in distillation apparatus. In some cases, extractors are fitted with internal miscella filter for sending miscella received from the extractor directly in the distillation process. After the separation of larger particles, the material is kept for storage in surge tank/ full miscella tank. The tank maintains continuous supply of miscella in the distillation process. The miscella contains about 25–30% oil and 70–75% solvent and maintained at temperature of 60 °C.

The full miscella tank supplies miscella to first rising evaporator, which is termed as economizer, and utilizes the waste heat received from desolventizer toaster and receive the material at 60 °C. The tube side of the evaporator is maintained at 300–400 mmHg absolute pressure and temperature of miscella reduces to 43–48 °C. The solvent starts boiling, and the bubbles start to rise. Additional heat provided from desolventizer vapours add heat to the miscella, which make it possible to drag a thin layer of miscella to inner wall of tubes creating high heat transfer rates. The foams of solvent vapour are broken and then centrifugally separated in evaporator dome. The concentrated miscella exist at the base of dome. It enhances the concentration of miscella up to 75–85% oil and maintained at a temperature of 48 °C.

The miscella is heated to about 75 °C before entering into the second-stage evaporator. The pressure in the second-stage evaporator is also maintained at 300–400 mmHg absolute pressure, which reduces the temperature similarly for vigorous evaporation. It enhances the concentration of miscella up to 95–98% oil and 2–5% solvent.

The material received from the second stage evaporator is fed to the oil stripper, which is a tall, thin and cylindrical vessel and usually operated at 150–300 mmHg absolute pressure. The steam is used into the vessel to initiate evaporation. The solvent and steam vapours exit at the top. The oil received from the stripper consists of 0.1–0.3% moisture and 5–200 ppm solvent at a temperature of 95–110 °C. The temperature is brought down to 70–80 °C and soft water at a concentration of 1–2% is added and agitated about 30–60 min in a tank for hydration of gums, which are then separated using high-speed centrifugal separator. The oil after degumming contains about 0.5% moisture, which is heated to 110 °C and fed into vertical cylindrical vessel, which is maintained at 50–80 mmHg absolute pressure for drying of oil. The oil received from oil dryer has 0.05–0.10% moisture and about 5–100 ppm of solvent only.

12.4.6.5 Solvent Recovery System

The modern processing plant recovers about 99.9% of solvent used in extractor. The process of recovery starts from condensation of solvent and water vapours followed by the separation of solvent and water, stripping of solvent from water and air streams and heating of solvent.

The vapours generated in all the processes in extraction system are usually condensed in common vacuum condenser. The vacuum condensers are generally a shell and tube heat exchanger having vapours on the shell side. The uncondensed vapours from the oil dryer are evacuated using steam ejector maintained at 50–80 mmHg absolute pressure.

The vapours of solvent and water received from the desolventizer are required to pass through a scrubber for the removal of meal particles from the vapours. The centrifugal and water spray scrubbers are used. The clean vapours received from the scrubbers are condensed. About 94% of solvent and 6% of steam is obtained at this stage.

The solvent and water collected from all the condensers are sent to a decanting tank, which removes the lighter solvent with a specific gravity of 0.65 and collect separately. The turbulence is avoided in the decanting tank to allow gravity decantation. The solvent received from the decanting tanks contains about 0.05% water, which is moved to solvent work tank. The solvent work tanks hold ample amount of solvent to reuse in the extractor. It also has a provision to allow excess solvent in solvent storage tank. The solvent is heated to 55–60 °C prior to use in extractors.

12.4.7 Refining Process

Crude oil is passed through filter press at higher speeds for sediment-free oil. The crude oil after extraction contains various impurities, waxes, gums, free fatty acids, phosphatides, etc., which may impart off odour and colour to the oil. Due to the presence of these components, the crude oil obtained needs to be refined either by physical refining process or by chemical refining process.

In this process, the FFA level is reduced to lesser than 0.1%. Generally, the refining is carried out either by physical or chemical method. The oil refined by chemical process produces lesser amount of free fatty acids and is better cost effective. The refining includes degumming, neutralization of fatty acids, bleaching and deodorization.

Usually degumming process requires 1–3% water addition at 60–80 °C for about 30–60 min based on the type of oilseeds; however, small amount of acid may increase the solubility of phospholipids, which are capable of binding calcium and magnesium.

The neutralization of oil is achieved by the reaction of oil with the solution of caustic soda (7–12%) and bleaching is performed with clays (adsorbents), such as silicates, activated carbon activated earth, etc. by mixing at 80–110 °C followed by filtration. The deodorization process is performed by steam distillation of oil at a temperature, generally in the range of 180–270 °C and at low pressure of about 1–6 mmHg to remove undesirable aroma compounds like aldehydes, ketones and alcohols.

In physical refining process, the free fatty acids are removed by distillation process, at high temperature and high vacuum conditions by injecting steam directly (Fig. 12.14a). The oil is neutralized using physical process which may include selective adsorption/experimentation of free fatty acids (FFAs). In a selective adsorption process, adsorption of FFA on selective ion exchangers is done. If the oils contain very high concentration of FFAs (>20%), then selective extraction process is employed in which oils can be extracted with ethanol or furfural to bring down the concentration of FFAs.

In the next step, oil is bleached by activated bleaching earth (ABE). The process temperature varies in between 60and 90 °C and the pressure is maintained at 50–200 mbar. After completion of the process, the used bleaching earth is removed by filtration process (1–2 mbar of residual pressure). After bleaching, deodorization is carried out in which steam is used at 180–240 °C under high vacuum conditions.

In chemical refining process (Fig. 12.14b), a pretreatment is given with diluted acid (e.g. phosphoric acid, citric acid). The acidic oil obtained is treated with alkali (7–12% NaOH) to neutralize the free fatty acids present in the oil; after that the soap is removed by centrifugation or by settling process and the oil obtained is washed with water to remove traces of alkali. Water is then removed by vacuum drying and reduced to minimum. The various by-products are separated during the refining, which can be further used for different applications (Table 12.3).

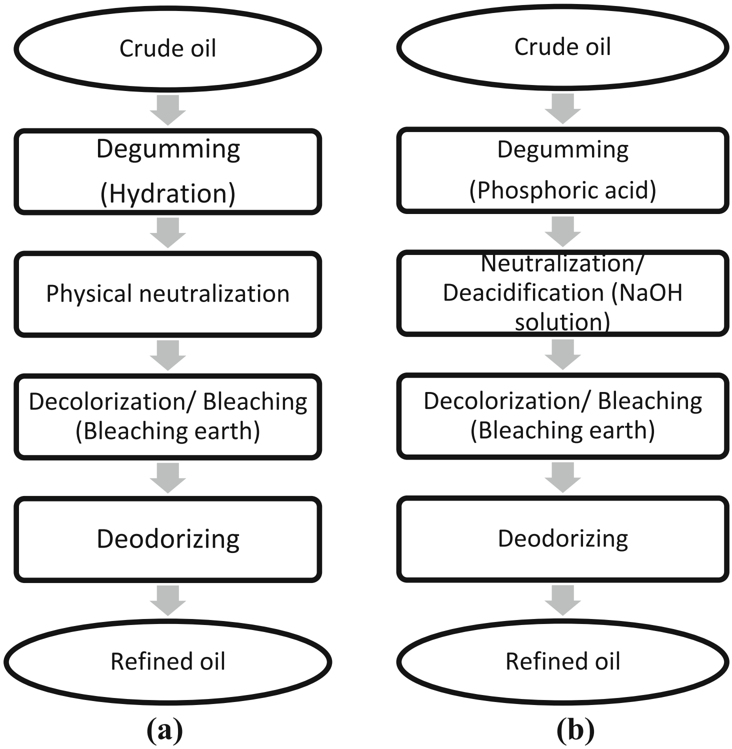


Fig. 12.14 Flowchart of oil refining process. (**a**) Physical refining. (**b**) Chemical refining

12.4.7.1 Bleaching

Bleaching is performed to remove the colour pigments, which was performed initially using bleaching clay. It is an essential process and is performed in single stage or multistage processes, which removes oxidation products, soaps, metals, phospholipids and other contaminants. This process is usually followed by deodorization. The vacuum bleaching was initiated to avoid oxidation and colour fixation and improvement in oxidative stability. Semi-continuous process remains energy efficient for bleaching process and produces improved bleached oil quality.

Bleaching Earth

Plate and frame filters were used to improve the process, while these had a limitation of producing high residual oil content about 35–40% in spent bleaching earth. The improved pressure filters restrict the residual oil content about 25–30% in bleaching earth. The residual oil content in bleaching earth remains a prime criterion for the selection of process as it reduces oil recovery and on the other hand increases the requirement of bleaching earth. The disposal cost of the bleaching affects the overall operating cost of the oil-processing plant. Therefore, lowering the requirement of bleaching earth enhances the efficiency of system.

Table 12.3 The by-products/waste during refining processes

Refining step	By products removed
Degumming/ washing	1. Hydratable non-oil constituents, mostly carbohydrates and proteins, are removed 2. Hydratable non-glyceridic lipids such as phospholipids are partially moved 3. Chlorophyll is partially removed, especially if phosphoric acid is used
Alkali refining	Saponified fatty matter containing the following constituents are removed/ reduced 1. Free fatty acids (FFA) and other materials such as phospholipids (gums), oxidized products, metal ions, etc. 2. Residual phospholipids 3. Proteinaceous materials 4. Colouring matter
Bleaching	Spent Earth containing following constituents are removed 1. Carotenoids 2. Chlorophyll and its derivatives 3. Gossypol-like pigments 4. Toxic agents, such as polycyclic aromatic (PCA) hydrocarbons (if carbon is used)
Deodorization	Volatiles collected in catchall containing the following constituents are removed/reduced 1. FFA, peroxide decomposition products, colour bodies and their decomposition products 2. Sterols and sterol esters 3. Tocopherols 4. Pesticide residues and mycotoxins

The efficiency of bleaching earth can be improved by acid activation using sulphuric or hydrochloric acid by increasing the surface area. The activated earth is commercially available for bleaching of oil. However, in case of palm oil, nonactivated earth is preferred for bleaching due to the formation of potentially toxic 3-monochloropropanediol (3-MCPD). Sometimes, natural and less activated soils are also used as bleaching earth. The decrease in particle size of bleaching earth also improves the bleaching process, but separation of oil from bleaching earth using conventional filtration remains problematic. The electrically charged agglomeration of fine particles followed by conventional filtration may remain effective in such cases.

The bleaching process is usually a single-stage process; however, it does not effectively use the capacity of bleaching earth. Therefore, multistage bleaching processes are preferred in the form of co-current, counter current or any other combination. The counter current process saves more bleaching earth in comparison to parallel combination but is quite complex in use. The prefiltration for removal of solid impurities, phospholipids and soaps are performed, which saves 10–15% of bleaching earth. Sometimes, silica hydrogel (silicon dioxide with high amount of water) is used to remove polar impurities like phospholipids, soaps and trace elements; but it has little effect on colour pigments. The silica of about 0.05–0.1% is added to the neutralized oil at temperature in the range of 70–80 °C and left for

15–30 min in contact at atmospheric pressure. The oil contained silica should be dried and then transferred to bleaching earth, and it saves about 40% of the bleaching earth due to enhanced ability of bleaching earth to absorb the colour pigment and improvement in filterability due to addition of silica.

Activated Carbon

Activated carbon is also used for bleaching the edible oils. It is produced using carbon-rich material, that is steam activated at very high temperature about 1000 °C to provide high surface area. However, the use of activated carbon is limited in oil processing due to availability of efficient bleaching earth. Activated carbon is used to remove polycyclic hydrocarbons from edible vegetable oils that might have gained by oil during heating during extraction of oil. Recently, it is also used for decontamination of sunflower and rapeseed oils.

The cost of activated carbon is higher than bleaching earth. Also, activated carbons have lower filtration capacity and high oil retention. That is why, these are used with bleaching earth. Activated carbon is added to the bleaching earth in a proportion of 10–20%. The high filterability filters like pressure leaf filters, pulse tube filters and membrane press filters are used with activated carbon powders. These filters can be squeezed to ooze out the oil from the activated carbon and provide reduction in used/spent carbon cake. The enzymatic bleaching can be used for the removal of specific colour pigments, viz. chlorophyll. The enzymes can drop down the chlorophyll content up to 50 parts per billion (ppb), which eliminates the need of bleaching earth. A cost-effective bleaching technique is needed to be established. The silica pretreatment, prefiltration with spent/used beaching earth, bleaching with bleaching earth and decontamination with activation carbon are used in multistage purification process. The efficiency of refining plants can be enhanced by adopting pretreatment and prefiltration process.

12.4.7.2 Deodorization

The vegetable oils retain undesirable odours after passing through processing steps including bleaching and hydrogenation. Due to the presence of substances like organic compounds, free fatty acids, alcohols, aldehydes, peroxides and ketones, off odours arise. Such substances are removed in deodorization process using vacuum steam distillation process at elevated temperature. This is very important and the last processing step of oils which influences the final quality of oil. Important process conditions for the minimum production of trans fatty acids and maximum removal of volatile compounds during this process include temperature, pressure, stripping time and stripping steam amount.

Temperature

An increase in deodorization temperature increases the rate of removal of compounds, responsible for off odours. Vapour pressure of such substances increases with increase in temperature. Vapour pressure of palmitic acid is 1.8 mm at 176.7 °C which increases to 72 mm at 260 °C. With increase in deodorization temperature, deodorization time decreases. However, very high temperatures may result in formation of trans fatty acids, polymeric triacylglycerols and colour reversion. Trans formation during deodorization process is significant between 220 and 240 °C. Above 240 °C the trans formation is almost exponential. The tocopherols start thermally degrading significantly above 260 °C. An appropriate combination of time and temperature must be determined because deodorizers operating at very high temperature may cause degradation of naturally present pigments in oils. Free fatty acid content in chemically refined oils is less as compared to physically refined oils. Therefore, chemically refined oils are much easier to deodorize. The oils with short chain fatty acids require lower temperature for deodorization as compared to the oils containing long chain fatty acids. During hydrogenation process, more distinctive odours and free fatty acids are produced; hence, hydrogenated oils are more difficult to deodorize.

Pressure

The vapour pressure of odorous substances decreases with decrease in absolute pressure. Therefore, if the odorous substances are to be distilled at low temperature, the distillation process must be carried out under vacuum. Vacuum systems used for low pressure generation consist of combination of mechanical vacuum pumps, steam jet ejectors and vapour condensers. The required vapour pressure for this process ranges between 2 and 4 mbar.

Steam

The amount of steam required depends on the operating pressure of the system, efficiency of mixing, depth of oil and type of oil. Agitation of oil is very important to expose the surface to low pressure. Excess amount of steam may cause hydrolysis and also increases energy consumption. For chemically refined oils, the amount of steam varies from 5 to 15 wt% of oil for batch type systems, whereas 0.5–2% for continuous systems.

Time

To remove the odorous substances from oil, stripping time should be selected very carefully. The stripping time at elevated temperatures for batch type system is more due to the depth of oil, as compared to continuous type deodorizing systems. For batch-type systems, the holding time varies between 3 and 8 h, whereas for continuous systems, it varies between 15 and 20 min. A specific retention period is provided by deodorizing systems at particular temperature to allow heat bleaching of oils and for certain reactions to occur for stabilized oil. The other factors, which may affect deodorization is material of deodorizer and chelating agents.

Material of Deodorizer and Chelating Agents

Some metallic compounds present naturally in soil are transferred to oils or during processing steps trace amounts enter into oil stream. Rate of oxidation of oil increases due to the presence of heavy metals. Copper acts as a good catalyst for oxidative reactions. The concentration of copper to produce noticeable oxidative effect is 0.005 ppm and for iron is 0.03 ppm. It has been reported that copper is the most harmful metal followed by iron, manganese, chromium and nickel. These metals act as prooxidants. To minimize the effect of prooxidants, chelating agents can be used before and after deodorization. Most commonly used chelating agents are citric acid, lecithin and phosphorus. Citric acid is used in the range of 50–100 ppm. But it can get decomposed at around 175 °C; therefore, it is added during the cooling stage. Phosphoric acid is used at a concentration of not more than 10 ppm, since excess amount may cause off flavours. Similarly, amount of lecithin used as chelating agent is about 5 ppm.

Deodorization Equipment

Deodorization equipment can be batch type, semicontinuous type and continuous type. Simplest form of deodorizers is batch-type systems which are insulated vertical cylindrical vessels with cone or dished head. Depth of oil varies between 8 and 10 feet and sufficient head space is required for efficient deodorization process. Steam is injected through a distributor into the bottom of deodorizer. Batch deodorizers also include systems for heating, cooling, pumping, temperature measurement, pressure measurement and filtration. Systems operating at low temperatures or high operating pressures may require up to 10–12 h for deodorization process. Amount of steam required may vary from 10 to 50 lb per 100 lb of oil. To prevent oxidation of oil, it should be cooled to a temperature as low as practicable (38–49 °C).

The semicontinuous systems consist of tall cylindrical structures with five or more steel trays stacked one above another which is under same relatively high vacuum. The trays do not contact the outer cylindrical structure. Each tray is fitted with steam sparger system and holds a measured amount of oil. The oil is deaerated while heating (160–166 °C) with steam on the top tray. Then the charge is dropped to the second tray automatically, and the upper tray is refilled with measured amount of oil. Again, the oil is heated, and this process continues as the oil reaches the bottom tray, cooled to 38–54 °C and discharge to a tank.

Continuous deodorizers can be tray type or thin film type. In continuous tray deodorizers, multiple trays are stacked one above another inside a vertical cylindrical structure. Oil levels of 0.3–0.8 m are maintained by overflow weirs. Discharge valves are used for drainage purpose. Thin film deodorizers have packed columns to create maximum surface to volume ratio. Oil comes in contact with sparging steam to strip off free fatty acids. Heat bleaching also takes place in the retention section of this system. The negative impact of thermal processing during deodorization can also be minimized by integration of packed columns.

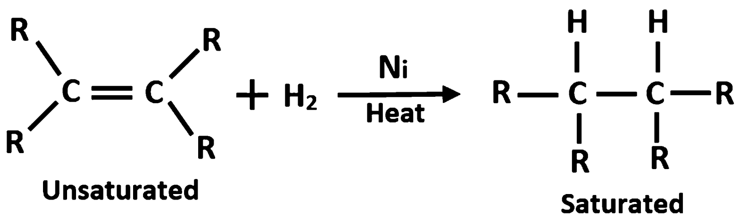
12.4.8 Hydrogenation

In hydrogenation process, hydrogen gas is used to convert unsaturated fatty acids into saturated form, which is more stable as the saturated fats contain single bonds. The hydrogenated fats have higher melting points at room temperature. The main advantages of hydrogenation process include:

1. Conversion of liquid oil into solid fat; which can be handled more easily, with sharp melting points.
2. Stability of fats towards oxidative changes increases.

Depending upon the degree of hydrogenation, type of oil used and processing conditions, a wide range of fats can be produced. Most commonly employed method is the liquid phase hydrogenation process with catalytic reactions. This process involves addition of hydrogen (99.8% or more purity) in the presence of a nickel catalyst (0.01–0.2%) to double (unsaturated) bonds. The moisture content in oil should be less than 0.05%. The unsaturated fatty acids such as oleic, linoleic acid, etc., which are liquid at room temperature, can be converted into stearic acid by hydrogenation process. After completion of process, the hot oil/ fat is filtered for removal of metallic catalyst. A general reaction of hydrogenation process is illustrated as follows:

$$\text{Oil} + H_2 \underset{\Delta}{\overset{Ni}{\rightarrow}} \text{Solid fat} \tag{12.5}$$



(12.6)

The reactions occurring during hydrogenation process may result into the production of saturated fats, trans fats, and fats with shifts in location of double bonds. Trans fats result from conversion of unsaturated fats into trans fatty acids due to twisting of the cis configuration into trans.

A schematic diagram of hydrogenation tank used at industrial level is shown in Fig. 12.15. During this process, it is very important to dissolve hydrogen gas into liquid oil in the presence of catalyst. Hence, the unsaturated fatty acids react with hydrogen atoms to complete the saturation of double bonds or to convert them into trans form or to change the position of double bonds. The completion of hydrogenation process can be measured using Solid Fat Index.

12.4.8.1 Factors Affecting Hydrogenation Process

During hydrogenation process, edible oil and hydrogen gas molecules react on the surface of catalyst when brought in close contact. Hence, any parameter that influences the catalyst surface, concentration of gas, level of catalyst, mixing speed, conditions for reaction to take place, e.g. temperature, pressure, will affect the overall process. Main factors influencing this process are:

a. Type of unsaturated fatty acid: The hydrogenation process depends on the type of unsaturated fatty acid and the number of unsaturated fatty acids present in a

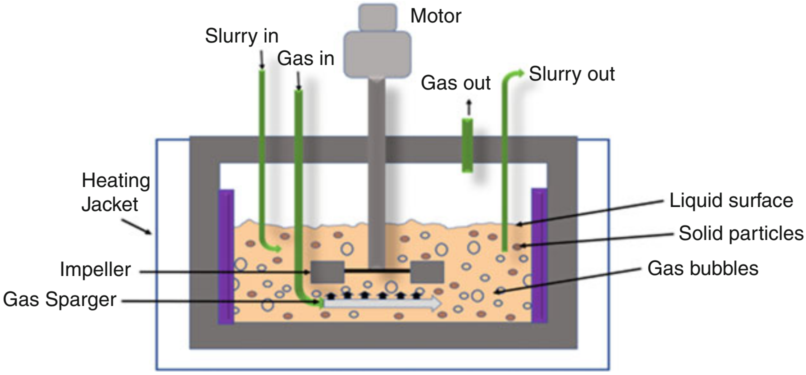


Fig. 12.15 Hydrogenation tank

triglyceride. Oils containing high levels of linoleic or linolenic acid tend to hydrogenate more quickly and possess higher melting points as compared to oils with high content of oleic acid.

b. Catalyst concentration: As the concentration of catalyst is increased, the rate of hydrogenation also increases up to a certain point and then it levels off. The reason being increased surface of catalyst available for the reaction to take place. At very high levels, the hydrogen dissolution will not be fast enough to supply the increased level of catalyst. Also, at very high concentrations, trans isomer formation and selectivity increase slightly.
c. Reaction temperature: Temperature is a very important factor influencing hydrogenation process. The rate of reaction increases with increase in temperature. But at high temperatures, the solubility of gas in oil decreases, which results in quicker removal of hydrogen, hence the quantity of hydrogen present on catalyst surface will be less. It also leads to the formation of trans-isomers. The maximum temperature of the reaction remains within 230–260 °C for most of the oils.
d. Agitation speed: During hydrogenation process, agitation is required to have a proper contact between hydrogen molecules and oil, and to supply dissolved gas to catalyst surface. Agitation is also required to maintain the required temperature during hydrogenation process.
e. Pressure: At high pressure, hydrogen can saturate the double bonds quickly. Therefore, maintenance of appropriate pressure is important because at low pressure the gas dissolved does not cover the catalyst surface. Normally this process is carried out at 0.7–4 bars. Increase in pressure results in increased hydrogenation rates and lower amount of trans isomers.
f. Type of catalyst: The selected catalyst for the process has a strong influence on the rate of reaction and isomerization. For hydrogenation of oils commonly used catalyst is nickel, which can be prepared by various techniques. For the production of nickel catalyst, usually nickel salt is reduced and supported on a solid

surface. Number of active sites present on the surface of catalyst decide the activity of catalyst. These sites can be located either on surface of solid or deep inside the pores. Products with good stability to oxidation and lower melting point can be produced with high selectivity catalysts. All catalysts produce almost same level of trans fats under similar conditions. Hence, the selectivity of catalyst is not related to the ability of catalyst to form trans isomers. Reaction with sulphur inhibits the catalyst to adsorb and dissociate hydrogen hence reduces the activity of catalyst. Catalyst treated with sulphur produces larger quantities of trans isomers.

g. Reuse of catalyst: It is always economical to reuse the catalyst if sufficient activity of catalyst remains after the previous use. But sometimes it may affect the reaction and selectivity for the process and may also result in filtration problems like fatty acids in oils can react with nickel to form nickel soaps which can result in blockage of filters. Secondly, the mechanical agitation results in colloidal nickel, which can pass through the screening filters. There might be decreased selectivity and increased production of trans isomers with each use of catalyst. After usage when catalyst is exposed to air, then there might be higher probability of production of trans isomers, when it is reused.
h. Presence of impurities: Oils after refining process may contain some impurities like soaps, free fatty acids, moisture, phosphatides, etc. Similarly, hydrogen gas may also contain impurities like ammonia, carbon monoxide, hydrogen sulphide, etc. which can poison the catalyst. These impurities can reduce the catalyst concentration and may influence the selectivity, rate of reaction and isomerization process. It has been reported that 1 ppm sulphur can poison 0.004% nickel. Similarly, same amount of phosphorus, bromine and nitrogen can poison 0.0008%, 0.00125%, and 0.0014% nickel, respectively.

12.4.9 Packaging

Crude, filtered and refined oils are packed in LDPE pouches, LDPE/HDPE bottles, glass bottles and metal containers.

12.5 Oilseed Processing: Case Studies

12.5.1 Rapeseed and Mustard

Rapeseed and mustard are very popular oilseeds for the extraction of oil. Mustard is available in white, brown and black colours. The oil extraction technology contains, drying, cleaning, grading, storage of oilseeds, oil expression and storage of oil.

12.5.1.1 Drying

The rape seeds generally can attain 8% moisture content at 70% relative humidity under ambient temperature. The harvested rapeseeds usually have 25–35% moisture content, which needs to be dropped to the level of 12–20% for threshing followed by further drying for safe storage up to the level of 7–8%. The storage room may be disinfected. Spraying by malathion in the ratio of 1:15 at a rate of a litre for 100 m^2 surface area before 24 h is recommended to keep the rapeseed inside the go down [33].

12.5.1.2 Cleaning and Conditioning

Mustard seeds are cleaned properly to remove any foreign particles, dust, straw, etc. using air screen cleaners. After cleaning the seeds, the next important step is conditioning. The main aim of conditioning is to make the oilseeds soft so that oil could be extracted more easily. The seeds are moistened by soaking in hot water for 1 h followed by steaming for 10 min. Conditioning causes coalescence of the small droplets of oils into bigger drops, which can be easily extracted during extraction process. High temperature also decreases the viscosity of oil; hence, maximum amount of oil recovery is obtained during pressing.

12.5.1.3 Decortications/Flaking

The moistened oilseeds may be fed to decorticator/flaker, which have pair of large-diameter rolls to press the seeds into required thickness flakes (Fig. 12.16). The main purpose of the decorticator/flaker is to rupture the outer shell and weaken the oil cells hence to facilitate the oil expression. The temperature and moisture contents are the important key factor for effectiveness of decortication. Optimum flake thickness varies between 0.25 and 0.38 mm. To obtain a uniform thickness of flakes, it is important to maintain high roll pressure using hydraulic systems. Rapeseeds being very small in size need to be handled carefully, so that all the seeds pass through the two rolls.

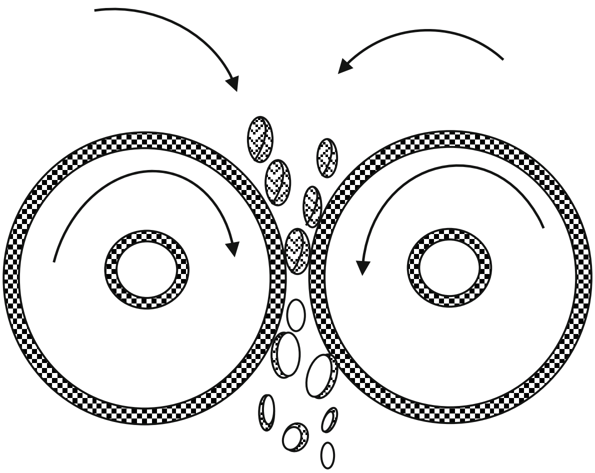


Fig. 12.16 Parallel cylinder decorticator

12.5.1.4 Heat Treatment

The moistened grains are dried for inactivation of enzymes, destruction of bacteria and moulds. Optimum heating temperature is 90–105 °C for drying up to 9–10% moisture content.

12.5.1.5 Extraction of Oil

Most commonly, screw press (expeller) is used for the extraction of oil. Conveyors are used for feeding purpose and the feeder controls the flow of material. Oil extracted during this process is collected at the base of the expeller. Residual material obtained during this process is removed for further processing.

12.5.1.6 Clarification of Oil

The oil extracted in press also contains some solid particles and impurities. These larger particles can be removed by using a screen, whereas smaller particles can be removed in the next stage using filters. Centrifugal separators are used instead of filters on large scale. If the solids obtained after filtration process contain high amount of oil, then theses solids are returned to the feed stream of press. Oil refining if needed can be done as discussed in the preceding section.

12.5.2 Soybean

Soybean is a rich source of protein as it contains all the essential amino acids except sulphur containing amino acids. Due to its high protein content, about 40%, it was initially introduced as a protein-rich food crop, but later, it has been found to be a crop mainly used for oil extraction, and the protein-rich meal is used as a by-product. Depending upon variety, beans vary in colour from yellowish to dark brown. The yellow bean is considered as the richest variety with respect to oil content. Generally, soy oilseed has moisture, 9–14%; oil, 18–22%; carbohydrate, 15–25%; protein, 33–39%; fibre, $\leq$7%; and ash, $\leq$6%. Cultivation of soya can be done in tropical or subtropical areas on various soils. The cultivation of soya is expanding mainly due to its high protein and oil content and seeds can be stored without major damage. Processing steps for soybean are shown in Fig. 12.17.

Cleaning is the important step in soybean processing. During cleaning, all the foreign particles, stones, etc. are removed. Cleaning, if not done properly may even lead to damage of equipment sometime. Cleaning is done using screens of variable mesh number. Oversized impurities like stones, leaves, sticks, etc. are retained on the upper screen, medium size impurities are retained on the second screen, whereas very fine impurities like sand, etc. pass through the third screen. Grading of seeds is important as uniform size of feed reduces the energy consumption of machine.

12.5.2.1 Preparation

The oil, present inside the cells, cannot be extracted effectively without pretreatment of seeds. This pretreatment is called preparation of seeds. The major benefits of

Fig. 12.17 Processing steps for soybean

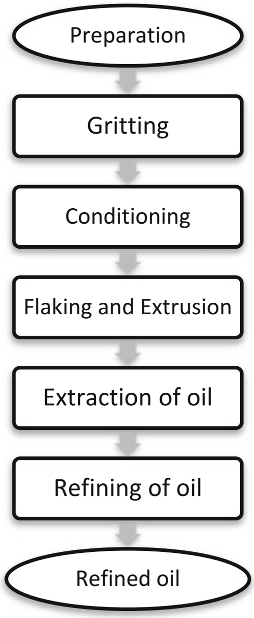
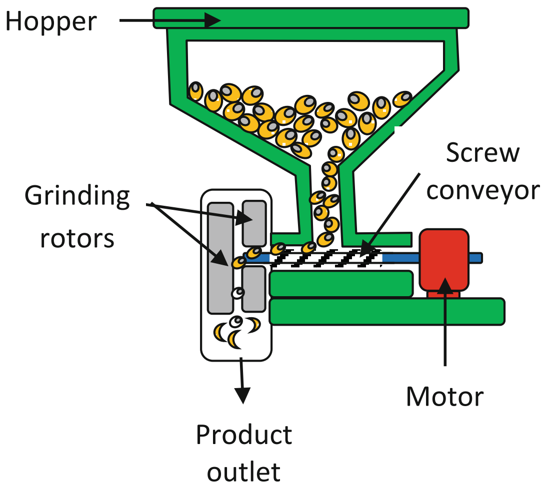


Fig. 12.18 Dry soybean cracking machine



preparation are to rupture the cells containing oil so that extraction could be made easier.

12.5.2.2 Gritting

This is a process in which soybeans are split into small pieces in mills. These mills are also called cracking mills, which are equipped with corrugated rolls (Fig. 12.18).

Soybeans are fed into the hopper, which is conveyed using screw conveyor to the corrugated rollers, which has two grinding plates, i.e. stator and rotor for breaking it into smaller grits.

12.5.2.3 Conditioning

Anti-nutritional factors, in raw soybean can be inactivated by applying heat treatment. Secondly, soybeans get softened due to heat treatment. Heat treatment is given at 60–70 °C and moisture content is then adjusted to around 10–11%. Two types of conditioners may be used: vertical and horizontal. Vertical conditioners are equipped with pans, which are stacked one above another in a vertical shell. These pans are connected to a rotating shaft. Small grits enter at the top and move to the bottom.

Horizontal conditioners are commonly used by large capacity plants. These are made up of parallel steam heated tubes in a cylindrical shell. In some designs, the tubes keep on rotating, whereas in others the entire shell rotates which helps in uniform heating of grits.

12.5.2.4 Flaking and Extrusion

The flaking process is same as mentioned in rapeseed processing. The hot, soft cracks leaving the conditioner are finally sent to flaking. The cells containing oil are ruptured and it becomes easier to extract oil from these weakened cells. Due to flaking process, the surface to volume ratio increases which facilitates the enhanced solid-liquid contact and the efficiency of oil extraction process. Followed by flaking process, extrusion is the optional step which is primarily done to increase the bulk density of the product and it reduces the retention of solvent in the material during extraction process. The extrusion equipment is made up of a horizontal barrel with a restriction. Materials are pushed through that restriction, and steam is introduced or desired temperature is maintained in the barrel. Due to moisture evaporation, expansion takes place as the material passes through the restriction; hence, the material attains a sponge like texture.

12.5.2.5 Extraction of Oil

Soybean oil can be extracted mechanically by using hydraulic or screw press or chemically by using solvent. Efficiency of mechanical process is low as compared to chemical process. In mechanical process, oil is not fully recovered since it is difficult to remove last 10% oil from the seeds. But in case of solvent extraction process, approximately 99% oil is extracted. Since the nature of oil is impervious, it has been found that oil extraction from whole or half beans is not possible without applying the pretreatments to break the cell wall. Therefore, flaking treatment is very important before extraction of oil.

12.5.3 Groundnut (Peanut)

Groundnut consists of mainly three parts: (a) nut, which contributes 69–73% of the total weight of the groundnut; (b) germ, 2–3.5%; and (c) hull, 2–3% of the total

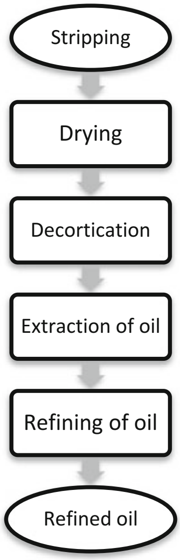


Fig. 12.19 Processing of groundnut

weight. Oil content varies from 31 to 46%, whereas carbohydrate 21–37%, and protein is 20.7–25.3% in groundnut. Groundnut is also rich source of vitamin B content and minerals. It is commonly consumed raw, in roasted form and fried form. Peanut butter is also prepared from crushed peanuts. Processing steps of groundnut are given in Fig. 12.19.

12.5.3.1 Stripping

First step for groundnut oil extraction is stripping, i.e. removal of groundnut pod from the plant. Stripping can be done manually or by using strippers, in which, the operator must hold the bundles of crop firmly against the rolling drum, on which spikes are provided to strip the pods from the vine (Fig. 12.19). In the next step, groundnut grading machines are used for grading purpose.

12.5.3.2 Drying

Groundnuts are dried from 26% to around 13% moisture content. Over drying of kernels must be avoided as it may lead to brittleness of kernels. It may also cause colour and flavour changes, which affect the final quality of groundnut. The method adopted for drying should not affect the economic viability of groundnut kernels; however, it has been reported that when groundnut is dried by mechanical methods, 1% oil content is reduced as compared to the natural shade dried methods (Figs. 12.20 and 12.21).

12.5.3.3 Decortication

Once the groundnuts are decorticated, it is difficult to store them for long period without any treatment, since the kernels may get rancid. For decortication process,

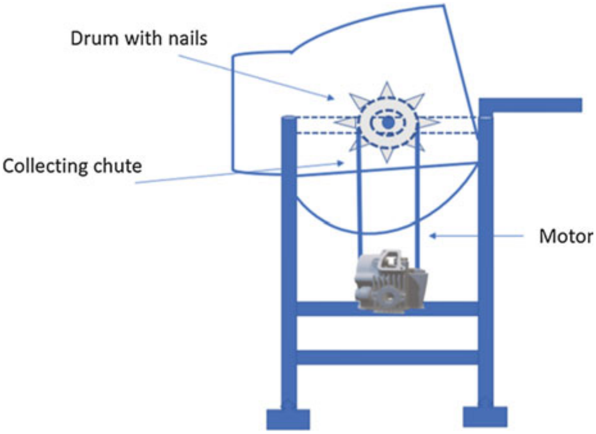


Fig. 12.20 Power operated groundnut stripper

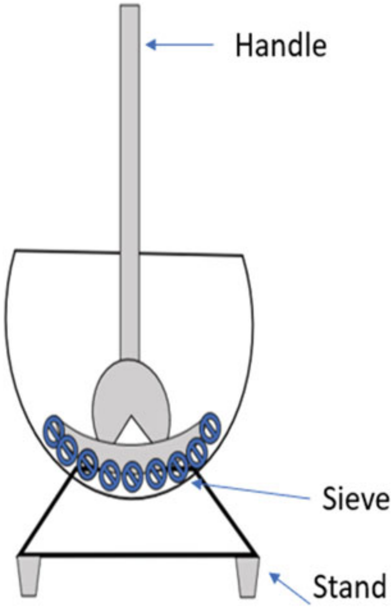


Fig. 12.21 Manual groundnut decorticator

corrugated rolls are used; and thereafter, centrifugation process is used for separation of husk. Using traditional process, groundnuts may be decorticated manually, but the process is very slow. Advanced decorticators have been found most suitable, and by use of these equipment, there is no adverse effect on germination of seeds. Power-operated groundnut decorticator has one HP electric motor with 94–96% efficiency, and this decorticator can decorticate about 150 kg pods/h. No breakage occurs during the process and 57–63% sound kernels are obtained.

Decorticated groundnuts should be stored carefully to prevent any damage from insects and loss of vitamins and high temperature. Sound and unbroken groundnuts are less likely to be attacked by insects. Once the groundnuts are decorticated, the chances of oil acidification increase. Groundnuts can be stored for at least 2 years at a temperature of 2–4 °C at relative humidity of 65%. Further improvement to storage conditions can be made by modifying the oxygen and nitrogen gas compositions. Polyethylene bags have been found most suitable for storage of groundnuts. If the groundnuts are not carefully stored, then fungi may develop, which can produce mycotoxins. Usually, *Aspergillus flavus* develops due to poor storage conditions, which produces *Aspergillus flavus*. This mycotoxin may be of carcinogenic under some specific temperature and humidity conditions. To retard the growth of *A. flavus,* temperature above 30 °C is safe with a relative humidity value below 65%. To prevent the production of aflatoxin, treatment with 5% hydrochloric acid for 1 h and 6% hydrogen peroxide for 1/2 h at 80 °C can be adopted. Groundnut cake treated with 1.5% ammonia becomes completely free from toxin, but if the cake is to be used as animal feed, treatment with 1% ammonia is recommended.

12.5.3.4 Extraction of Oil

Methods for extraction of groundnut oil are hydraulic press and screw press. Hydraulic press consists of a cylinder and a cage with a system of levers. Pressure is applied to the seeds inside the cylinder by means of piston. Due to increased pressure inside the cylinder, oil is released from the groundnut seeds and flows through the cage slots. The major disadvantage of this system is high cost and higher maintenance. There may also be chances of contamination of oil by hydraulic fluid.

In screw press, the main components are: expelling unit, driving pulleys, speed reduction gear, hopper, etc. Seeds are fed through the hopper, then crushed inside the machine and transported by a rotating screw in a barrel. Pressure level required is achieved by continuous transport of material by the screw shaft, which increases the friction inside the barrel hence increases the temperature. Due to increased temperature, viscosity of oil decreases; hence, flow rate increases. Seeds can be preheated by roasting and optimum speed of screw for better extraction of oil is can be fixed.

12.5.4 Sunflower Oil

Sunflowers are botanically known as *Helianthus annuus*. Sunflower seeds are generally 0.6 cm long and 0.3 cm wide with a black seed coat having dark stripes. Oil content of seeds is around 38–50%. The high linoleic acid (44–75%) makes it prone to rancidity. The storage warehouses must be properly ventilated with low temperature and low humidity. For storage, seeds must have a low moisture content (nearly 10%). The various steps involved for processing of sunflower are explained below.

12.5.4.1 Cleaning, Dehulling and Grinding

The sunflower oilseeds are passed over magnetic separators to remove any trace of metal and passes through other cleaning machines to remove foreign particles before being de-hulled. To obtain a good quality of oil and meal, seed hulls (20–30%) are sometimes removed before oil extraction. For de-hulling appropriate moisture content is 3–5% after cleaning. The process consists of cracking the seeds by the mechanical action (by abrasion or using pneumatic sheller). Winnowing process is used to separate the separated hulls from the kernels. To enhance the surface area, de-hulled kernels are ground to obtain a coarse meal. Grooved rollers or hammer mill can be used for this purpose. Heat treatment can be applied in the next step to facilitate extraction of oil.

12.5.4.2 Pressing

Screw press is used for pressing purpose. The heated meal is then fed continuously into a screw press. As the meal passes through the barrel of screw press, pressure increases from 68,950 to 206,850 kPa, and the oil is pressed out through the barrel slots.

12.5.4.3 Extraction of Oil with Solvents

Although a major portion of oil is expelled by mechanical pressing and squeezing, to obtain higher yield, the cake may be treated with solvents, so that residual oil can be extracted.

12.5.4.4 Oil Refining

The degumming process involves heating the oil to 200 °C, then centrifugation is used to remove the gums. In neutralization process, the oil is heated to 107–188 °F and an alkaline substance like sodium hydroxide or sodium carbonate is added to remove free fatty acids. This soap in the form of foam is removed by centrifugation process. Phosphatides present as ‘gums’ are also removed during this step. To get rid of undesirable colours bleaching process is carried out. Oil is filtered through activated carbon or clay, Fuller’s earth that can adsorb the colour pigments from oil. The oil used for salads is rapidly chilled and filtered to remove the waxes in the form of crystals.

To remove undesirable odours, deodorization process is employed where steam is passed over hot oil in vacuum at 210–270 °C to distil the volatile compounds. After that, 1% citric acid is added to prevent any oxidation due to presence of any trace metals that may cause oxidation.

12.5.5 Cotton Seed

Cotton is a shrub of warm-weather and belongs to *Malvaceae* family. It is grown as an annual crop and mainly cultivated to obtain cotton fabrics. Principal species of cotton are: *barbadense, hirsutum, herbaceum* and *arboretum.* Further, various varieties of these species can be developed by conventional breeding process. Production of cotton seed is highest in China whereas India stands on the second. Cottonseed oil is used as a cooking oil obtained from decorticated cottonseeds. Percentage of oil in cottonseed is about 18–25% along with 18–25% good quality protein. High smoke point of this oil (232 °C) also makes it suitable for cooking

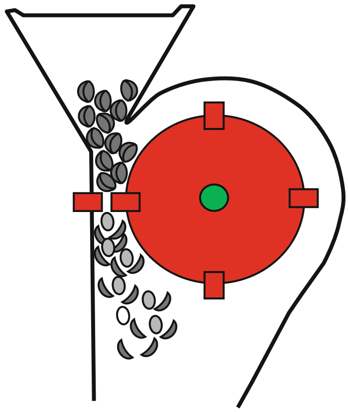


Fig. 12.22 Bar and drum decorticator

purpose. Cottonseed oil also finds applications in biodiesel production and in paint industry. The stability of oil is more due to inhibition of rancidity by tocopherols (65 mg/100 g). Presence of linoleic (55%), linolenic, oleic (19%), palmitic (22–26%) and some portion of stearic and myristic, fatty acids make it healthy for consumption.

Cotton ginning is the important step in its processing, in which the fibres are separated from the seeds. Double roller ginning method is the most widely used over single roller ginning because of high ginning cost.

Cotton seed oil can be extracted either by traditional method in which seeds are crushed without delinting or by mechanical pressing method using bar and drum decorticator (Fig. 12.22). In this method, pressure rolls are used for pressing the seeds and to form thin flakes. These flakes are then cooked in steam pressure to rupture the oil containing cells. Then the flakes are processed in screw expellers or hydraulic press for the extraction of oil. Solvent extraction can be used for the extraction of cottonseed oil.

The oil is mixed with alkali to remove free fatty acids, resins, etc. in the form of soap for neutralization process. Then by centrifugation process, the soap part is removed. Then bleaching is performed to remove the trace elements, pigments and other impurities, which is performed using bleaching clay. It is an essential process, which removes oxidation products, soaps, metals, phospholipids, and other contaminants.

Winterization/dewaxing is a process to maintain the clearness of oil at lower temperature. The process is performed by cooling and lowering the temperature to below the crystallization of waxes, which is then removed by filtration. This process is mainly beneficial for the oil to be used as salad oil so that it does not show cloudiness at lower temperatures. Deodorization by steam distillation process is carried out under vacuum. Cottonseed oil can be deodorized at low temperatures, and in this way, tocopherols can be retained.

12.5.6 Castor Seed Oil

Castor plant is resistant to pests and droughts, it can be grown anywhere easily. In various geographic regions, it grows naturally under a wide range of climatic conditions. The castor oil-producing countries in large amount are Brazil, China and India. The seeds are dried and then oil extraction is done either by solvent extraction method or by mechanical pressing.

Oil content of castor seed is approximately 30–50% depending on the variety, climatic conditions and the method used for oil extraction. Castor seeds have been reported to be toxic due to the presence of toxic castor bean allergen (CBA), glycoprotein, ricin and toxic alkaloid, ricinine. But castor oil does not contain these toxins. The density, viscosity, thermal conductivity, specific heat, flash point, melting point, pour point and refractive index of castor oil are 0.959 g/ml, 889.3 centistokes, 4.727 W/m °C, 0.089 kJ/kg °K, 148 °C, −2 to −4 °C, 2.7 °C and 1.480, respectively. Castor oil in crude form appears in a pale colour, which turns colourless after going through refining processes. The major fatty acid of castor oil is the ricinoleic acid, 87–90%. A hydroxyl group at C12 of the ricinoleic acid, double bonds, presence of the ester linkages cause polarity. This is the reason that it is used in waxes, natural and synthetic resins, polymers, etc. After oil extraction, the meal contains toxic protein called ricin; therefore, the meal is not suitable for animal feed; hence, it is used as a fertilizer since toxic compounds are not carried to soil. Castor oil has applications in the following fields: fuel and biodiesel, polymer materials, soaps, waxes, greases, lubricants, hydraulic and brake fluids, fertilizers, coatings, pharmacological and medicinal use.

Castor oil can be extracted using different methods like solvent extraction, mechanical pressing or a combination of solvent extraction and pressing. Screening process is used for cleaning of seeds. Iron particles or other magnetic particles can be removed by magnetic conveyor belts. Drying is done until the outer shell of the seeds splits. Beans are dried to moisture content of about 5–7%. It can be done either mechanically using a dehuller or the shell can also be removed manually. The shells are removed by winnowing process using air at high velocity. During this process, seeds are heated in steam cookers. This process helps in oil extraction process, which makes the seed hull open. The dried seeds are fed to the hydraulic press or screw press for crushing of seeds. Size reduction is important to rupture the cell walls to make the oil extraction easier. A high-pressure continuous screw press is used for oil extraction. The extraction of oil using screw press is termed as preprocessing. It provides about 45% of oil recovery at normal temperatures, which can be enhanced up to 80% by elevating the temperature. Cold press oil contains lower iodine and acid content and lighter in colour. Filter press is used for filtration process. Refining can be done as per the method illustrated in processing section.

12.6 FSSAI Standards for Different Refined Oils

As per the Food Safety and Standards Authority of India (FSSAI, 2006), 25 oils were categorized in refined oils category including cottonseed oil, coconut oil, soybean oil, sunflower oil, rapeseed oil, mustard oil, and groundnut oil. The oil should be clear and free from rancidity and adulterants. Some important parameters for different refined oil are listed in Table 12.4.

It is also suggested to keep the flash point above 250 °C except coconut oil for the oils obtained using solvent extraction process. The flash point must remain above 225 °C in case of coconut oil.

12.7 Utilization of By-Products/Waste from Oilseed Processing

After extraction of oil, the cake is obtained as a by-product. Huge amount of oilcake is obtained after processing of various oilseeds. These oil cakes are very good source of protein, fibre, acid insoluble ash, etc.; hence, these cakes can be used for food supplementation or important antibiotics, and vitamins. Enzymes can be produced from these cakes using biotechnological tools. Composition of various oil cakes is given in Table 12.5. The de-oiled cake is also sent to cattle feed processing industries or directly fed to the animals. The residual amount of oil affects the storage life of the cake. Several factors affect the composition of oilcake, which include variety of oilseed, oil extraction method, storage conditions, etc.

Soybean oil cake is rich in various amino acids like tryptophan, threonine and lysine. Dehulled sunflower oil cake contains about 34.1% crude protein. Rapeseed cake has 33% protein content and it is rich in amino acids but deficient in lysine. Cottonseed cake contains 40% protein and 15.7% fibre.

12.7.1 Food Supplementation

As the oilseed cakes are rich in fibre, protein, antioxidants, minerals and vitamins, therefore efforts can be made to make use of these cakes for food supplementation. Suitable processes and treatments can be applied to enhance the palatability of the cakes and may be tried in various food products. Sesame cake is excellent source of antioxidant activity. Heat treatment can be used to inactivate the antinutritional compounds like pepsin and trypsin inhibitors, phytates and tanins, etc. Incorporation of some of the treated oilseed cakes may enhance the fibre content of food material. High fibre content is associated with treatment of number of diseases like coronary heart diseases, colonic cancer, diabetes, etc.

Table 12.4 Qualifying parameters for refined vegetable oils

Name	Moisture content, % by weight (max.)	Butyro refractometer reading at 40 °C	Saponification value	Iodine value (WIJS method)	Acid value (max.)	Unsaponifiable matter % by weight (max.)	Additional requirements
Coconut oil	0.10	34.0–35.5	240 (min)	7.5–10.0	0.5	1.0	Polenske value—14.0 (min)
Cottonseed oil	0.10	55.6–60.2	190–198	98–112	0.5	1.5	No turbidity after keeping filtered sample at 30 °C for 24 h. Bellier test 19–21 °C
Mustard/ rapeseed oil	0.10	58.0–60.5	168–177	96–112	0.5	1.2	Bellier test 23–27.5 °C, Test for hydrocyanic acid—negative, test of argemone oil—negative, polybromide test—negative
Soybean oil	0.10	58.5–68.0	189–195	120–141	0.5	1.5	Phosphorus—not more than 0.02%
Sunflower oil	0.10	57.1–65.0	188–194	100–145	0.5	1.5	–
Safflower oil	1.10	62.4–64.7	186–196	125–148	0.5	1.0	Bellier test (turbidity temperature acetic acid method) not more than 16 °C

Source: Food Safety and Standards Act 2006) [34]

Table 12.5 Oil cake composition

Oil cake	Calcium (%)	Phosphorus (%)	Ash (%)	Crude fibre (%)	Crude protein (%)	Dry matter (%)	Reference
Mustard oil cake	0.05	1.11	9.9	3.5	38.5	89.8	[35]
Soy bean cake	0.13	0.69	6.4	5.1	47.5	84.8	[35]
Coconut oil cake	0.08	0.67	6	10.8	25.2	88.8	[36]
Palm kernel cake	0.31	0.85	4.5	37	18.6	90.8	[37]
Cottonseed cake	0.31	0.11	6.8	15.7	40.3	94.3	[38]
Sesame oil cake	2.45	1.11	11.8	7.6	35.6	83.2	[35]
Sun flower oil cake	0.3	1.3	6.6	13.2	34.1	91	[39]
Groundnut oil cake	0.11	0.74	4.5	5.3	49.5	92.6	[35]
Canola oil cake	0.79	1.06	6.2	9.7	33.9	90	[40]
Olive oil cake	–	–	4.2	40	6.3	85.2	[41]

12.7.2 Enzyme Production

Cakes can be used for the production of enzymes using solid state fermentation process or these can be used as a supplement for the production medium. Physiological and biological conditions can be optimized for the process. Lipase enzyme can be produced from oil cakes using fungal strains, *Penicillium* spp. Groundnut oil cake and cottonseed oil cake can be used as substrate for phytase production in solid state fermentation process using strains of *Rhizopus* spp. Similarly, soybean oil cake can be used for the production of protease enzyme using *Bacillus clausii* and α-amylase can be produced from *A. oryzae* using groundnut oil cake as substrate. Sunflower oil cake has been used for production of pectinolytic enzyme by *Cryptococcus albidus* var.

12.7.3 Mushroom Production

Waste oil cakes (soybean oil cake, sunflower oil cake, cottonseed oil cake, etc.) can be used for the production of mushrooms. The supplementation of oil cake with rice straw substrate can increase the yield significantly. Cottonseed oil cake supplemented mushrooms have higher amount of protein and fat but lesser carbohydrate content.

12.7.4 Antibiotics Production

Antibiotics can also be prepared using oil cakes. Oil cakes can be used as carbon source and buffers for production of antibiotics.

12.7.5 Utilization as Feed

The deoiled cake may be used as high protein cattle feed. The high protein diet plays a major role to increases the milk production in the milking cattle. This high protein cake can also be used to feed poultry and fish. The sunflower deoiled cake can be used as feed for swine and poultry and can also be used as fertilizer.

12.8 Exercise

Q1. 650 kg of groundnut seed (43.5% oil and 5.8% moisture) is fed to hydraulic press for oil extraction. The cake obtained after oil extraction contains 5.3% oil and 11.7% moisture. Determine the quantity of oil extracted and amount of moisture present in oil.

Ans: Oil recovered: 261.68 kg; Moisture in oil: 8.7%

Q2. A system involves mixing of rapeseed cake (83% solids, 7% oil, 10% water) with sunflower oilseed cake (79% solids, 6% oil, 15% water) to make a 100kg mixture containing 12% water. Determine the amount of rapeseed cake and sunflower oilseed cake.

Ans: Rapeseed cake = 60 kg, Sunflower oilseed cake = 40 kg

Q3. Determine the amount of oilseed cake containing 72% solids and another oilseed cake containing 85% solids that must be mixed to produce 100 kg of a mixture containing 80% solids.

Ans: 38.47 kg of cake with 72% solids, 61.53 kg of cake with 85% solids

Q4. How much weight reduction would result when the moisture content of an oilseed sample is reduced from 12% to 2%?

Ans: 10.21%

Q5. In a solvent extraction process, deep bed extractor with 3.1 m bed thickness is used. Determine the distance of washing nozzle till miscella collection vessel, if forward flow velocity of the material is 0.32 m/min and downward velocity of miscella is 0.29 m/min.

Ans: 1.88 m

Q6. What is role of solid fat index (SFI) for the determination of oil quality? Also discuss the techniques for SFI measurement.

Q7. Discuss the importance of rheological properties of oil.

Q8. Enlist the advantages and disadvantages of solvent extraction technique for oil extraction.

Q9. Discuss various process parameters influencing the solvent extraction process.

Q10. Elaborate the deodorization process in oil refining. Also discuss advantages and disadvantages of this process.

Q11. Illustrate various oil extraction techniques.

Q12. Explain the importance of pretreatment for oil extraction.

Q13. Differentiate between saturated and unsaturated fatty acids with examples.

Q14. Discuss about fatty acid composition of vegetable oils.

Q15. Why study of optical properties of oils is important?

Q16. Enlist various points to be considered for appropriate handling and storage of oilseeds.

Q17. Why heat treatment is important to be carried out prior to mechanical/solvent extraction of oil?

Q18. Elaborate the working of hydraulic press for extraction of oil.

Q19. Enlist different parameters to be considered for sorting and grading of oilseeds.

Q20. Discuss the working operation of major parts of an oil expeller.

Q21. What are important parameters influencing the oil extraction process.

Q22. Describe the role of meal desolventizer toaster and sparger tray.

Q23. Demonstrate the working of miscella distillation system.

Q24. Explain the factors affecting quality of deodorized oil.

Q25. What do you understand by hydrogenation process? Discuss the factors affecting hydrogenation process.

Q26. Comment on utilization of by-products from oilseed processing.

Q27. Explain the role of catalyst in hydrogenation process.

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Processing of Fruits and Vegetables

13

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Abstract

In this chapter, proximate composition and important properties and nutritional profile of fruits and vegetables are discussed. Processing technologies involved in the preservation and retention of key quality parameters have also been discussed. Thermal processing and preservation techniques are employed for the preservation and value addition of fruits and vegetable-based products. Key unit operations involved in the processing of fruits and vegetable products have been elaborated. Processing of fruits and vegetables aseptically is also explained. Recent techniques including high pressure processing, ultrasonic, electromagnetic radiation microwave processing, electromagnetic radiation radio frequency, and high-intensity pulse electric field are also briefly discussed. The effect of different processing techniques on the quality physicochemical characteristics and quality attributes of fruits and vegetables has been explained. The intervention of various processing technologies involved in the manufacturing of various fruits and vegetable-based products is discussed in detail. Value-added products, viz., pickles, jam, jelly, and pectin, are also discussed using flow charts. Hand tools and mechanized equipment for peeling are explained using schematic diagrams. The cutting mechanism and effectiveness are explained using worked

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examples. The different shaped cutting knives for specific purposes are also discussed.

Keywords

Proximate composition · Properties · Processing and preservation (techniques, storage, chemicals) · Processing of value added products (pickles, jam, jelly, marmalade and pectin) · Types of peelers and peeling mechanisms · Cutting mechanism, and different cutting devices

Fruits and vegetables represent an essential part of the world agriculture and are broadly acclaimed for consumption owing to their health-promoting properties. If consumed every day in adequate amounts, fruits and vegetables can help to protect from common diseases like CVDs and various cancers. Fruits and vegetables have importance in dietary guidance as they contain vitamins, minerals, and phytochemicals. In addition, fruits and vegetables are considered good source of dietary fiber. The WHO and FAO of the United Nations suggest adults to consume at least five servings of vegetables and fruits per day excluding starchy vegetables because of large number of biologically active phytochemicals.

Vegetables and fruits, besides the yield, possess additional prominence in the world economy. India is also the second leading producer of vegetables followed by China. In fruit production, China ranks first with 246.6 MT, then India (104.2 MT) at the second position, and Brazil (40.1 MT) at the third position among the total fruit production of 883.4 MT in the world during the year 2019. As per the general recommendations, FAO/WHO suggested that the fruit and vegetable intake is at least 400 g/person/day [1]. Likewise, Indian national nutrition guidelines suggest an average intake of 300 g/day for vegetables and 100 g for fruits [2].

13.1 Proximate Composition of Important Fruits and Vegetables

The average composition of some of the important fruits and vegetables are given in Table 13.1.

13.2 Important Properties of Fruits and Vegetables

13.2.1 Appearance

Color is one of the desirable factors responsible for consumer acceptance of fruits and vegetables. The color changes with the maturation and ripening stages. Vital pigments, which impart color to fruits and vegetables, are anthocyanins (blue, red), betalains (red), flavonoids (yellow) soluble in water, chlorophylls (greenish), and

Table 13.1 Proximate composition of important fruits and vegetables [3]

S. no.	Name of the food product	Moisture (g)	Protein ($N \times 6.25$)	Fat (g)	Minerals (g)	Crude fiber (g)	Carbohydrates (g)	Energy (kcal)
Fruits								
1.	Amla	81.8	0.5	0.1	0.5	3.4	13.7	58
2.	Apple	84.6	0.2	0.5	0.3	1.0	13.4	59
3.	Avocado pear	73.6	1.7	22.8	1.1	–	0.8	215
4.	Bael fruit	61.5	1.8	0.3	1.7	2.9	31.8	137
5.	Banana (ripe)	70.1	1.2	0.3	0.8	0.4	27.2	116
6.	Bilimbi	94.4	0.5	0.3	0.3	1.0	3.5	19
7.	Cherries (red)	83.4	1.1	0.5	0.8	0.4	13.8	64
8.	Fig	88.1	1.3	0.2	0.6	2.2	7.6	37
9.	Grapes (blue variety)	82.2	0.6	0.4	0.9	2.8	13.1	58
10.	Grapes (pale green variety)	79.2	0.5	0.3	0.6	2.9	16.5	71
11.	Guava (country)	81.7	0.9	0.3	0.7	5.2	11.2	51
12.	Guava (hill)	85.3	0.1	0.2	0.6	4.8	9.0	38
13.	Jackfruit	76.2	1.9	0.1	0.9	1.1	19.8	88
14.	Lemon	85.0	1.0	0.9	0.3	1.7	11.1	57
15.	Lichi	84.1	1.1	0.2	0.5	0.5	13.6	61
16.	Lime	84.6	1.5	1.0	0.7	1.3	10.9	59
17.	Mango (ripe)	81.0	0.6	0.4	0.4	0.7	16.9	74
18.	Orange	87.6	0.7	0.2	.03	0.3	10.9	48
19.	Pears	86.0	0.6	0.2	0.3	1.0	11.9	52
20.	Tomato (ripe)	94.0	0.9	0.2	0.5	0.8	3.6	20
Vegetables								
21.	Ash gourd	96.5	0.4	0.1	0.3	0.8	1.9	10
22.	Beans (scarlet runner)	58.3	7.4	1.0	1.6	1.9	29.8	158

(continued)

Table 13.1 (continued)

S. no.	Name of the food product	Moisture (g)	Protein ($N \times 6.25$)	Fat (g)	Minerals (g)	Crude fiber (g)	Carbohydrates (g)	Energy (kcal)
23.	Bitter gourd	92.4	1.6	0.2	0.8	0.8	4.2	25
24.	Brinjal	92.7	1.4	0.3	0.3	1.3	4.0	24
25.	Cabbage	91.9	1.8	0.1	0.6	1.0	4.6	27
26.	Cauliflower	90.8	2.6	0.4	1.0	1.2	4.0	30
27.	Cucumber	96.3	0.4	0.1	0.3	0.4	2.5	13
28.	Knol-khol	92.7	1.1	0.2	0.7	1.5	3.8	21
29.	Ladyfingers	89.6	1.9	0.2	0.7	1.2	6.4	35
30.	Pumpkin (fruit)	92.6	1.4	0.1	0.6	0.7	4.6	25
31.	Pumpkin (flower)	89.1	2.2	0.8	1.4	0.7	5.8	39
32.	Sword beans	87.2	2.7	0.2	0.6	1.5	7.8	44
33.	Tinda (tender)	93.5	1.4	0.2	0.5	1.0	3.4	21
34.	Tomato (green)	93.1	1.9	0.1	0.6	0.7	3.6	23
35.	Lettuce	93.4	2.1	0.3	1.2	0.5	2.5	21
36.	Mint	84.9	4.8	0.6	1.9	2.0	5.8	48
37.	Parsley	74.6	5.9	1.0	3.2	1.8	13.5	87
38.	Safflower leaves	91.1	2.5	0.6	1.3	–	4.5	33
39.	Spinach	92.1	2.0	0.7	1.7	0.6	2.9	26
40.	Turnip greens	81.9	4.0	1.5	2.2	1.0	9.4	67

carotenoids (orange, yellowness, and crimson), which are fat-soluble. Water-soluble grey-, black-, and brown-colored pigments are affected by enzymatic and non-enzymatic browning. The polyphenol oxidase (PPO) accelerates the browning reaction by oxidation of phenolic compounds. The chlorophylls are prone to acid and heat but are stable in alkali. Carotenoids are considered sensitive to oxidation but remain moderately stable to heat. The presence of lipoxygenase accelerates the degradation of carotenoids, which also catalyzes the polyunsaturated fatty acids and lipids. Anthocyanins are prone to pH and heat effects. Betalains are also destroyed by heat. The flavonoids are heat sensitive and these are oxidized using polyphenol oxidases [4]. Shape and size are affected by maturity, cultivar, environment, and production inputs. Some traders associate greater size with advanced quality.

13.2.2 Acidity

Fruits are classified as acidic fruits and contain substantial amounts of naturally occurring acids. Malic acid is predominantly found in apples and pears. Apple also contains a good amount of citric acid, whereas quinic acid is present in pears.

13.2.3 Flavor

Aroma compounds are volatile in nature and are sensed primarily using the nose; however, taste receptors are in the mouth, which provide information whenever food fragments are chewed. Taste is mainly distributed into five prime tastes—sour, bitter, salty, sweet, and umami. Umami is the taste associated with the salts of nucleotides and amino acids [5]. Sourness of fruits and vegetables is produced due to the presence of citric acid, sweetness of fruit is induced by quality and composition of sugar, bitterness is reflected in fruits due to tannins and in vegetables due to glucosinolates and calcium, while saltiness is due to the presence of sodium chloride. Aroma volatiles are considered to be inhibited throughout the storage period of 10 months at 1 °C in the atmospheres having 3% CO_2 or 1–3% O_2.

Vegetables can be divided into two main categories, depending on the flavor attributes. The first category is with aroma, which could be attributed to a single or group of compounds present. *Allium* species (onions), for example, with characteristic sulfur compounds, bananas with isoamyl acetate, and celery, with distinct phthalides, are some of the examples of the first group. In the second category, aroma is due to volatiles, and they do not carry the distinctive aroma. Some examples in the second group are snap muskmelons, beans, and tomatoes.

The off-flavors are developed by the enzymatic activities like peroxidase or lipoxygenase, which form responsive hydroperoxide free radicals and may catalyze the oxidation of lipids. Whenever these types of reactions take place, the impact could possibly be the development of off-taste considered as stale. Nevertheless, there are examples of enzyme-catalyzed reactions, which provide characteristic flavor like hydroperoxidelyase, which catalyzes the production of characteristic tomato flavors [5].

13.2.4 Texture of Fruits and Vegetables

Textural properties are generally sensed with touch, when picked up by hand or in the mouth, when chewed, and are the groups of physical characteristics. The physical characteristics are derived from the structural formation of the food and are sensed by the touch. The physical properties are measured by functions of time, distance, and mass and are related to the disintegration, deformation, and flow of the food under a force. The word texture is used primarily for semi-solid or solid foods. Tomatoes are example of a fruit vegetable, comprising approximately 93–95% water and 5–7% total solids (roughly 10–20% insoluble solids and 80–90% soluble solids). The insoluble solids are the major contributor to the consistency of tomato products.

13.2.5 Nutritional Value

Fruits and vegetables mainly contain both “macro” nutrients like carbohydrates and fiber and “micro” nutrients like vitamins, minerals, and the trace constituents such as polyphenolics, carotenoids, and glucosinolates. Water-soluble nutrients contain vitamin C, vitamin B complex, glucosinolates, and polyphenolics. Fat-soluble nutrients comprise of vitamin A, D, E, and K and various other carotenoids like β-carotene and lycopene. Vitamin C is a highly sensitive vitamin and is degraded rapidly by light, oxygen, and heat.

Various features add to the nutritional value of a vegetable/fruit such as the growing conditions (light, temperature, etc.), genetics, maturity at harvest, production practices (fertilization, irrigation.), and postharvest handling conditions. Cutting increases the production of ethylene, which enhances respiration and senescence causing brisk loss of essential vitamins. Vitamin C can be considered as an index of freshness.

13.3 Processing and Preservation

13.3.1 Thermal Processing

Fruits and vegetables are processed to add value and preserve them for a long period of time. These are generally blanched and then pasteurized or sterilized depending upon the requirement. Juices, RTSs and nectars are generally pasteurized at 85 °C for about 25–30 min, depending on the nature and size of the container [6].

13.3.1.1 Blanching

Blanching is generally considered as a pre-treatment technique, mainly carried out in hot water or steam, prior to processing. Foods can be blanched, by hot air, microwave, or infrared radiation. The heating deactivates enzymes in the products and the extent of inactivation of enzymes authenticates the efficiency of the blanching process. The action of polyphenol oxidase is traced within many fruits, compared to vegetables that contain peroxidase/catalase. Blanching has direct or indirect effect on color. At elevated temperatures, a greater rise in green color is found, followed by a quick loss at different treatment times such as in the case of peas, asparagus, green beans, and broccoli. In these green vegetables, chlorophyll is chiefly responsible for green color. Chlorophyll (a) and chlorophyll (b) ingredients of green vegetables are influenced by blanching time and temperature with the transformation of chlorophyll into epimers and pheophytin. Blanching can:

a. Reduce drying time
b. Assist to get rid of the intercellular air within the tissue cells
c. Help in softening of the texture and to retard the production of objectionable flavors and odors during storage by inactivation of enzymes
d. Eliminate bitterness, mostly in onions
e. Cause soluble solid loss

Air removal from the tissues may cause the following: (1) In vegetables, tissues are distorted and the cellular material beneath the surface gets protection to a greater extent from the impact of oxygen. This is mainly evident in products, which consist of sufficient amount of starch, such as potatoes. (2) In fruits, it can cause crystallinity in the cellulose-rich produces, which may bring changes in texture.

Individual Quick Blanching (IQB)

Lazar [7] coined the term steam bleaching as the individual quick blanch (IQB) procedure. IQB consists of heating and holding steps. Heating is generally carried out in a condensing steam entity to inactivate enzymes (>87.7 °C). Lazar [7] additionally explained that “pre-conditioning” carrots prior to blanching by heating and fractional drying could reduce the waste. The green vegetables blanched by IQB technique using heat pre-conditioning exhibited no change in the quality to the commercial blanched samples and a sharp reduction in the solid loss can be achieved.

13.3.1.2 Pasteurization/Sterilization

Beverages and juices from fruits and vegetables are generally processed through thermal techniques. Other technique alternatives to thermal processing have also been successfully developed due to certain inherent drawbacks of thermal processing such as lesser retention of nutrients, degradation of functional compounds, lesser sensory score, and slow heat transfer. Generally, the juices and the beverages are processed at either mild or high temperature, and low temperature is generally not preferred. Generally, the pasteurization of juices is based on 5 log reduction of the most resistant organism [8]. For juices and beverages, the temperature can be classified as pasteurization (lesser than 100 °C), canning (approximately 100 °C), and sterilization (greater than 100 °C).

1. Mild-temperature, long-time (MTLT) thermal processing: The temperature for thermal treatment is kept below 80 °C but for more than 30 s of holding time to enhance the shelf life [9]. It provides retention of vitamin C, β-carotene, and phenolic compound, preserving the color. Amla juice, apple juice, apple-orange-blend juice, banana, orange, strawberry smoothie, black jamun juice, bottle gourd juice, and carrot juice can be successfully processed using MTLT thermal processing.
2. Mild-temperature, short-time (MTST) thermal processing: The temperature of thermal processing and time in MTST is limited to 80 °C or lesser for a period of 30 s or lesser than 30 s [9], which shows minimal changes in product characteristics. The sensory quality is preserved and inhibition of peroxidase activity is attained. The MTST thermal processing is used in pineapple, mango, and orange juices, apple smoothie, sweet cherry juice, and tomato juice.
3. High-temperature, long-time (HTLT) thermal processing: The temperature of thermal treatment is kept equal or higher than 80 °C for more than 30 s [9, 10]. The juice with more than 4.5 pH requires more thermal treatment, i.e., higher temperature and/or longer time. These are used for amla, aonla, bottle gourd, ginger, lemon , apple, banana, blackberry, beetroot, and carrot juices.
4. High-temperature, short-time (HTST) thermal processing: The temperature of thermal treatment is kept equal or higher than 80 °C for lesser than or equal to 30 s [9]. The method is preferred due to easy handling of large volumes, high energy efficiency, minimal changes in food, and effective regeneration. It is successfully used for enzymatic and microbial inactivation in juices.

   It has the following advantages:

1. Minimizes the flavor loss and maximize retention of vitamins
2. Economy of space and time.
3. Consistent heating (Thus, the cooked taste is minimum.)

13.3.1.3 Sterilization

Sterilization refers to the destruction of all microbes. By this process, all microbes are killed at elevated temperature. The time–temperature combination is essential for sterilization and differs from product to product. Products from tomato are sterilized for 30 min at 100 °C to destroy the microbiota, which are highly sensitive to acidity [11]. Vegetables like okra, beans, green peas, etc., having non-acidic nature and having extra starch, need more severity of the treatment to destroy the spore-forming microbes.

13.3.1.4 Important Parameters to Describe the Effectiveness of Heat

1. Decimal reduction time (D-value): The time needed at a given temperature or set of conditions to achieve a log reduction is referred as D-value. One log reduction indicates killing of 90% of microorganism. D-value remains the same for each log cycle. In other words, D-value is the heating time at constant temperature that results in reducing microorganism by a factor of 10 D-value with a subscript indicating the temperature.

Mathematically,

$$D = \frac{t}{\log N_0 - \log N}$$

where D is the decimal reduction time, t is the processing time, and N_0 and N are the number of microorganisms initially and after processing at time t.

2. Thermal resistance constant (Z-value): It is the defined as the change in temperature required to achieve one log reduction in D-value or temperature change for one log cycle reduction in D-value that gives Z-value. It can be expressed as

$$Z = \frac{T_2 - T_1}{\log\left(\frac{D_1}{D_2}\right)}$$

where D_1 and D_2 are the decimal reduction time at temperatures T_1 and T_2, respectively.

3. F-value: It is defined as the time required to kill a specific microorganism at a particular temperature. For a process, F-value can be defined as the time in minutes required to kill a known population of microbes in a food under the set of specified conditions.

The standard reference temperature is usually set as 121.1 °C, and the relative time (in min) needed to sterilize a particular selected microorganism at 121 °C is referred as the F-value of that microorganism. F-value can be calculated as

$$F = D\,(\log N_0 - \log N)$$

where F and D are the thermal death time and decimal reduction time and N_0 and N are the number of microorganisms initially present and after processing. The commercial sterility for low acid foods is attained at F-value of $12D$, which indicates 12 log reductions in the population of spores per gram. If a low acid food contains 10^6 spores per gram, it will be reduced to 10^{-6} spores per gram.

Further, F-value for a process can also be presented as

$$F_R^z = \int_0^t 10^{\frac{T-R}{Z}} dt$$

where R is the reference temperature and T is the desired processing temperature. In the case of processing at constant temperature with time, the equation can be reduced to

$$F_R^z = t \times 10^{\frac{T-R}{z}}$$

In the case of self-stable food, F is generally set to 12 D at 121 °C, and F_{121}^{10} indicates the time needed for a given microbial spore population reduction at Z-value of 10 °C at 121 °C. F_0 without a subscript indicates temperature of 121.1 °C.

Q1. Concealed tubes contain the same number of spores obtained from a spoiled food. The food sample is subjected to heating for 12 and 17 min at 118 °C, respectively; the numbers of survivors are 4000 and 120, respectively. The lag time for heating tube is 0.5 min at the heating temperature.

Solution: The heating times (12 and 17 min) are greater than lag time (0.5 min) at 118 °C. As we know,

$$D = \frac{t}{\log N_0 - \log N}$$

$$D = \frac{(17 - 12)}{\log(4000) - \log(120)} = \frac{5}{3.602 - 2.079} = \frac{5}{1.523} = 3.28 \text{ min}$$

Q2. During the thermal processing of the suspension containing spores at 117 °C for 98 s results in a 7-log killing of the spores. To attain the same reduction at 102 °C, 20 min is required. Estimate the D- and Z-values for thermal destruction of spores.

Solution: The decimal reduction time at the two temperatures is

$$D_{117} = \frac{98}{7} = 14 \text{ s}$$

$$D_{102} = \frac{20 \times 60}{7} = 171.4 \text{ s}$$

The Z-value for the process can be expressed as

$$Z = \frac{T_2 - T_1}{\log\left(\frac{D_1}{D_2}\right)}$$

$$Z = \frac{102 - 117}{\log\left(\frac{14}{171.4}\right)} = \frac{-15}{-1.088} = 13.79^{\circ}\text{C}$$

Q3. A pasteurization process is recommended to use reference temperature of 72 °C with a Z-value of 8 °C. Estimate *F*-values at reference temperature, if pasteurization process is operated at temperature of 90 °C for 30 s.

Solution: We know that

$$F_R^z = t \times 10^{\frac{T-R}{z}}$$

$$F_{72}^8 = 30 \times 10^{\frac{90-72}{8}} = 5334.84 \text{ s}$$

13.3.1.5 Drying

A number of techniques are used for the drying of agricultural produce. Sun drying is one of the important conventional techniques of drying food products and is still prevalent throughout the world.

Tunnel Drying

Tunnel dryers are widely employed by several food industries due to ease and versatility. Food of particular size and shape can be dehydrated. Within this process, trays holding the material are gathered on trolleys that go into the tunnel at one end and travel through the tunnel and leave at the other end. Hot air passes between the trays, which contain food materials. Tunnel dryers can also work in co-current, counter-current, or mixed current manner. The trolleys can move steadily (continuously) throughout the tunnel or the movement might be semicontinuous. In general, tunnel dryer may be 25 m long with cross-section area of 2 × 2 m^2. The loading of the vegetables in trays may vary in the range of 10–30 kg/m^2.

Spray Drying

It is mostly used for drying of liquid foods and slurries. This method works on the principle of atomization. The feed is converted into a spray or fine mist in a spray-forming device called as an atomizer. The size of the droplet varies from 10 to 200 μm; however, larger droplets can also be produced for certain applications. The spray is brought in contact with hot air in a drying chamber. Due to relatively smaller droplet size, larger surface area is available for evaporation of the moisture, and moisture has to migrate relatively shorter distance to the drying surface. Thus, the drying time takes only 1–20 s. Most of the drying occurs under constant rate condition. Heat damage is limited, if the particles are eliminated rapidly from the drying chamber after drying is completed. Thus, spray drying is used to dry heat-sensitive food products.

In the drying process, air is drawn from the inlet fan and passes through the filter and then heating unit before entering the drying chamber. The pump brings the materials from reservoir to an atomizer, which transforms feed into spray and comes in contact with hot air in the drying chamber, in which drying occurs. The dried product is removed by the valve and carried pneumatically via duct into a storage bin. Air subsequently leaves the chamber and moves through separators to recover the fine powder. The exhaust air from the drying chamber carries with it some fine powder that should be removed from air, because it may pollute environmental surroundings near the plant. Big dry cyclone separators are generally employed, either singly or even in sets, to handle this process. Powdered dust/particles are washed out from the air using sprinkler system and reprocessed to the drying chamber. These devices are referred as wet scrubbers.

The droplet size produced by the atomizer is an important parameter for determining the efficiency of spray drying. If the droplet size is too large, drying can be non-uniform. The drying conditions should be in such a way that the bigger droplets reach the desired level of moisture content. This could possibly make tiny droplets getting overexposed to the hot air. Size of the droplets may have negative impact on certain essential characteristics of the dry powder, like its flow and rehydration characteristics. Atomizers can be classified as centrifugal atomizer, pressure nozzle, and two-fluid nozzle.

A centrifugal atomizer consists of a disc, wheel, or bowl. The slurry is fed onto disc close to the middle of its rotary motion. Because of centrifugal force, it moves toward periphery of the disc and is spun off, in the threads, which splits into tiny droplets. Disc diameter varies from 50 to 300 mm and revolves at 50,000–10,000 rpm. They produce uniform droplets and are able to handle viscous material without any blocking or abrasion by insoluble solids.

Feed is pumped at high pressure, 5.0–50.0 MPa through a pressure nozzle that has a small orifice, having 0.4–4.0 mm diameter. Spinning motion to the liquid can be produced from the insertion of a grooved core before the orifice. Pressure nozzles produce uniformly sized droplets, if the pumping pressure is kept steady. However, nozzle can be blocked by the insoluble solids; therefore, nozzles are mainly used to handle homogeneous liquids, of relatively low viscosity.

A pneumatic nozzle, also known as two-fluid nozzle, has an annular opening for the gas, mostly air that exits at high velocity. Feed exits through an orifice, which is concentric with the air outlet. A venturi effect is produced, which leads to the transformation of liquid into a spray. The lower feed pumping pressure is needed as compared to pressure nozzle. The presence of insoluble solids in feed can result in abrasion or blocking these nozzles also. The uniformity in size of the droplets is generally lesser by two-fluid nozzle as compared to other two types of atomizers, when high viscosity liquids are handled.

Freeze-Drying

In this technique, the shelves are cooled to −5 °C quickly, which is maintained for 20 min, and temperature again is dropped to −50 °C rapidly. The product temperature reaches to −45 °C and high vacuum (0.1 mmHg) is maintained. The primary drying starts initially and the temperature is brought to −10 °C and it took about 65 h. The temperature is increased to 5 °C, holding for 5 h and finally to 35 °C for 4 h for the completion of drying. In this technique, sublimation of ice to vapor takes places without being passed into the fluid phase. The product remains extremely hygroscopic, better in flavor and taste, and could be reconstituted easily. Orange juice concentrate, mango pulp, and guava pulp can be dehydrated by this technique.

Osmotic Dehydration

This phenomenon includes the removal of water from vegetables and fruits, from lesser concentration of solute to higher concentration via a semipermeable membrane that allows water to pass through till the equilibrium is achieved. In osmotic dehydration, the solutes used are usually salt (sodium chloride) with vegetables and sugar with fruit slices. In this process, water flows from vegetables or fruits to solution, and along with water, certain other compounds of fruits and vegetables like vitamins, minerals, fruit acids, etc. also move toward the solution. It is basically a dynamic method, where water and acid are removed at first and then move slowly, while penetration of sugar is slight at first and rises with the time. Thus, the properties of the product could be altered by controlling sugar syrup concentration, temperature, concentration of osmosis solution, and time of osmosis. Osmotic dehydration is widely used to preserve fruits and vegetables, as it reduces the water activity. It is preferred over other processes due to better retention of flavor, texture, color, and nutritional constituents.

13.3.1.6 Canning

Canning is a technique of sealing the food hermetically in cans/containers and sterilizing them using high temperature for long duration. In 1804, Nicholas Appert in France designed a method of sealing food items hermetically inside cans as well as sterilizing. Nicolas Appert is known as the father of canning. Peter Durand, in 1810, gained the first UK patent of invention regarding canning of food items in tin cans. William Underwood, in 1817, established canning of many fruits at industrial level in the USA. Canning process extends the shelf stability of food products and makes their availability round the year.

Process

Destruction of microbial load within a sealed container by using high temperature is the fundamental principle for canning. The canning is achieved by filling the food product in pre-sterilized cans and then hermitically sealing them for long-term storage. The following flow sheet illustrates the canning method (Fig. 13.1).

Selection of Fruits and Vegetables

- Fresh and dirt-free fruits and vegetables are to be picked up.
- Firm and mature fruits are to be selected. Fruits that are overmatured should be prohibited because they may be infested by microbes. Unripe fruits should be omitted because these fruits may usually shrivel.
- Vegetables must be tender excluding tomatoes.
- Vegetables must be fixed, firm, ripe, and deep red in color especially tomatoes.

Grading

The designated vegetables and fruits are categorized as per their color and size to attain a uniform quality. This can be done manually or by machines like screw and roller grader. Plums and cherries are sorted whole, whereas mangoes, pears, peaches, apricots, pineapples, etc. are generally graded after cutting into slices or pieces.

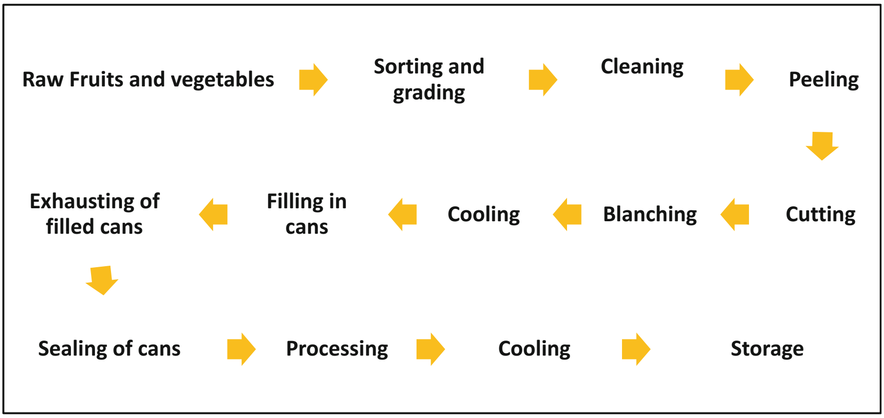


Fig. 13.1 Flow sheet for canning process

Washing

It is essential to eliminate pesticides and filth from vegetables and fruits. One gram of soil comprises roughly of 10^{12} spores. Thus, the elimination of microbes by washing with water is important. Vegetables and fruits can be washed by different methods. Root crops are washed by soaking in water having 25–50 ppm chlorine. Other methods of washing consist of steam washing, spray washing, etc.

Peeling

The primary purpose of peeling is always to remove external covering. Peeling can be done as:

- Hand peeling: It is primarily carried out for erratic fashioned fruits, like papaya and mango.
- Steam peeling: Peaches are steam peeled in a variety of methods. Tomatoes and potatoes are peeled using boiling water or steam.
- Lye peeling: Peaches, oranges, apricots, and vegetables, e.g., sweet potatoes and carrots, are peeled by sinking them in 1–2% hot caustic soda mixture for half a minute to a couple of minutes depending upon the product. Lye slackens the surface skin simply by breaking up the pectin. A trace of alkali is eliminated simply by cleaning with water or sinking for a couple of seconds inside 0.5% citric acid mixture. It is an instant procedure wherein wastage and cost of peeling are decreased.
- Mechanical peeling: Mechanical peeling is now carried out to save time and thoroughly for different fruits such as peaches, apples, cherries, and pineapples and veggies like turnips, carrot, potatoes, etc.

Cutting

Pieces of desired dimensions are chopped for canning. Core, stone, and seeds are eliminated. Various berries (plum, etc.) are canned as a whole.

Blanching

Normally fruits are not blanched; occasionally fruits are reheated for half a minute to 5 min, depending on the variety at 180–200 °F in water, followed by cooling by immersion in cold water. This softens the texture and thus can result in a higher weight to be pushed in the container without any damage to the fruit. Blanching is generally accomplished for vegetables simply by dipping in boiling water for 2–5 min and then cooling. The following can be achieved:

a. It deactivates the plant enzymes that may cause discoloration (polyphenol oxidase), mustiness, toughness, off-flavor (peroxidase), nutrient loss, and softening.
b. It reduces the area of leafy vegetables by wilting or shrinkage, which makes packaging easier.
c. Inside the tissue, it eradicates gases that minimize sulfides.
d. It diminishes microbial population.
e. It improves the color of a number of vegetables like broccoli, peas, and green spinach.
f. It eradicates saponins in peas.
g. It removes the sharp taste of peel and undesirable acids.

Cooling

Fruit and vegetables are submerged inside cold water after pasteurization for convenient handling and maintaining the natural conditions.

Filling

Metal cans are rinsed by using hot water. Automated can filling equipment are employed in many countries; however, top-quality fruits are likely to be packed manually to prevent bruising in some countries.

Exhausting

It is the method of elimination of air from the cans. It is very essential to avoid the pin holing and corrosion of tinplate during the storage. For exhausting, heating method is generally used but can also be done by mechanical means. The metal cans are subsequently moved through a reservoir of heated water having a temperature of 82–87 °C for 5–10 min. After exhausting, temperature at the center of the metal cans needs to be around 79 °C.

Sealing

Metal cans are sealed airtight, immediately after exhausting. In the event of glass containers, a rubber band is positioned in between the lid and hook area of container, to ensure that it is airtight. The temperature of the can may not be below 74 °C during the sealing process.

Processing
In the processing, heating or cooling of canned foods is done in order to ensure the destruction of most heat-resistant bacteria. Temperature and processing time vary with can size and nature of food.

Storage
After labeling of cans, they must be packed in corrugated cardboard cartons or strong wooden cases and stored in a cool and dry place.

Aseptic Canning

Aseptic canning is a method where the foodstuff is sterilized separately in the can and then aseptically placed in pre-sterilized cans followed by sealing in aseptic conditions. This process is known as Martin aseptic canning, which had been firstly commercialized in 1950. The process is basically a high-temperature, short-time (HTST) sterilization technique. It comprises of instant heating followed by rapid cooling and aseptic product packaging. This process includes four individual steps and is done one after another within an enclosed coordinated equipment:

a. Product sterilization is done by suitable rapid heating for a specific holding time and then cooling.
b. Sterilization of can/containers and shelter.
c. Aseptic nourishing of cooled and sterilized product into the sterile containers.
d. Aseptically sealing of the cans under sterile condition (Fig. 13.2).

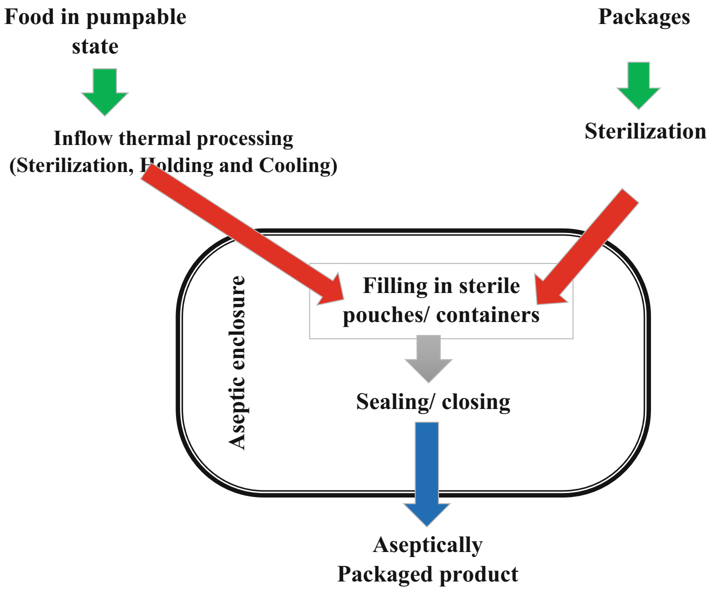


Fig. 13.2 General process for aseptic canning

Aseptically, sterilization temperature may go to 149 °C and the product can be kept for 1–2 s to retain the quality of the product.

13.3.1.7 Aseptic Processing of Juices

The word "aseptic" is originated from the Greek word "septicos" that means the absence of putrefactive microorganisms. Aseptic process is actually a heating technique in which the can and the product are sterilized individually and then brought together in aseptic environment. It involves all the unit operations such as pumping, deaeration, and sterilization, followed by holding for a specific period, then cooling, and finally packaging in a sterilized container. The use of HTST (as compared to conventional canning) in aseptic conditions yields a high-quality and shelf-stable product under the ambient conditions.

Aseptic packaging material should be designed as per the product requirements and compatibility with the product. Physical structural integrity of the package is a must to maintain the sterility and containment of the product. The package should protect the product and retain all its quality attributes in its original form to the extent possible. The most common forms of aseptic packaging are Tetra Pak cartons. Tetra package possesses six coatings. These types of packages have the ability to survive for extended time period. These types of cartons are made by three standard substances, which produce a secure, reliable, and low-weight package. Every material executes a specific purpose. These types of materials consist of paper (75%) to provide rigidity and durability, polyethylene (25%) to manufacture packages fluid proof and to offer an obstruction to microorganisms, and aluminum foil (5%) to stop air, light, and off-flavors (https://www.tetrapak.com/en-in/sustainability/planet/good-for-you-good-for-the-earth/tetra-pak-cartons-recyclable#:~:text=Tetra%20Pak%20cartons%20are%20primarily,%2C%20air%2C%20dirt%20and%20moisture).

The combination of these materials, such as paper, polyethylene, and aluminum foil, has led Tetra Pak to create a packaging with excellent characteristics. This packaging gives safe, hygienic, and better retention of nutrients in foods. It preserves freshness and taste of the product and keeps juices for months without preservatives and any refrigeration. These packs are lighter in weight. The packed juices and nectars, to the proportion of nearly 61%, are now packed in Tetra Pak.

13.3.2 Other Processing Techniques

13.3.2.1 High Pressure Processing (HPP)

HPP is an advanced non-thermal food processing technique and offers numerous advantages such as freshness, minimum damage by heat, and retention of vitamins and flavor. Moreover, high hydrostatic pressure (up to 700 MPa) can inactivate/destruct enzymes and microbes responsible for the spoilage of food. Pressure at 500 MPa and 600 MPa can decrease the number of *Escherichia coli* O157:H7 by 3.5 logs and 5.7 logs, respectively [12]. HPP can sometimes damage the tender tissues of fruits and vegetables that may affect the quality. Although in treating cut carrot and cabbage, the application of 500 MPa can lead to total microbial destruction but results in change in texture and appearance during the 2-weeks storage [13]. In high pressure processed vegetables, pathogenic microbes can be eliminated and hardly cause any profound effect on sensory and nutritional properties. It has also been observed that the tissue and texture of fresh-cut carrot and tomatoes treated with 500 MPa for 5 min or 400 MPa for 20 min remain unchanged [14].

13.3.2.2 Ultrasonic

Ultrasound process is a rapid, reliable, and nondestructive method, which can be used in food processing industries to increase the shelf life and other purposes. Power ultrasound, 20–100 kHz, can be potentially applied to decontaminate fresh produce. High-power ultrasound can be used as single treatment to destroy the most resistant microbes. The process of ultrasonication in combination with chlorine can result in a reduction of 2.7 logs of *Salmonella typhimurium* in iceberg lettuce and shredded carrots, which is comparatively greater than ultrasound alone, because it can help to release the microbes from difficult access locations in the vegetables [15]. However, the combination of ultrasonic and chlorine can cause destruction of yeast and molds in shredded carrots more effectively than the chlorine alone [16].

13.3.2.3 Electromagnetic Radiation Microwave processing

Electromagnetic radiation, wavelength of 1 mm to 1 m with a frequency range of 300 MHz to 300 GHz, is known as microwave radiation. The microwave frequencies of 915 MHz, 2450 MHz, 5.8 GHz, and 24.124 GHz can be used for domestic, scientific, industrial, and medical applications. Microwaves can be produced by a device called as magnetron and interact with the material by either ionic conduction or dipolar rotation. The microwave radiation penetrates food deeper than infrared radiation (IR); thus, “volumetric heating” is attained with microwaves. The interaction of microwave radiation and food depends on water. Additionally, an inorganic ion from salts and other constituents of food and ingredients dissolved in food also interact with microwave.

The major drawback in microwave drying process is the occurrence of cold and hot spots due to non-uniform electrical field in the cavity and the rapid increase in temperature with the reduction of water. To overcome such limitations, the material needs to be in constant motion during microwave processing so that the whole material gets the same energy and/or low levels of microwave power density. The temperature of foods can be controlled through the controlled duty cycle, i.e., combinations of “on” and “off” cycles for a specific power level.

13.3.2.4 Electromagnetic Radiation Radio Frequency

The radio frequency (RF) band includes the longest wavelengths of electromagnetic spectrum in the range of 3 kHz to 300 GHz with a wavelength of 1 mm to 100 km, which also includes microwave radiation. RF radiation, when absorbed, can generate volumetric heating throughout the material [17]. RF heating is affected by the square of the applied voltage, frequency, the product dimensions, and the dielectric loss factor of the material. RF energy can penetrate deep into the food and generates more uniform heating as compared to microwave processing and is suitable for heating large particles [17]. However, RF drying is less common in food industries than microwave drying. Postharvest disinfestations of fruits, blanching, and microbial deactivation of liquids are some of the common applications of RF processing.

13.3.2.5 High-Intensity Pulsed Electric Field (HI-PEF)

The treatment of material with a direct current electric field at a strength of 0.5–1.5 kV/cm for a treatment time within micro- to milliseconds to produce uniform drying but without heating the sample is referred to as high-intensity pulsed electric field (HI-PEF). This technique has been shown to be effective in increasing the drying rate of vegetables like carrot [18]. HI-PEF processing depends on the factors like the number and duration of pulses, field strength, and total treatment time. HI-PEF can effectively be combined with osmotic dehydration to improve the rate of mass transfer. The short pulses of electricity are created in food material for inactivation of microbes. It is a non-thermal processing method, while microwave created heat through ionic and dipolar radiation of water molecules. Therefore, it triggers lesser-quality changes.

13.4 Preservation

13.4.1 Cellar Storage

Cellars (underground rooms) are in which products are kept nearly at 15 °C. This low temperature is enough to inhibit the activity of various spoilage-causing microorganisms or plant enzymes. The decomposition of fresh produce slows down considerably. Potatoes, apples, onions, root crops, and similar food products could be stored during the winter season.

13.4.2 Chilling (0–5 °C)

The chilling temperatures are achieved using mechanical refrigeration or ice. Vegetables, fruits, and their products could be well preserved for several days to a couple of weeks at this temperature. The most effective storage temperature for a variety of food items is above 0 °C; however, this varies with the foods. Additionally, the relative humidity, temperature, and the composition of gases can affect the shelf life and preservation of food products. Industrial cold stores having proper ventilation system and automatic control over temperature have become useful for extending the shelf life of semi-perishable foods like apples and potatoes. This helps to make these products available throughout the year and cost-effective.

13.4.3 Freezing (−18 °C)

In this method, microbial growth is inhibited along with reduction in the chemical reaction rate. In frozen storage, plant foods should be blanched prior to freezing to improve and avoid undesirable quality defects. At temperatures less than the freezing point of water, the microbial growth and enzymatic activity are retarded. The majority of sensitive food products can be preserved for months, when temperature is reduced rapidly (quick freezing) and is stored at such temperatures. Food freezing can be achieved rapidly by:

1. Keeping the produce in touch with the coil springs in which the refrigerant circulates
2. Keeping inside blast freezer, where colder air blows over the products
3. Sinking in liquid nitrogen

Frozen foods keep their freshness and their quality even after thawing because of very small ice crystal formation during rapid freezing.

13.4.4 Freezing of Fruits and Vegetables

Under frozen storage, the microbiological growth is prohibited entirely and the activity of food enzymes is arrested. The freezing rate of food rests upon a number of features like the temperature, method used, air or refrigerant circulation, shape and size of the package, type of food, etc. At −18 °C, fresh fruits mostly hold excellent value for a year and 8–12 months in the case of vegetables.

The different freezing methods are discussed below:

13.4.4.1 Slow Freezing

This process was initially employed in 1861 that consists of freezing via air circulation, employing fans. In slow freezing, temperature may vary from −15 to −20 °C and freezing takes nearly 3–72 h. The longer duration of freezing results in large crystal formation, which causes cell disruption. Therefore, the thawed tissues are unable to regain their initial structure.

13.4.4.2 Quick Freezing (Rapid Freezing)

In this process, heat is removed so quickly that very little time is there for dehydration of cells. The maximum ice crystal formation occurs in less than 30 min at 0 to −4 °C. This method is responsible for the development of very small ice crystals and thus causes the minimum disruption to the cell structure. The three quick freezing methods used for foods are:

By Direct Contact Systems

Immersion Freezer

The unpacked food material comes in contact with the refrigerant and sharp freezing takes place. The refrigerant should remain clean, pure, odorless, and nontoxic in nature, as food material gets direct exposure of refrigerant.

Immersion with Low-Freezing-Point Liquid

Liquids are good conductors of heat. Foodstuffs are directly immersed in a liquid at lower temperature. Products are frozen using sugar solution, sodium chloride, and glycerol, which have lower freezing point. The refrigeration liquid remains unfrozen/in liquid state at −18 °C. In this process, there is a close contact between the refrigerant and food or package, so resistance to heat transfer is reduced. This is essential with irregularly shaped food pieces to be frozen very quickly like mushrooms, loose shrimp, and other foods.

Immersion with Cryogenic Liquid

The products like sliced tomatoes, mushrooms, raspberries, and whole strawberries need rapid freezing. Products are dipped in liquid carbon dioxide/liquid nitrogen in which temperature is kept below −60 °C. When liquid nitrogen is used as refrigerant, freezing is accomplished by (1) spraying of liquid, (2) immersion in the liquid, or (3) circulation of its vapors over the product to be frozen. The liquid nitrogen has several advantages, viz., lower boiling point for greater heat transfer, spreading all around irregularly shaped fruits or vegetables, eliminating the need of primary refrigerant, nontoxic and inert, to reduce the oxidation by removing air from food material.

By Air Blast (Air Blast Freezing)

This technique refers to the dynamic flow of cold air to freeze the food product. In this method, the temperature is in between −30 and −45 °C and the air velocities are kept as 10–15 m/s. This method is cheap and a variety of fruits in different shapes and sizes can be frozen. This process can work as a batch or continuous process.

In continuous process, freezing is performed by placing the products upon trays or on belt, which are passed through an insulated tunnel comprising cold air within it. The freezer tunnel may remain simple, multi-teared, and spiral for effective utilization of space. The uniformity of airflow and direction remain important factors for designing the system. The direction of material flow may remain in parallel, counter, and cross flow arrangement. The counter-current arrangement remains effective than other methods. In the case of batch air blast freezer, air cooler with fans is fitted in a well-insulated container, and material may be loaded through a moveable belt or stacked trays in freezing containers. The different designs of air blast freezers can also be used in indirect contact freezing application.

Fluidized Bed Freezing

This technique is a modified version of air blast freezing. Food is fluidized to make bed of particles, which is then frozen by passing cold air from the bottom of the freezer by the belt, which partly lifts or suspends the particles. The depth of the bed of particles varies from product to product. Products having a size from pea to strawberry can be frozen by this method with a depth of 1–5 inches. Corn, peas, green beans, and French beans are the most common products frozen by this method.

By Indirect Contact Systems

This technique refers to the freezing by the interaction between the produce and a metallic surface, which is cooled itself by freezing with refrigerating media or with brine. It is an old technique of freezing in which the food product is placed in proximity with the channel through which the refrigerant passes.

Plate Freezing

In this technique, food is brought in contact with the cold surface, most commonly using a metal surface, which is constantly kept cold using a refrigerant. Fruit juices are frozen using tubular scraped surface heat exchangers. Plate freezing is considered as an economical method.

Batch Plate Freezers

These freezers handle the material in batches and have horizontal and vertical arrangements of plates. Horizontal plate freezers have horizontal pockets between adjacent freezing plates and provide double contact freezing. In horizontal freezers, the material is loaded on the bottom plate initially; the next upper plates are lowered for loading till complete loading. Horizontal freezers are used for the bare and the packed products.

The vertical plate freezers are best suited to the unpackaged products, which are fed directly between the plates. After freezing, product falls out from the bottom of the freezer. Rapid rate of cooling is achieved in these freezers, and freezing plates do not allow bulging of the product, which makes the product suitable for easily stackable. Horizontal plate freezers are used for freezing chopped vegetables, ready-made meals, meat pulps, and seafood, while vertical plate freezer are used for freezing the fish, meats, fruit puree, and liquids. These are commonly available in 250–1800 kg per batch capacity.

Continuous Plate Freezers

The plate freezer handles the material continuously and operates on drum systems or belt systems. The drum system holds the material between the two rolling plates through the conveyor belts. In belt freezers, either continuous moving plastic films are used to convey the material between two stationary refrigerated plates or two continuously moving stainless steel belts are used to hold the product. The configuration having stainless steel belts does not allow the product in direct contact with refrigerant evaporator and therefore is not considered as the plate freezer in true sense. These are usually used for thin or flat product, which require shorter freezing times.

13.4.5 Innovative Freezing Technologies

Some of the novel freezing technologies are presented in Table 13.2:

Table 13.2 List of novel freezing techniques and their applications [19, 20]

S. no.	Name of freezing	Details	Application	Advantages
1.	Impingement freezing	The fluid is directed through a jet or jets at the surface to bring a change. Impingement jets, having high velocity (up to 50 m s^{-1}), are used to break the layer of gas in the surrounding of the food product [20]	Burgers or fish fillet, carrot	Freezing times and weight of the product is reduced
2.	High pressure freezing			
(a)	Pressure-assisted freezing (PAF)	A pressure range of 100 to 1000 MPa is generally used [19]. It is the process in which temperature is lowered to the freezing point of the sample under constant high pressure.	Meat, kinu tofu	The uniform distribution of small ice crystals can be achieved
(b)	Pressure shift freezing (PSF)	In this, temperature is reduced below zero degrees centigrade under pressure and then pressure is quickly released. Consequently upon releasing the pressure, rapid nucleation takes place throughout the food, which results in uniform, homogenously distributed small ice crystals	Carrot, potato, broccoli, strawberry	Less tissue damage, smaller ice crystals, and better nutrient retention
3.	Ultrasound-assisted freezing	Ultrasound wave with low frequency (18–20 kHz to 100 kHz) and high intensity (generally higher than 1 W/cm^2) [21] is used in ultrasound freezing	Potato, apple, strawberries, mushrooms, broccoli	Decreases freezing time, increases freezing rate
4.	Pulsed electric field (PEF)-assisted freezing	It generates high-voltage intense electric pulses for extremely short period of time in foods placed between two conductive electrodes. It affects the permeability of cell membranes and improves the mass transfer	Potato, spinach leaves, apple	Cell wall structure remains unaffected and improves the freezing process
5.	Magnetic resonance–assisted Freezing	Very small (<1 milli tesla) field strengths are used [20]. In this technique, induction coils and permanent magnets are used to produce a weak magnetic field in the freezing chamber.	Sweet potato, spinach, garlic	Small ice crystals are formed with less cellular damage

(continued)

Table 13.2 (continued)

S. no.	Name of freezing	Details	Application	Advantages
		This oscillating magnetic field acts on polarized water molecules to delay formation of ice crystals		

Table 13.3 List of class I and class II preservatives [23]

Class I preservatives	Class II preservatives
Sugar	Sulfurous acid
Common salt	Benzoic acid
Dextrose	Calcium and sodium propionates
Glucose syrup	Sorbic acid and its Na, K, and Ca salts
Spices	Nitrates or nitrites of K or Na
Vinegar	Methyl or propyl parahydroxybenzoate (parabens)
Honey	Propionic acids
Edible vegetable oils	Lactic acid

13.4.6 Preservation by Chemicals

Preservative Any substance that can prevent, delay, or stop the process of acidification, fermentation, or food decomposition from its incorporation is generally referred to as preservatives. These substances are also capable of preventing and retarding microbial spoilage in food products. As per the food laws in different countries, the preservatives are categorized as:

1. Class I preservatives: These preservatives widely include naturally occurring substances, and there is no maximum limit for their uses under the law.
2. Class II preservatives: These are basically chemical substances incorporated into the food material. These preservatives being chemical substances have a maximum limit beyond which these should not be added into different food products. When two or more preservatives are incorporated into the food material, their ratio can be calculated proportionally to their maximum limit [22]. Examples of class I and class II preservatives are given in Table 13.3.

Microbial decomposition of foods can be kept under control by using various chemical preservatives. The preventive effect arises from their interference and inhibition to the growth of bacteria as well as enzymatic activity. The weak organic acids inhibit the fungal and bacterial outgrowth. Sorbic acid also inhibits the bacterial growth. The preservative works effectively at lower pH because uncharged molecules move freely in the plasma membrane and enters the cell. The major factors associated with the inhibition of growth due to weak acid preservatives are accumulation of toxic anions [24], membrane disruption [25], inhibition of essential metabolic reactions [26], stress on intracellular pH homeostasis [27–30], and biochemical reactions. The antimicrobial peptides such as nisin and pediocin are also used as food preservatives and their mode action is also considered as the disruption of the cell membrane.

Cordials, crushes, and squashes that are pasteurized possess cooked taste. Whenever the vessel is unsealed, they spoil and ferment in less time, mostly in tropical climatic conditions. To evade this specific problem, it is very important to utilize preservatives (chemicals). Crushes and squashes conserved by chemical preservatives could be retained for an extended duration even after unsealing the container. The practice of using chemical compounds is properly regulated, due to the fact that their unproportionate usage can be detrimental. These chemicals should not be detrimental to health. The two significant preservative chemicals acceptable in several nations are:

1. Benzoic acid (include benzoates)
2. Sulfur dioxide (including sulfites)

Benzoic Acid Benzoic acid is considered to be the vital compound in its soluble form of water. Sodium salts of benzoic acid (sodium benzoate) are mostly used as preservative. The requirement of sodium benzoate depends upon the nature of the product and the need to be preserved.

Sulfur Dioxide Potassium metabisulfite is generally employed as the source of sulfur dioxide. It reacts with the juice and forms potassium salt and sulfur dioxide. The liberated sulfur dioxide reacts with the water of the juice and produce sulfurous acid. Sulfur dioxide has detrimental effect against bacteria and mold spores than yeast and also prevents enzymatic activity. It may act as an antioxidant to retain carotene, ascorbic acid, and other oxidizable compounds. It can also hinder discoloration or non-enzymatic browning of the food material. Its efficiency depends on the temperature, pH, acidity, and other compounds present in the fruit juice. The preservatives in fruit juice and beverages as per Food Safety and Standards Authority of India (FSSAI) are given in Table 13.4.

Table 13.4 Limits for permitted preservatives in fruit juice and beverages [23]

Fruit juice/beverages	Preservative	Part per million (ppm)
1.Fruit pulp or juice for conversions into jams and other products		
a. Cherries	SO_2	2000
b. Strawberries and raspberries	SO_2	2000
c. Other fruits	SO_2	1000
2. Fruit juice concentrate	SO_2	1500
3. Fruit juice, squashes, fruit syrup, crushes, *sharbats*, cordials, and barley water	SO_2 or Benzoic acid	350 600
4. Sweetened ready-to-serve beverages	SO_2 or Benzoic acid	70 120

13.5 Effect of Processing on Physicochemical Properties and Quality of Fruits and Vegetables

These processing methods have varying impact on physicochemical properties of vegetables and fruits and the magnitude of impact largely depends upon the processing conditions (temperature and time) of product as shown below:

- Conventional methods of processing have a substantial effect on minimizing the microbiological load and inactivation of undesirable enzymes. However, undesirable changes are induced in texture, color, aroma, pigments, firmness, and nutrient composition of the fruits and vegetables.
- High drying temperature harms heat-sensitive bioactive compounds, primarily identified as natural antioxidants with health-promoting benefits (polyphenols, flavonoids, glucosinolates), reduces the nutritional value (amino acid destruction, oxidation of fatty acids, protein denaturation), degrades the heat-sensitive vitamins, and decreases the weight and volume of the produce. However, it causes a significant reduction in moisture content, restricts the microbial growth, and increases shelf stability [31].
- High operational process temperature during cooking, boiling, sterilization, pasteurization, steaming, and frying causes disruption of surface cells and rupturing of the plasma membrane and reduces the external resistance to mass transfer [32].
- Osmotic dehydration affects on minerals, vitamins, pigments, phenolic compounds, and toughness due to leaching out of compounds from produce.
- Fluctuations in freezing rate and temperature during freezing damage the texture and physical appearance of fruits and vegetables because of the ice crystal formation and the resultant breakdown of cellular structure, which affects the quality of produce. Ineffective freezing–thawing process affects on the nutritional composition and the taste of the product.

- Thermal processing such as canning is widely applied to increase shelf stability but affects on firmness and texture due to the disintegration of cells and tissues because of the high temperature [33].
- Fruits and vegetables undergo serious deterioration in color, flavor, pigments (chlorophyll, carotenoids, and anthocyanins), and water-soluble compounds during processing due to browning reactions and high temperature [28].
- The dehydration of cell takes place during freezing and the amount of damage is dependent upon the formation of crystal and rate of freezing.
- Structural damage induced by rupturing the cells during slow freezing does not allow water to be reabsorbed in the cell and contributes to drip loss during thawing.

13.6 Value-Added Products

13.6.1 Pickles

It is the most ancient process to preserve fruits and vegetables. Pickles are excellent appetizers and enhance the palatability of a meal and increase the flow of gastric juice, which aids in digestion. Pickling is caused by the fermentation by lactic acid–forming bacteria that are present in enormous numbers on the fruit and vegetable surface. Mango pickle ranks first followed by onion, cauliflower, lime, and turnip pickles. The growth of spoilage microorganisms can be prevented by brine containing 10–12% salt. Figure 13.3 shows the general outlines of pickle preparation.

Mango pickle is prepared using cut mangoes and is popular than any other pickles especially in South Asia. It is prepared from the mango variety, which can remain crisp during pickling and storage. However, it can be prepared from any raw mango. It is served as a condiment with the meals especially in India. The process flow chart for the preparation of mango pickle is shown in Fig. 13.4.

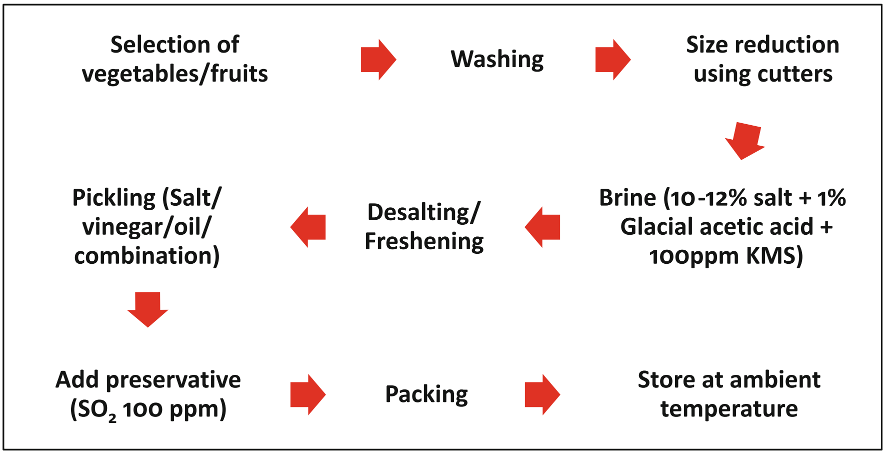


Fig. 13.3 General flow chart for pickling process from fruits and vegetables

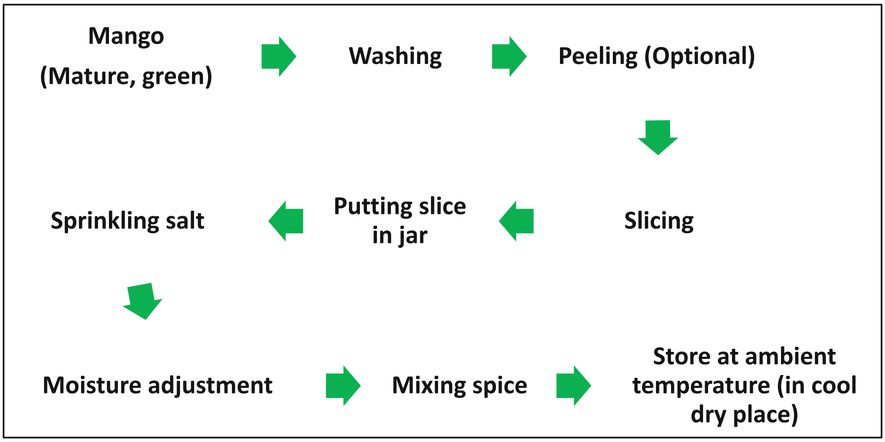


Fig. 13.4 Flow sheet for mango pickle

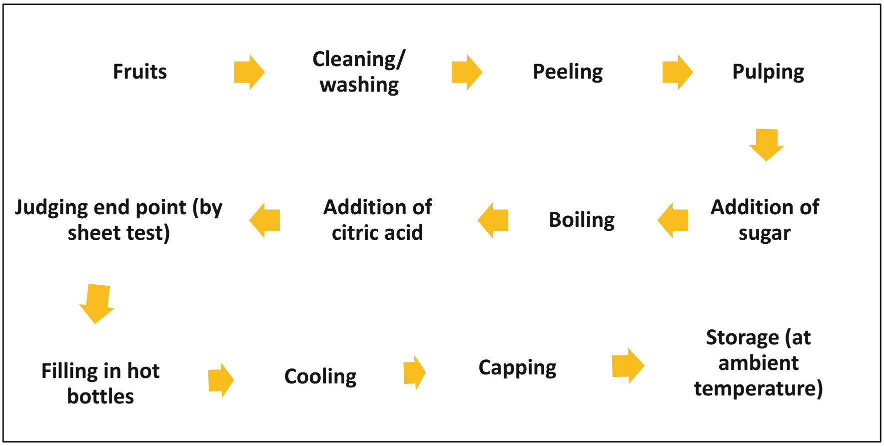


Fig. 13.5 Flow sheet for preparation of jam

13.6.2 Jam

Jam is a produce made by boiling the fruit pulp with an adequate amount of sugar to a reasonably thick, uniform, and firm consistency enough to keep the fruit tissues in place. Pear, apricot, sapota (chiku), loquat apple, papaya, plum, raspberry, carrot, strawberry, mango, muskmelon, grapes, tomato, etc. are used to prepare jams. Jam can be prepared from one or more fruit. Tutti frutti can be manufactured from fruit scraping, pieces of raw fruit, and core, which are there in canning industries (Fig. 13.5). Jam consists of 0.5–0.6% acid and invert sugar mustn't be raised above 40%.

Table 13.5 Specifications for jams, jellies, and marmalades [23]

Product	Specifications
Jam/jelly/ marmalade	• Minimum percentage of prepared fruit in the final product except strawberry/raspberry = 45% • Minimum percentage of prepared fruit in strawberry/raspberry = 25% • Total soluble solids (TSS), greater than 65% • Citric/fumaric/L-tartaric/malic/ascorbic acid, GMP • Artificial sweetener – Aspartame, maximum 1000 ppm – Sucralose, maximum 450 ppm – Sorbitol, maximum 30% – Aspartame, maximum 1000 ppm • Preservatives – Sulfur dioxide (SO_2), maximum 40 ppm – Benzoic acid, maximum 200 ppm – Sorbic acid, maximum 500 ppm • Antifoaming agent – Dimethylpolysiloxane, maximum 10 ppm – Mono- and diglycerides of fatty acids of edible oils, GMP • Colors – Chlorophyll, GMP – Synthetic, maximum 200 ppm • Firming agent: calcium chloride (for Jam and jelly only), maximum 200 ppm for use on fruit pieces only • Natural/artificial flavoring substances, GMP • Thickening agent (calcium alginates), GMP

Where GMP means "good manufacturing practices" and the food additives can be used under the following conditions: (1) It should be added in the lowest possible quantity to food to accomplish its desired effect. (2) The quantity of the additive becomes a component of food as a result of its usage in processing or packaging. (3) It is handled and prepared in the same way as any other food ingredient

Problems in jam making involve:

- Crystallization: The finished jam must have 30–40% glucose or invert sugar to avoid crystallization of cane sugar during storage.
- Sticky or gummy jam: 55 parts of sugar is necessary for every 45 parts of fruit. Due to the high % of total soluble solids (TSS), jams tend to become sticky or gummy.
- Premature setting: This is because of high pectin content and low soluble solids in the jam and hence could be avoided by incorporating more sugar.
- Microbial spoilage: Occasionally molds can spoil jams during storage (Table 13.5).

13.6.3 Jelly

Jelly is semi-solid product, made by boiling (at about 105 °C), clear, strained solution of pectin containing fruit extract, free from the pulp, after the incorporation of acid and sugar till it sets. A perfect jelly must be well set, transparent, but not stiffer and must possess unique flavor of the fruit. It must be of attractive color and should keep its shape even when it is removed from the mould. It must be stable

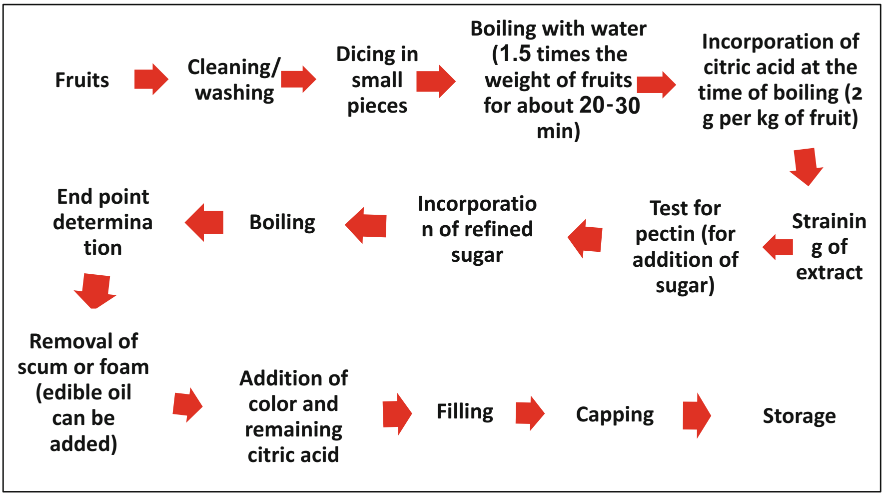


Fig. 13.6 Flow sheet for preparation of jelly

enough to keep a sharp edge. It must not be gummy, syrupy, or sticky or have crystallized sugar. It must be free from dullness, with no syneresis and should have 45% of fruit juice, TSS 65%, and 0.5–0.75% acid.

As per the pectin and acid contents, fruits are grouped as:

1. Rich in pectin and acid: Grape, sour and crab apple, sour guavas, jamun, plum (sour)
2. Rich in pectin but low in acid: Unripe banana, apple (low-acid varieties), ripe guava, fig (unripe), pear, sour cheery, peel of grapefruit and orange
3. Low in pectin but rich in acid: Sweet cherry, apricot (sour), sour peach, pineapple, strawberry
4. Low in pectin and acid: Pomegranate, ripe apricot, raspberry, strawberry, and various overripe fruit

Important Considerations in Jelly Making

Sugar (65%), acid, pectin, and water are the four vital elements for the jelly. Pectin test and endpoint of jelly are the significant parameters. The preparation of jelly is shown in Fig. 13.6.

13.6.4 Pectin

Pectin substances existing in the form of calcium pectate are accountable for the firmness of fruits. It is considered as an integral part for jelly. Pectin under appropriate conditions forms a gel with acid and sugar.

13.6.4.1 Pectin Preparation

Pectin is a structural heteropolysaccharide present in the primary cell walls of terrestrial plants. It is manufactured commercially as a white to light-brown powder. It can be extracted from citrus fruits or its peel such as passion fruit, lime, orange, and lemon or from apple "pomace" (material remaining after juice is extracted).

In pectin extraction, peels are cut into thin slices (1cm width) and other fruits are coarsely chopped. They are added to 8:1 ratio (raw material:water) and heated gently (simmered) for 20–30 min. This extracts pectin and also removes water to concentrate the pectin. However, overheating can degrade the pectin quality and loss of its gelling power. The extracted pectin can be stored for few days. The peels are then removed and the pectin solution can be used as an ingredient in various food preparations such as jam/jelly making. The pectin is extracted under reflux using acidified water (97°C for 30 min). The pulp is then removed from the acid extract using cheese cloth as the filtration medium. The filtrate is then cooled (4°C) followed by precipitation by using twice the volume of ethanol. The mixture (solvent and precipitate) is then mixed till the pectin floats. Pectin is filtered by cheese cloth or centrifugation followed by drying, as shown in Fig. 13.7.

13.6.4.2 Determination of Pectin Content

The pectin content of the extract can be estimated by alcohol test and jelmeter test:

1. Alcohol test: In this method, precipitation of pectin with alcohol occurs in a beaker, one teaspoon of drained extract is obtained, which is cooled down, followed by three teaspoons of methylated spirit that are added along the side of the beaker followed by rotating the mixture and then held for several minutes. (a) An individual, crystal clear mass or coagulum is created in case the extract consists of significant pectin. An equivalent amount of refined sugar has to be put into the extract to make jelly. (b) When the extract possesses average amount of pectin, then the coagulum will likely be less firm and disconnected. Three-fourths the amount of refined sugar has to be incorporated. (c) If the extract consists of significantly less pectin, several smaller-sized granular coagula is going to be developed. One-half the amount of refined sugar has to be included.

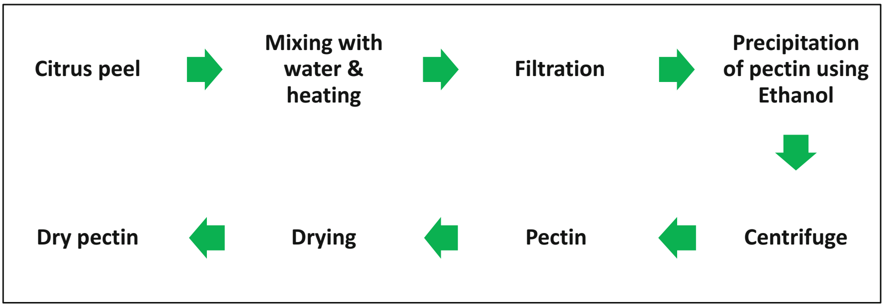


Fig. 13.7 Flow chart for pectin extraction

2. Jelmeter test: In this test, the equipment is hold in the left hand by using the forefinger and thumb. The base of jelmeter tube is shut with the tiny finger. The extract is put into the jelmeter using a scoop and held in right hand, till it is stuffed up to the top. Following this, the tiny little finger is gradually taken off the base and the extract is allowed to trickle for a moment, and after that, the little finger is placed back once again. Reading of the jelmeter is determined.

13.6.5 Marmalade

Marmalade is actually a fresh fruit jelly in which pieces of fruits or its peel are suspended. The word marmalade is generally used for the food products, prepared from lemons and oranges where the tattered peel is utilized as suspended ingredient. Marmalades are categorized into (a) jelly marmalade and (b) jam marmalade.

1. Jelly marmalade: The excellent quality of marmalade can be obtained from:
   a. Orange (Malta)/mandarin orange/sweet orange, khatta or sour orange *(Citrus aurantium*), and galgal *(Citrus iimonia*) are used in the proportion of 2:1 by weight. Scraps of Malta orange peel are used.
2. Jam marmalade: The making is similar to jelly marmalade. In this preparation, whole fruit pulp is used. Sugar is incorporated conferring to the weight of fruit, usually in the ratio of 1:1. The pulp–sugar mixture is prepared till the TSS content reaches 65%. The preparation of marmalade is shown in Fig. 13.8.

13.6.5.1 Problems in Preparation of Marmalade

The browning reaction during the storage is a common phenomenon that can be stopped by using 0.09 g of KMS per kg of marmalade and not filling in tin containers [35]. KMS is liquefied in a small amount of water, which is then incorporated to the marmalade while cooling. KMS also assists to stop the decomposition due to molds.

Table 13.6 shows the detailed specifications for jams, jellies, and marmalades laid down by the Food Safety and Standards Authority of India [20].

13.7 Peeling of Fruits and Vegetables

The removal of peel from fruits and vegetables is one of the important unit operations for the different value-added products. Peel contains various nutrients (fiber, antioxidants, vitamins, minerals, etc.); therefore, it can be utilized as by-product in various food products. The raw apple with skin contains about 1.5 and 3 times more vitamin A and K, respectively; unpeeled boiled potato has 70% more vitamin C as compared to peeled boiled potatoes.

The different devices and machines used for peeling are described as follows:

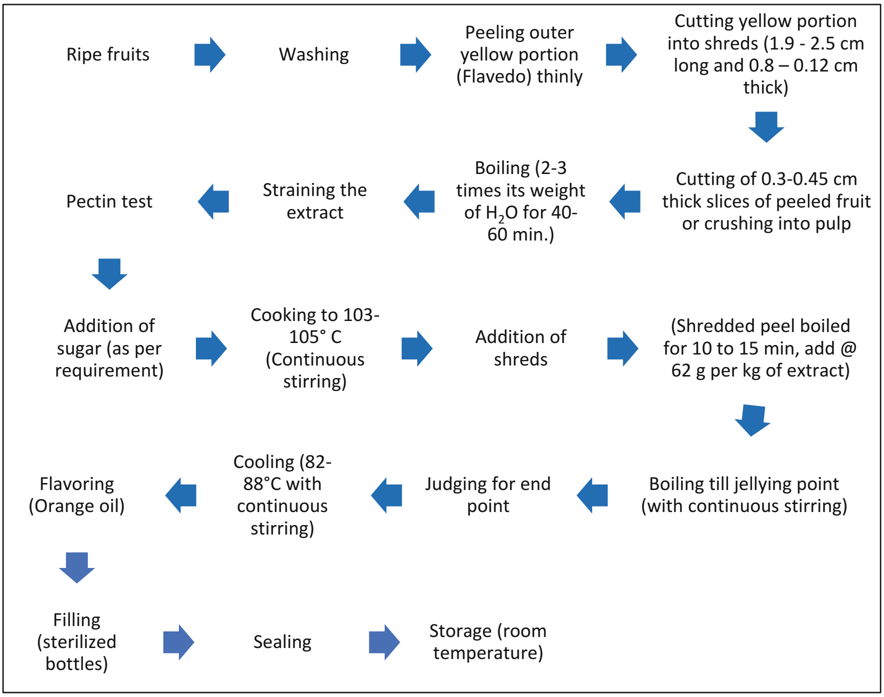


Fig. 13.8 Flow sheet for the preparation of jam/jelly marmalade [34]

Table 13.6 Microbiological limits [23] of food products (jams, jellies, and marmalades)

Microorganism	Permissible limits
Mold count	Positive in not more than 40.00% of the field examined
Yeast and spores	Not more than 125 per 1/60 mm^3
Escherichia coli	Absent in 1 g/ml
Staphylococcus aureus	Absent in 25 g/ml
Shigella	Absent in 25 g/ml
Salmonella	Absent in 25 g/ml
Clostridium botulinum	Absent in 25 g/ml
Vibrio cholerae	Absent in 25 g/ml

13.7.1 Knife Peeling

The manual knife is used to peel the skin from fruits and vegetables. The sharp edge is forced tangentially on the vegetables, which removes the peel in a thin layer. The effectiveness of peeling is dependent on the sharpness of knife, thickness and hardness of peel, and expertise of the workers. Turning knife is a flat knife and the blade is curved to ease the peeling operation. The slotted peeling knife has a thin

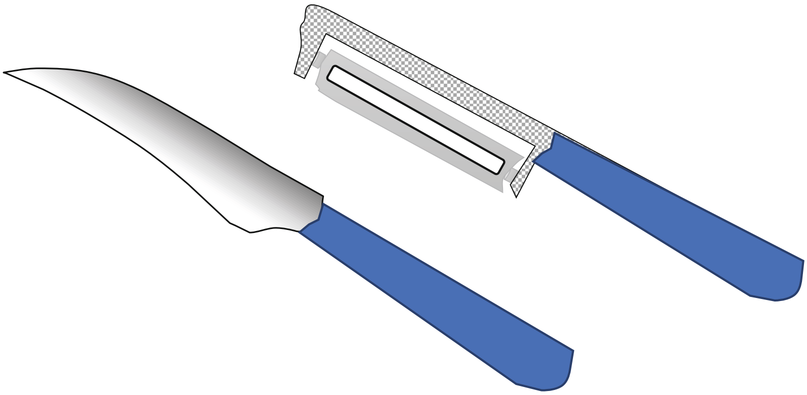


Fig. 13.9 Knives: (i) turning knife and (ii) slotted peeling knife

blade, which is pivoted on the head and base that allows free movement of the blade on the surface of fruits or vegetables for effective peeling (Fig. 13.9).

The slotted peeling knife performs better than turning knife as one edge slides over the surface of fruits and vegetable and maintains a thin layer of peel through the slotted space provided in the knife. While the peel layer in turning knife depends on the expertise of the worker.

13.7.2 Mechanical Knife Peeling Machine

These machines have circular plate, which is rotated in a clyndirical vessel. These are used in batch operations and suits well for potato peeling. The peeling of the product depends on the rotating speed, raw material, and duration of peeling operation. The removeable blades may be increased/decreased and may differ in size to increase the efficiency. The peeling effectiveness can also be improved by adjusting the blades. The drum also have rubbery wall to minimize the bruises and loss. Projection with small heights on the plates is also provided for providing tumbling action and controling the thickness of peel (Fig. 13.10). These machines operate with 1 horsepower motor and are available in 10–20 kg/h capacity.

13.7.3 Abrasive Peeling Machine

The abrasive peeling machine works on the principle of rubbing the surface of fruits and vegetables with the abrasive surface. The machine has base, which has housing for motor and related parts necessary for rotating the abrasive plate. The material is fed into the cylinder (Fig. 13.11(i)). The plate also has projections to provide tumbling action to the material fed inside the cylinder (Fig. 13.11(ii)). The flow of water is also provided to remove the torn skin from the cylinder abrasive surface and

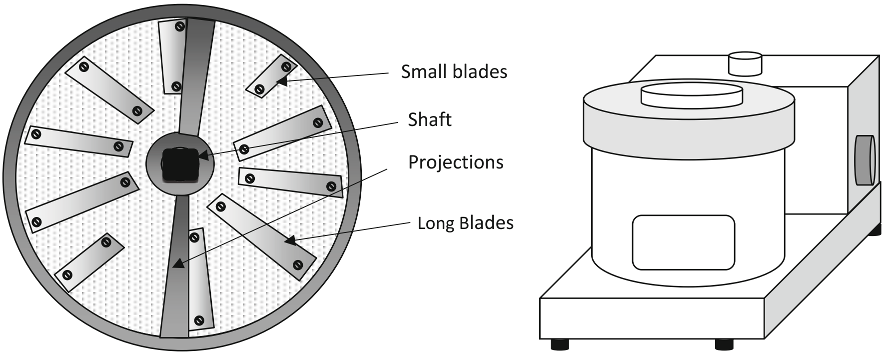


Fig. 13.10 Knife disc of mechanical knife peeling machine

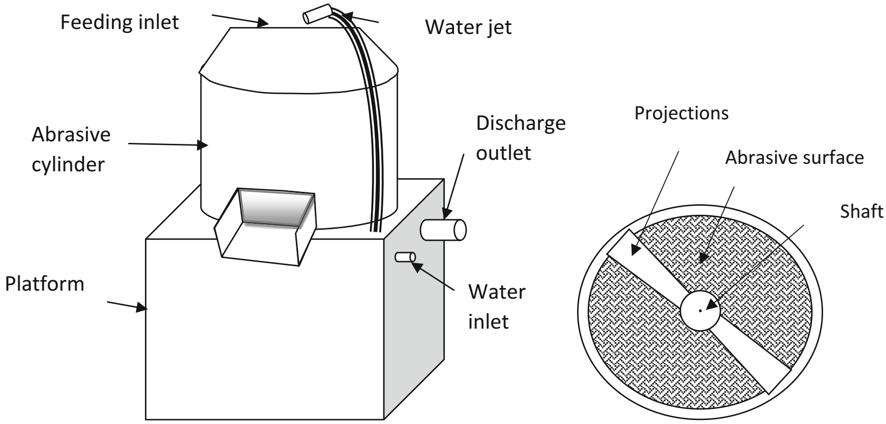
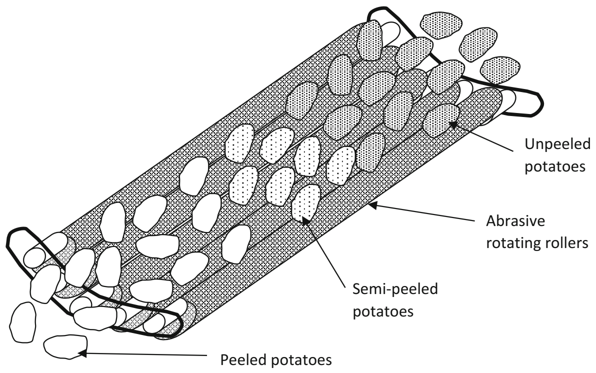


Fig. 13.11 (i) Abrasive peeling machine and (ii) abrasive disc

make the vegetable surface clean. The effectiveness of the cleaning machine can be controled by speed of rotation, feed rate, and cleaning time. These are operated with 1–3 hp motors and are available in 5–30 kg/h capacity.

Another version of abrasive peeler has a number of rotating abrasive rollers, which are arranged in such a way to create a channel (Fig. 13.12). The fruits or vegetables to be peeled are fed in the channel with rotating rollers, which moves due to the slope provided. The material gets scratching action and the peeled material is obtained at the outlet. The speed of operation, slope of rollers, and feed rate affect the peeling efficiency. These are available in large handling capacity of 3500 kg/h and can work in continuous operations.

Fig. 13.12 Abrasive roller peeler



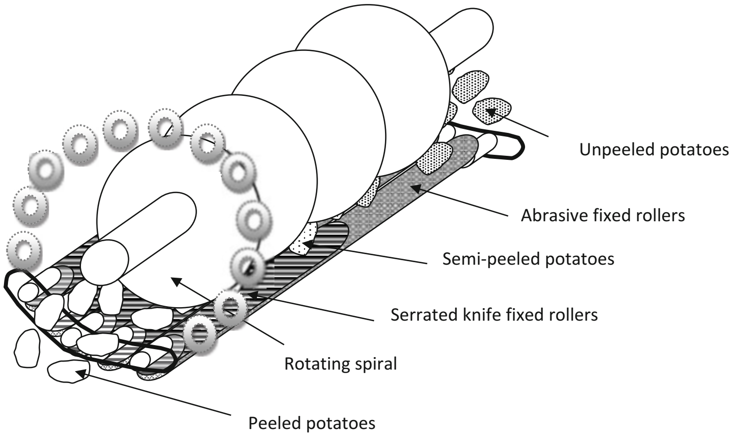


Fig. 13.13 Combi (abrasion and knife) peeler

13.7.4 Combination Peelers

The abrasive surface rollers can also be modified to have stainless steel–based sharp-edged rollers, which provides knife action for peeling the material. The material peeled by this peeler provides clearer surface than abrasive peeler. The abrasive surface rollers may remain fixed, and spiral/auger moves the material from inlet to outlet (Fig. 13.13). The rollers are placed to form a circular drum for movement of the material. These are compact and have a capacity of about 600–1100 kg/h.

13.8 Cutting of Fruits and Vegetables Using Knife

The fruits or vegetables should be supported well with the fixed platform and should remain strong and able to resist the cutting. The failure may occur due to impact or shear stresses or it can be combination of both. In general, material is compressed, which induces bending as a deformation initially.

13.8.1 Mechanism

The organic matter has got more flexibility and the molecules have got binding through weak interactions such as van der Waals forces and hydrogen bonding; therefore, cutting is a straightforward process. The knife with straight edge blade, in general, is held perpendicular to the fruits/vegetable surface, and force is applied to push under the applied force, F. The material starts to deform and indent of the surface is formed up to the maximum thickness δ till the cutting initiates. The deformation (δ) may show the plastic or elastic behavior, which depends on the type of fruits or vegetables. As the knife moves further, a crack is started, and blade moves into the material, and force is increased till a steady state is obtained. The length of cut in the material is denoted by h. As the knife is removed from the material, the deformation (δ) is usually recovered, and effective cut remains equal to distance h (Fig. 13.14).

The cutting force can be represented using stiffness graph with cutting distance travelled by the knife (Fig. 13.15). Initially, the stiffness increased up to certain

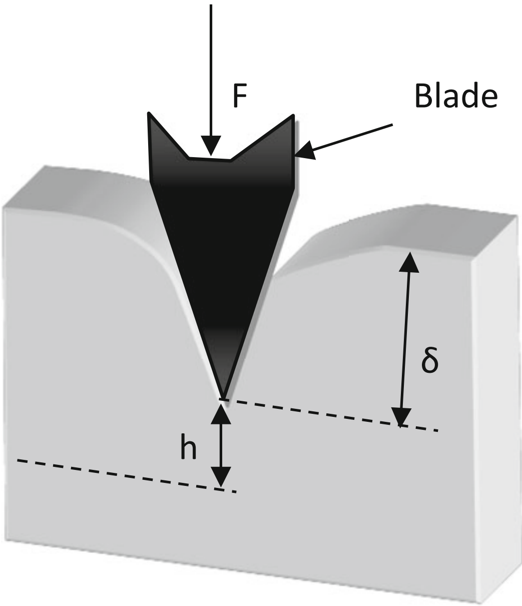


Fig. 13.14 Cutting force and strain

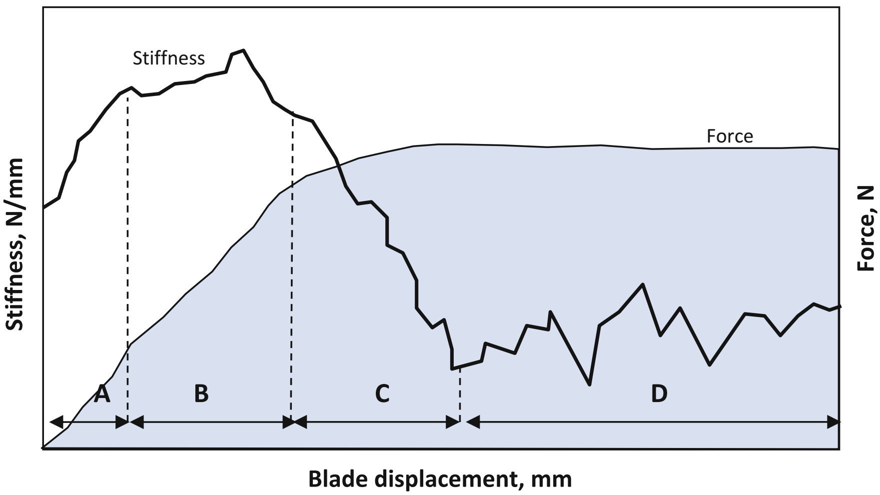


Fig. 13.15 Variation in stiffness with distance while cutting a material using knife

stiffness, which is an indicator of increase in force induced for the indentation on the material (A). After the initiation of the cut, the stiffness remains constant, which represents a new surface is created due to cut of fruits or vegetables, and almost similar stiffness is observed in this region (B). Thereafter, stiffness reduces as now the knife moves ahead to cut the remaining material, while the material surface regains almost its initial shape, and this indicates a decrease in stiffness (C) till the steady state of the cutting force is achieved (D).

13.8.2 Knife Effectiveness Parameters

13.8.2.1 Indentation Parameter

This parameter is measured by applying equal amount of stress and measuring the indentation made in millimeters on specific fruits or vegetables with similar physical characteristics. The higher value of indentation indicates higher sharpness of knife in comparison to other knives. This parameter is used by dropping a knife till the average depth of indentation/depression is achieved.

13.8.2.2 Blade Sharpness Index (BSI) Parameter

This is measured by moving a knife at a constant speed and measuring the force and can be estimated using the following expression [36]:

$$\mathrm{BSI} = \frac{\int_0^{\delta_i} F(x)\, dx}{\delta_i \times J_{IC} \times t}$$

$$\text{BSI} = \frac{E_i}{\delta_i \times J_{IC} \times t}$$

where $F(x)$ is the force at the indentation of x, N; δ_i is the distance from top to the point of indentation till the cutting initiates, mm; J_{IC} is the fracture toughness of material, kJ/m^2; and t is the thickness of material, mm. The fracture toughness is an intrinsic property of the material, and it is equal to the amount of energy required to create a unit area of cut surface. The facture toughness can be estimated by cutting test in steady state:

$$J_{\text{IC}} = \frac{(X - P) \times u}{A_{\text{knife}}}$$

where X is the force applied during steady-state cutting, N; P is the force applied during cutting of the material in the second run at the same location of the first cut, N; u is the distance of indentation, mm; and A_{knife} is the area of surface in contact, mm^2. The blade sharpness index (BSI) of sharp blades of knife remains smaller than the blunt blades in a similar set of conditions. Therefore, sharpness of two blades can be compared for cutting specific fruits and vegetables.

Q4. A sharp knife is used to cut a vegetable; the $\delta_i = 2.03$ mm, $J_{\text{IC}} = 3.67$ KJ/m^2, $E_i = 3.87$ N mm, and $t = 2.25$ mm. Estimate the blade sharpness index of the knife used for cutting the vegetable.

Ans.

$$\text{BSI} = \frac{E_i}{\delta_i \times J_{\text{IC}} \times t}$$

$$\text{BSI} = \frac{3.87}{2.03 \times 3.67 \times 2.25} = 0.231$$

Q5. A blunt knife is used to cut a vegetable; the $\delta_i = 4.07$ mm, $J_{\text{IC}} = 3.67$ KJ/m^2, $E_i = 9.9$ N mm, and $t = 2.25$ mm. Estimate the blade sharpness index of the knife used for cutting the vegetable.

$$\text{BSI} = \frac{E_i}{\delta_i \times J_{\text{IC}} \times t}$$

$$\text{BSI} = \frac{9.9}{4.07 \times 3.67 \times 2.25} = 0.525$$

13.8.3 Cutting Device: Knife

A knife is used in peeling, cutting, slicing, and dicing of fruits and vegetables. Knives are ancient tools known and used by the people from the time immemorial. Initially, these were fabricated using sharp stone, bones, and stones. Over the period

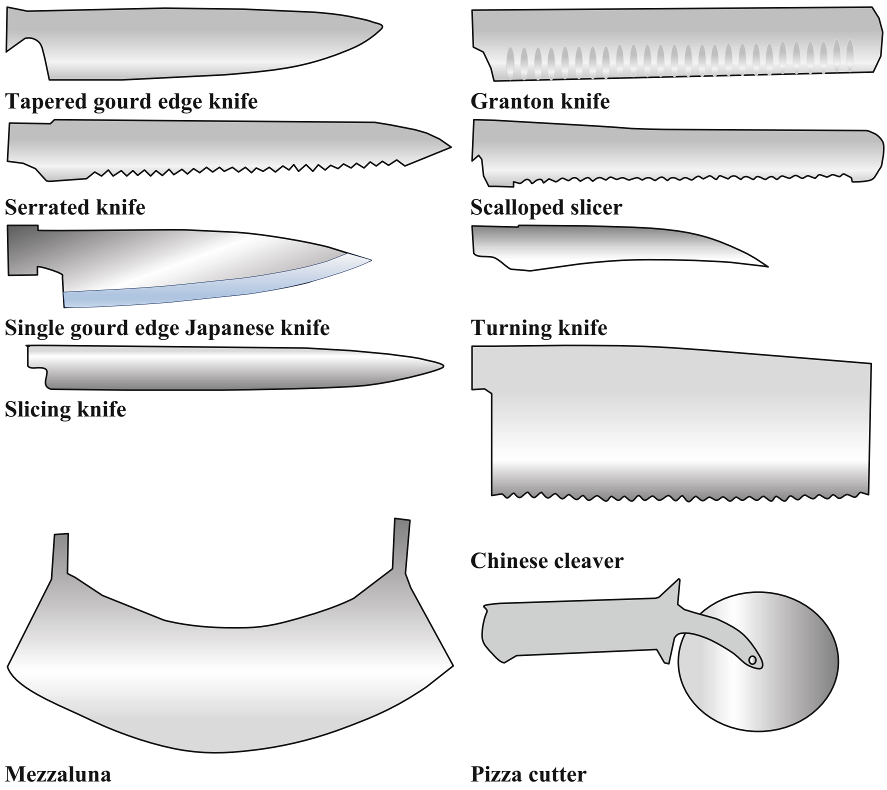


Fig. 13.16 Types of knives for cutting and peeling operations

of time, these are generally made of steel; however, the pattern and styles vary according to the use or origin (Fig. 13.16) [37].

13.8.3.1 Types of Knife

Tapered Ground Edge Knife

The tapered ground edge knife has a thin and long blade, which is tapped from spine to cutting edge. This is also known as general purpose knife and is popular in slicing and chopping of fruits and vegetables.

Granton Knife

This knife has identical oval depression/identical dimples on each side of the knife blade. It has straight edge similar to the general purpose knife. The air pockets are formed while cutting of material, which do not allow the material, especially spongy textured material, to stick on the blade of knife. These work well for moist food material.

Serrated Knife

A serrated knife has a number of sharp teeth on the cutting edge of the blade. The distance between two consecutive teeth may vary according to the requirement. If the serrations are very close, these appear as V-shaped serrations, and in the case of distant serrations, these appear as U shaped. The knife has advantages in cutting the tough skins, e.g., tomatoes, cucumber, breads, etc., for slicing operation.

Scalloped Slicer

These knives are longer than serrated knife and do not have conical tip. The tip is also not pointed. These blades remain sharp for longer durations. The teeth also help to protect the cutting edges. These remain ideal for large fruits, e.g., melons, breads, and cakes.

Single Ground Edge Japanese Knife

These knives are sharp, hard, and brittle. These have supreme edge, which is protected by the hard spine for providing stability. The cutting edge remains exposed to the material and provides great strength and stability. These are beveled on one side only and usually sharpened using waterstones.

Turning Knife

This knife has a short, curved blade and known as peeling blade. This works well in peeling the round-shaped fruits and vegetables. The tip of the knife is being used for carving various shapes.

Slicing Knife

These knives are thin with a pointed tip. These are used for cutting slices of cooked fruits and vegetables. These are also used for slicing cooked or smoked meat, poultry, and fish.

Chinese Cleaver

Chinese cleavers have large rectangular blades. These are available in various blade thicknesses. Thin blades are used for fine slicing of vegetables; however, thick blades are used for butchery. These are used for slicing, chopping, and mincing of ingredients, e.g., garlic cloves.

Mezzaluna

Mezzaluna has single or double blades and is used to chop the coriander, mint bunches, and garlic cloves effortlessly. This is preferred for providing tireless chopping. It has a curved blade, which is used to rock safely to chop the soft and hard ingredients. Usually, large handles are provided on both sides. More ingredients can be handled in double-blade-based mezzaluna. These are also preferred for preparing topping of the food recipes. The cutting is performed by rocking it backward and forward till the chopping is achieved.

Pizza Cutter
These are made of stainless steel and are generally popular for cutting pizza smoothly and swiftly, which provide less contact area with the sticky materials. A safety ground with handle is usually provided.

13.9 Exercise

1. State the importance of fruits and vegetables in diets.
2. What is the role of blanching in processing of fruits and vegetables? State its effect on the processing and storage stability of the finished product.
3. What is difference among MTLT, MTST, HTLT, and HTST thermal processing technologies? Explain in brief.
4. A food is heated up for 20 and 25 min at 110 °C. The numbers of survivors are 4600 and 160, respectively. Determine D-value. The prior experiments reported the lag time as 0.5 min. [Ans.: 3.43 min]
5. D_0 value for a microorganism is 1.5 min. What is the heating time required to reduce given microorganism from 10,000 to 10 at 121.1 °C? [Ans.: 270 s]
6. Calculate the processing time required for 12 log cycle reduction of *Bacillus stearothermophilus* microorganism at 130 °C. The D-values at 121.1 °C and 140 °C are 1.2 min and 0.02 min, respectively. [Ans.: 2.09 min]
7. F_0 for a microorganism is 2.6 min. If each container contains 10 spores having a D_0 of 1.206 min. What will be the possibility of spoilage? [Ans. 7 in 100 cans]
8. Find equivalent process time, at 101 °C, which will deliver the same lethality as the required F_{121} value of 5 min (Z-value = 10 °C). [Ans. 500 min]
9. Write the advantages and limitation of spray drying. Also, explain the working of spray dryers.
10. Write various processes involved in canning of fruits and vegetables.
11. Draw a flow process for aseptic processing and discuss its advantages.
12. What are advantages of using high pressure processing over thermal processing?
13. Discuss the use of various freezing processes involved in fruits and vegetables.
14. Which chemicals are used for preservation of fruits and vegetables? Discuss their uses as per FSSAI guidelines.
15. Which changes occurred during processing of fruits and vegetables? Discuss in brief.
16. Draw process flow diagrams for pickling/mango pickle and explain the process in detail.
17. What is pectin and how is it prepared from fruits and vegetables? Discuss in detail.
18. What are the problems faced during the marmalade preparation?
19. Which equipment or tools are used for peeling operation? Explain their working with a suitable sketch.
20. Discuss the cutting mechanism by a knife and how effectiveness of knives is being measured.

21. Estimate the blade sharpness index of the knife used for cutting the vegetable, if the distance from top to the point of indentation till the cutting initiates is 1.03 mm. Fracture toughness of material = 1.67 KJ/m^2, E_i = 2.87 N mm, and thickness of the material = 3.25 mm. [Ans.: BSI = 0.513]
22. Draw diagrams of various knives used for cutting of fruits, vegetables, and value-added products and explain their working.

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Appendix A

Table A1 Selection for the type of bucket elevator according to food material

S. No.	Food material	Bulk density/ kg/m^3	Belt/ chain	Type of elevator
1.	Baking powder	800–900	Chain/ belt	Positive discharge or continuous
2.	Barley	600	Chain/ belt	Positive discharge or continuous
3.	Castor beans	580	Chain/ belt	Centrifugal discharge or continuous
4.	Coffee	350–510	Chain/ belt	Centrifugal discharge or continuous
5.	Corn		Chain/ belt	Centrifugal discharge
(a)	Cracked	680–720		
(b)	Sugar	500		
(c)	Meal	600–640		
6.	Cotton seed			
(a)	Dry and delinted	400	Belt	Centrifugal discharge
(b)	Dry with lint	290–400		
(c)	Cracked or cake	640–720	Belt/ chain	
(d)	Hulls	190		Continuous
(e)	Meal	560–640	Chain	Centrifugal discharge
(f)	Meats	640		
7.	Flaxseed		Belt/ chain	Centrifugal discharge
(a)	Cake	780–800		
(b)	Meal	400		
8.	Wheat flour	560–640	Belt	Centrifugal discharge
9.	Ice—crushed	560–720	Chain	Centrifugal discharge or continuous
10.	Linseed meal	680	Belt/ chain	Centrifugal discharge

(continued)

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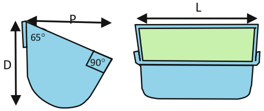
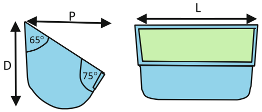
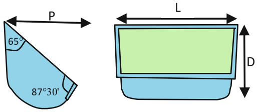
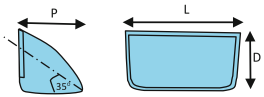
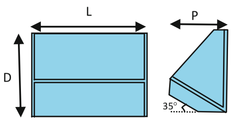
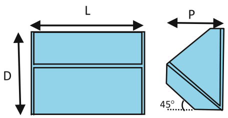
Table A1 (continued)

S. No.	Food material	Bulk density/ kg/m^3	Belt/ chain	Type of elevator
11.	Malt		Belt/ chain	Centrifugal discharge or positive discharge
(a)	Dry and ground	320–335		
(b)	Dry and whole	430–480		
(c)	Meal	570–640		
(d)	Wet and green	640–720		
12.	Rice		Belt/ chain	Centrifugal discharge
(a)	Bran	320		
(b)	Grifts	670–720		
13.	Salt		Belt/ Chain	Centrifugal discharge or continuous
(a)	Dry fine	1120–1280		
(b)	Dry coarse	720–800		
14.	Soybean			Centrifugal discharge
(a)	Cracked	510–580	Chain	
(b)	Flour	430	Belt	
15.	Starch	720	Belt	Centrifugal discharge or continuous
16.	Sugar beet			
(a)	Dry pulp	170–240	Chain	Positive discharge or continuous
(b)	Wet pulp	400–720	Chain	Continuous
17.	Sugar			Centrifugal discharge
(a)	Raw	880–1040	Belt/ chain	
(b)	Refined	800–880	Belt/ chain	
18.	Wheat—cracked	640–720	Belt/ chain	Centrifugal discharge

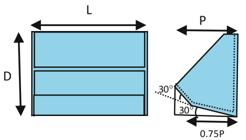
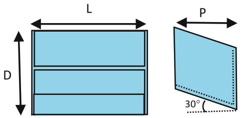
Reference: Indian Standards (1974). Code for selection and use of bucket elevators, IS 7167: 1974, Indian Standard Association, New Delhi, India

Table A2 Type of buckets, specifications, and recommended applications

Bucket designation	Design/description	L (mm) × P (mm) × D (mm)	Capacity, liters	Recommended application	Elevator type
A1		150 × 95 × 100 to 1000 × 250 × 260	0.87–36.50	Powdered, free flowing material	Centrifugal and positive discharge
A2		150 × 100 × 110 to 1000 × 255 × 270	0.87–38.0	Pulp and chemicals	Centrifugal and positive discharge
A3		150 × 90 × 130 to 410 × 165 × 230	0.71–6.80	Wet and sticky material or coarsely broken food material	Centrifugal and positive discharge
A4		150 × 115 × 100 to 410 × 180 × 140	0.735–4.470	Sugar, salt, and pulverized material	Centrifugal and positive discharge
B1		150 × 75 × 145 to 610 × 300 × 460	0.81–41.0	Pulverized and sluggish material on inclined elevators	Continuous
B2		150 × 75 × 145 to 610 × 300 × 460	0.81–41.0	Average material for vertical elevating	Continuous

(continued)

Table A2 (continued)

Bucket designation	Design/description	L (mm) × P (mm) × D (mm)	Capacity, liters	Recommended application	Elevator type
B3		150 × 75 × 145 to 610 × 300 × 460	0.93–48.6	Material with large lumps	Continuous
B4		150 × 75 × 145 to 610 × 300 × 460	0.81–41.0	Not more than 70° inclination from horizontal	Continuous

Where L length, W width, P projections

Reference: Indian Standards (1973). Specification for bucket and bucket elevators, IS 6883: 1973, Indian Standard Association, New Delhi, India