Chapter 4
Mechanical Processing Equipment

4.1 Introduction

Size reduction or enlargement of solid foods can be attained by mechanical methods, without use of heat. Size reduction refers to the production of large or small pieces and several particle sizes. Enlargement includes agglomeration or coating of small food pieces or particles, which may be facilitated by adding small quantities of liquids or steam. In the case of liquids, size reduction of particles is achieved in the homogenization. The following sections, Sects. 4.2 and 4.3 deal with solid foods, while Sect. 4.4 deals with size reduction of liquids. Finally, mixing refers to liquid and solid foods and formation in operations dealing with extrusion and other processes giving the final shape/form of foods.

4.2 Size Reduction

4.2.1 Introduction

In size reduction, food is cut into large or small pieces of certain or random shapes, or it is reduced to particles down of the micrometer range. There are several methods of size reduction discussed by Lawrison (1974), Rumpf (1965), and Zogg (1987). Basic criteria in classification of size reduction processes are (a) the final size of size-reduced products, (b) the kind and way the forces are applied, and (c) the construction characteristics of size-reduction equipment.

Based on the final size of the products, the following main methods of size reduction are distinguished: (a) cutting, (b) crushing, and (c) grinding.

Considering the kind and way the main forces are applied, the following classification may be made:

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1. Main forces: (a) compression, (b) shear, and (c) impact. Quite often, various combinations of these forces are applied, such as bending (compression and tension), punching (compression and shear), or impact.
2. Application of forces: (a) pressure and/or friction of material placed between tool surfaces, (b) shear force on material, (c) collision between particles or impact between particles and tools, and (d) friction through medium surrounding the particles.

Based on the construction characteristics of equipment, size reduction may be classified according to the number of size reduction tools used and the kind of forces applied:

1. Use of two tools (compression of the material between two surfaces): (a) compression (e.g., presses), (b) compression and shear (e.g., gyratory crusher), (c) impact and shear (e.g., ball mill), and (d) shear (e.g., cutting)
2. Use of one tool (hitting the material with one tool): (a) impact (e.g., hammer mill) and (b) shear (e.g., attrition mill)
3. Size reduction through the surrounding medium (attrition of the material by nai air stream): (a) impact (e.g., counter jet mill) and (b) impact and shear (e.g., circular jet mill)

Figure 4.1 presents the different kinds of size reduction equipment and their range of application with respect to the end size of products. Details of the equipment of this figure are presented in the following sections of this chapter. As indicated in Fig. 4.1, the borders among the different categories of size reduction are not exact (Rumpf 1975; Perry and Green 1997; Zogg 1987). The following distinction of size reduction operations is suggested with respect to the final size of products:

(a) Breaking: >0.15 cm
(b) Crushing: 0.15 cm–8 mm
(c) Fine crushing: 8 mm–750 μm
(d) Milling: 750–50 μm
(e) Colloidal and fine milling: <50 μm

Food products can be classified as hard, e.g., nuts or bones, or soft, such as fat (Loncin and Merson 1979). Furthermore, distinction is made between strong and weak materials. A hard material can be, e.g., an egg shell, or a strong material (e.g., bones). It can be brittle (e.g., zwieback toast bread) or ductile (e.g., dough) (Fig. 4.2). Some foods, such as gums, are elastic, while others are viscoelastic (e.g., meat, raisins). However, most foods combine more strength characteristics, due to their original texture, to their biological character (no absolute similarity among foods is possible), and to the fact that processing, handling, and storage conditions influence their texture and strength.

The main forces applied during size reduction are compression, impact, shear, or combinations of these forces. Brittle materials are broken down to smaller pieces or particles easier than viscoelastic or elastic materials. Grindability is often used for

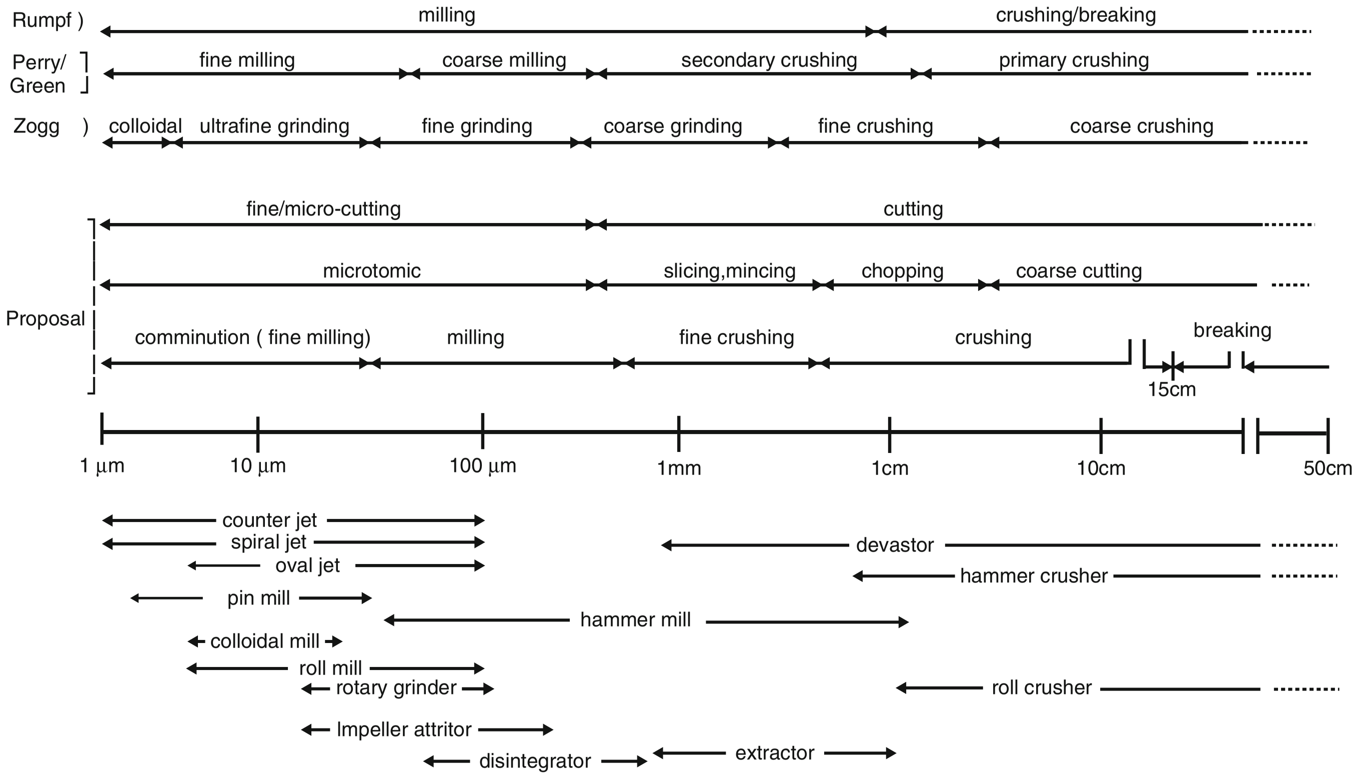


Fig. 4.1 Range of application of size reduction equipment. Data from Rumpf (1975), Perry and Green (1997), and Zogg (1987)

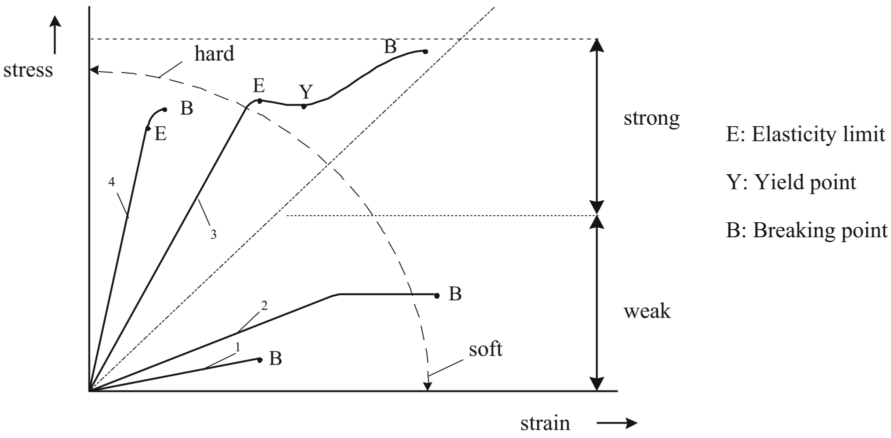


Fig. 4.2 Stress-strain diagram for foods

characterizing the rate of size reduction by a certain size reduction equipment (mainly mill). It is defined as the amount of product that meets the requirements of a particular specification (e.g., kg of product passing through a screen of certain mesh per hour) (Perry and Green 1997). Grindability is related to the modulus of elasticity and hardness. Therefore, hardness is often used in estimations of size reduction, which in turn is estimated according to the scale of Mohs. This scale is based on a bilateral comparison of hardness. A harder material engraves the next material in the scale. Table 4.1 gives the hardness of several materials.

Size reduction is important for the following reasons:

(a) Getting the size that specific products required (e.g., chocolate powder, sugar powder, meat slices, etc.).
(b) Increasing the specific surface. This facilitates several processes, such as heat exchange, extraction, and chemical and biological reactions (e.g., blanching, sterilization, freezing, extraction of seed oil, acidification).
(c) Enhancing mixing and blending (e.g., spices, confectionery, and fruit mixtures).
(d) Gaining certain products (e.g., juice by squeezing, flour from wheat grain).
(e) Facilitating transport (e.g., meat carcasses, exact weighing of powders) and proportioning (e.g., in preparation of ready meals).

The disadvantages of size reduction can be related to economic factors or the influence of the process on the sensory characteristics and the nutritive value of the products. Some negative aspects of size reduction are:

(a) Increased energy requirement (e.g., the finer the size reduction, the higher the energy requirement).
(b) The cost of equipment increases significantly with the size reduction and the cutting precision.

Table 4.1 Mohs hardness scale

Mohs hardness	Material	Category
10	Diamond	Hard
9	Corundum, sapphire	
8	Topaz	
7	Quartz, granite	
6	Feldspar, hornblendes	Medium hard
5	Bauxite, apatite	
4	Magnesite, limestone	
3	Marble, calcite	Soft
2	Gypsum, crystalline salt	
1	Talc, wax	

Data from Perry and Green (1997) and Loncin (1969)

(c) Changes in taste and flavor, e.g., due to increased oxidation of products (nuts) and color (bleaching of flour). These changes increase with the length of storage. Aroma loss, due to escape of volatiles, is caused by heat production during grinding.

(d) Loss of nutrients, e.g., vitamins during dicing or slicing of fruits and bran during polishing of rice.

(e) Influence on texture, e.g., softening due to increased enzyme activity or hardening due to juice loss, when cells are broken down, and *f*0 increase of microbial attack, such as due to increase of the product-specific surface and release of nutritive substances.

4.2.2 Cutting

4.2.2.1 General Aspects

Cutting is applied to ductile, viscoelastic, and elastic materials. Products of cutting are large pieces (e.g., meat), slices, diced products (e.g., small cubes of fruits), flakes, and pulps. The main forces exercised are shear forces. Distinction is made between cutting up and dissecting. Methods of cutting up are slicing and dicing, while examples of dissecting are shredding and carving. Cutting of food is performed by knives, saws, shears, and thin wires. Table 4.2 presents a classification of cutting equipment and tools. The selection of the right cutting tool depends on the product, its condition (e.g., fresh or processed), and the desired quality of the cut. Knives and other cutting tools can be portable for manual use, or they may be part of machines.

The factors influencing cutting depend on the method applied. There is quite a great difference between manual and automatic cutting. However, there are some factors that influence both kinds of cutting, such as (a) product to be cut, (b) sharpness of cutting tool, (c) cutting force, (d) direction of force applied, and (e) cutting speed.

Table 4.2 Classification of cutting tools

Basic type	Motion	Tool
Knife	One direction	Straight or curved knife
		Sickle
	Reciprocation	Straight knife
	Rotation	Disc
		Straight or curved knife, or sickle
Saw	Reciprocation	Knife
	Rotation	Disc
		Belt
Guillotine	Reciprocation	Inclined
	Rotation	Chopper
Wire	Fixed one direction	Single wire or system of vertical/horizontal wires
Shears	Shears	Parallel counter moving knives
Water jet	One direction	Water beam

The advantages of cutting processes are (a) wide product range of application (from meters to micrometers), (b) increasing the value added, (c) limiting of environmental pollution, and (d) screening out of undesired material that otherwise would burden processing.

The disadvantages of cutting processes are (a) large differentiation of required equipment; (b) skilled personnel; (c) low production per employee; (d) high safety requirements; and (e) frequent wear out of cutting tools.

At cutting, a relative motion between cutting tool and product is aimed. There are two main possibilities: (a) the cutting tool is fixed, while the product moves toward the tool, and (b) the cutting tool moves toward the fixed product that has to be cut. In some cases, both tool and product move in counter direction, increasing cutting effectiveness.

Basic element of almost all cutting equipment is the knives. When a knife cuts, two zones near the cutting edge are distinguished, the zone of plastic deformation, which lies directly on the cutting edge, and the zone of elastic deformation, which lies between the previous zone and the product (Fig. 4.3a). The effectiveness of cutting depends on the cutting edge (α) of a knife and the "cutting angle" λ, which is the inclination between the knife axis and the perpendicular to the cutting direction (Fig. 4.3b). Factors influencing the cutting edge are (a) the quality/hardness of metal, (b) the fineness (width, s) of cutting blade, and (c) the wedge angle, α (Fig. 4.3c). The finer a cutting blade and the narrower a wedge angle, the finer the cut. Nevertheless, due to strength and wear limits, there are also limits to the reduction of the width of knife blade and to the angle of its wedge.

Figure 4.4 indicates the forces exercised c and by a rotating disk knife. The force F during cutting depends on the normal force (F_N), the tangential force (F_T), and the cutting angle λ.

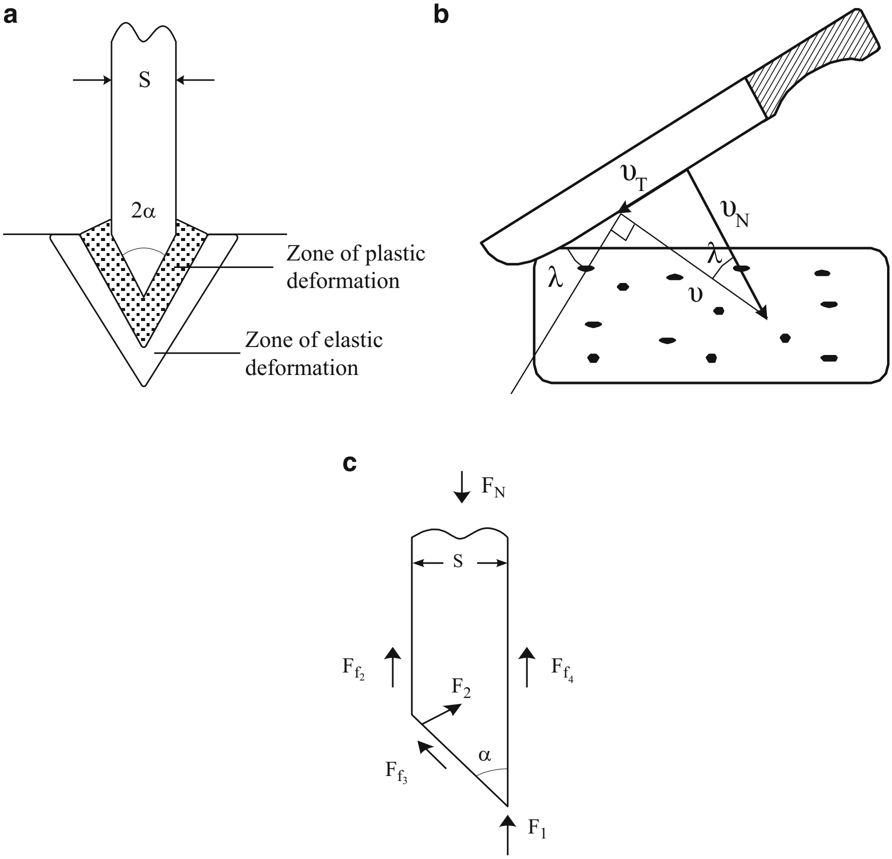


Fig. 4.3 Angles at knife cutting (see text)

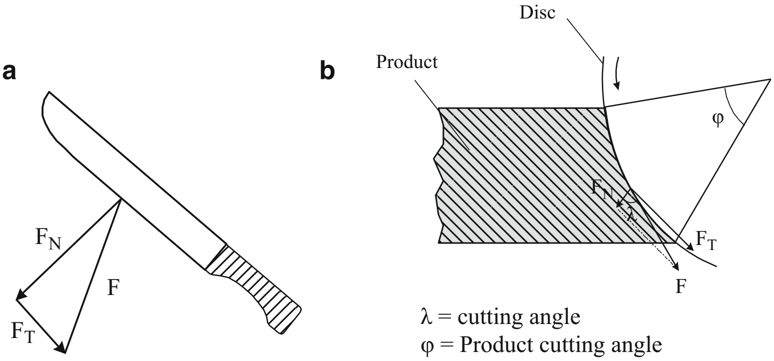


Fig. 4.4 Forces during cutting. (**a**) Hand knife; (**b**) cutting disk

Table 4.3 Specific cutting forces of foods

Product	Specific cutting force (N/m)
Cabbage	1000–1200
Onions	1700–1800
Potatoes (fresh)	600–700
Meat (fresh)	5000–8000
Meat (frozen)	23,000–30,000
Fat	10,000–15,000
Fish (frozen)	3200–3700
Apple	330

Data from Tscheuschner (1986)

$$F = \left(F_{\mathrm{N}}^2 + F_{\mathrm{T}}^2\right)^{1/2} \tag{4.1}$$

where $F_{\mathrm{N}} = F\cos(\lambda)$ and $F_{\mathrm{T}} = F\sin(\lambda)$. When $\lambda = 0$, the normal cutting force (F_{N}) is

$$F_{\mathrm{N}} = F_{\mathrm{f1}} + F_{\mathrm{f2}} + F_{\mathrm{f3}}\cos(\alpha) + F_2\sin(\alpha) + F_1 + F_{\mathrm{M}} \tag{4.2}$$

where

F_1, cutting resistance of the product; F_2, side force on the wedge of knife
F_{M}, force for displacing the product mass M during cutting
$F_{\mathrm{f1}} + F_{\mathrm{f2}} + F_{\mathrm{f3}} = F_{\mathrm{R}}$, friction forces on knife; and α, wedge angle of knife (see also Fig. 4.3)

According to Daurskij and Macihin (Tscheuschner 1986), the selection of the right type of cutting tool depends on the relation among the forces mentioned above:

(a) For cutting fresh meat ($F_1 \gg F_2$; F_{R}), the angle α must be small.
(b) For cutting butter or margarine ($F_{\mathrm{R}} \gg F_1$; F_2), a cutting wire is recommended.
(c) For cutting hard fat or chocolate ($F_2 \gg F_1$; F_{R}), the angle α must be small or another size reduction method must be chosen (e.g., grinding, milling).

Table 4.3 shows the specific cutting force of some foods, as discussed by Daurskij and Macihin (Tscheuschner 1986).

4.2.2.2 Cutting Tools

Cutting Elements

As indicated in Table 4.2, the basic cutting tools are knives, saws, guillotines, wires, and shears. Saws are effectively toothed knives. Guillotine is a type of knife related to choppers and shears, and it is composed of two knives. Therefore, besides knives,

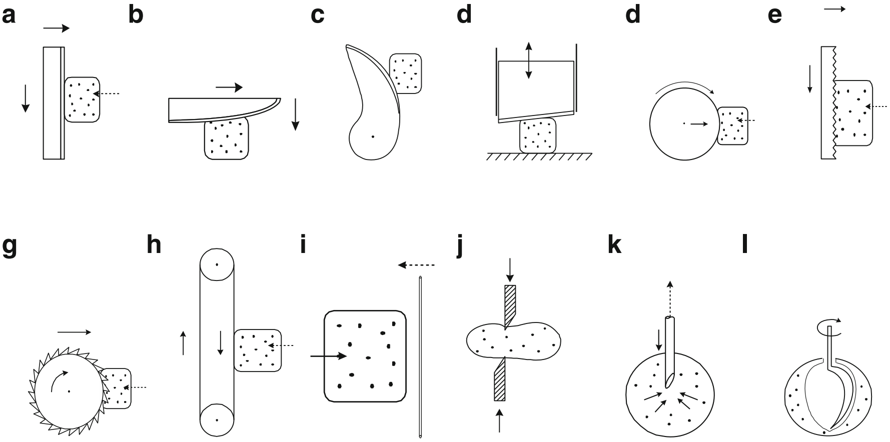


Fig. 4.5 Cutting elements (see text)

only wires constitute another basically different category of mechanical cutting tools. Figure 4.5 shows several cutting tools. As indicated in this figure, a simple knife may be straight (a) or curved (b, c). Knives can operate independently or they may be part of some other cutting mechanism, as in the case of shears (j), in which two knives swing parallel opposite to each other. The motion of simple straight and curved knives during cutting may be one way or reciprocating. However, there are also cases of simple knives rotating around their support at one end. Sickle knives (c) rotate or swing. Usually they have the form of a logarithmic spiral (Tscheuschner 1986). In some cases, as in meat cutters, two or more sickle knives are bound together to form a uniform knife system. In several cases, combinations of knives assembled in different ways (e.g., vertically or horizontally) cut products in certain form (e.g., cubes). For rotating knives (e), Tscheuschner (1986) recommends a ratio of disk diameter to disk thickness of 2.5/3.0. Saws (f, g, h) are either straight or have the form of discs. Straight saws reciprocate or saw in one direction only. This is the case when toothed band saws are used (h). These are especially used in cutting off relatively larger pieces of fresh meat or frozen products as meat and fish. They can be fixed or portable. Saws replace common knives, when the length of the actual cutting edge is significantly reduced. Guillotines (d) are oblique, thick blades slipping along guides. They are used in cutting large pieces, such as blocks of frozen food, in smaller ones. For safe use of guillotines, there is an OSHA regulation. Wires (i) are mainly used in cutting sticky products. Wire reduces the influence of adhesion, since its surface is smaller than that of blades. According to Daurskij and Masihin (Tscheuschner 1986) in the range of wire thickness $d = 0.1–1$ mm, the reduction of the required cutting power is proportional to the diameter of wires. Wire cuts better bread, producing less waste and crumb. Tube knives (k) may be used in boring food for sucking its juice. They are also used in removing blood from fresh slaughtered animals. Spiral or other types of knives

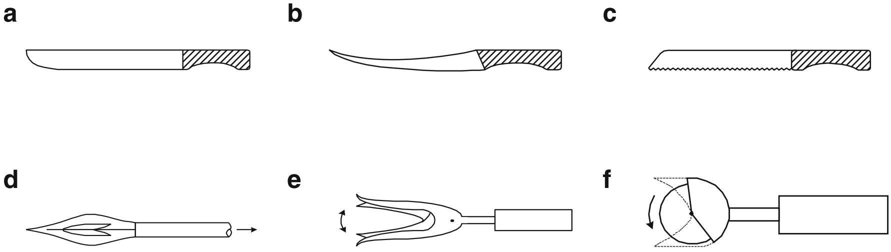


Fig. 4.6 Portable cutting tools. (**a**) Steak knife; (**b**) boning knife; (**c**) saw-toothed knife; (**d**) sticking knife; (**e**) bone knife; (**f**) cutting wheel

(l) are used in special operations as, e.g., cutting the flesh around clingstone peaches.

National and international safety standards/regulations exist for several cutting machines. Such regulations have been prepared by *OSHA* (e.g., 29CFR-1910.212 about safety measures concerning the guards of guillotines, cutters, shears, and saws). Further standards for safety and hygiene of food processing machines have been prepared by the European Organization for Standardization (CEN). The following CEN standards refer to cutting machines (prEN = provisional European standards):

(a) Slicing machines: No. prEN 1974
(b) Vegetable cutting: No. prEN 1678
(c) Rotating bowl cutters: No. prEN 12855
(d) Mincing machines: No. prEN 12331
(e) Band saw machines: No. prEN 12268
(f) Circular saw machines: No. prEN 12267

Portable Cutting Tools

Portable cutting tools for manual operation include knives, saws, and shears. Simple knives (Fig. 4.6) usually get their name from products they cut and operations in which they are involved (e.g., steak knife, boning knife, sticking knife). The blades are made by stainless steel. However, nowadays ceramic blades are also used. These as indicated in Chap. 2 may increase their corrosion resistance, cutting precision, and self-life of blades. Large portable cutting tools are electrical or air powered. In this case, since their weight may be significant, cutting tools are hung from a chain, connecting them to a swinging hoist mechanism, which secures a flexible operation in any position (Fig. 4.7). The weight of portable cutting tools varies between 1.5 and 2.5 kg. For safety reasons, parts of the blades and rotating discs and shears, not directly involved in the cutting, are covered. When tools are used in special operations (e.g., cutting of animal legs or horns), special covers are adapted for facilitating these operations (Fig. 4.6e, f). For portable and hand-operated food processing machinery and appliances, there are European

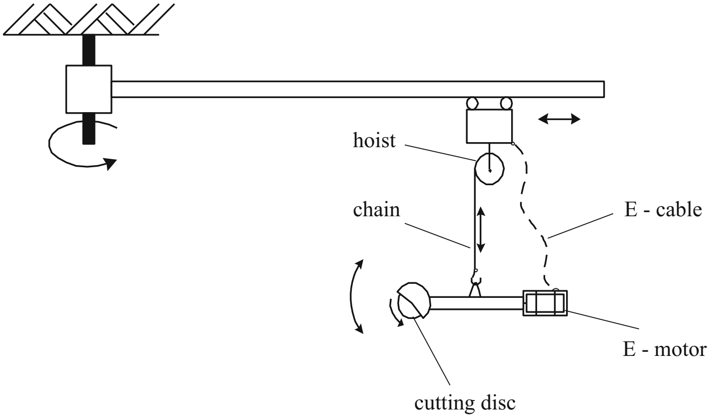


Fig. 4.7 Supporting mechanism of portable cutting tools

Table 4.4 Technical characteristics of portable cutting tools for meat

Cutting tool	Weight (kg)	Characteristic dimensions	Power	Remarks
Foot shear (pigs, lambs)	2.5	Clearance of open shear (70 mm)	Air, 140 bar	Speed (opening–closing of shear) (1–2 s)
Horn and leg shear (beef)	15	Clearance of open shear (120 mm)	Air, 220 bar	Speed of shear movement (2 s)
Saw disk (pig/lamb foot, brisk)	20	Disc diam. (280 mm)	Electric, 2 kW	Cutting depth (100 mm)
Disc saw (pig brisk)	20	Disc diam. (280 mm)	Electric, 2 kW	
Band splitting saw (beef)	60	Band length (500 mm)	Electric, 2 kW	Up to 60 beef per hour
Reciprocating breaking saw	7	Saw length (400 mm)	Electric, 1 kW	Splitting of all kind of animals

standards (CEN No. prEN 12984). Table 4.4 gives technical characteristics of some portable cutting tools, used in the meat industry.

Cutting Equipment

Most of size reduction machines are product specific. Special cutting machines have been developed for meat, fish, fruit, etc. Furthermore, even in the case of the same products, different types of machines are often used (e.g., peeling or cutting of fruits). In all cases, the previously described knives are basic elements of cutting equipment. The meat industry belongs to the food processing industries for which a great variety of machines has been developed. In some cases, such machines may be also used for other products as well (e.g., a meat cutter for cheese). A description of some common cutting machines is as follows:

Band Saws

Such machines are used for cutting frozen products in straight pieces (e.g., cutting fish blocks in fish fingers). Bands are usually stretched between an upper and a lower wheel, which is driven electrically. Cutting is done on a processing table by the front band. The height of the processing table is adjustable, and it can also be removed when more thorough cleaning is required. The width and length of cutting bands/blades varies with the type and dimensions of machines. Bands are automatically adjusted to the right tension. The band can be automatically cleaned up during operation and easily removed for further cleaning. The motor compartment is sealed off from the processing area. All parts of the band, except that in the cutting area, are covered for safety reasons. Indicative values for a band are length, 1.5–2 m; width, 1–2 cm; and thickness, about 0.05 cm. Power requirement is about 2.5 kW. The overall dimensions of such machines are 0.5 × 0.8 × 1.5 m, and their weight is about 0.5 ton.

Slicers/Dicers

Slicers cut products such as meat, ham, sausages, fish, cheese, fruits, vegetables, etc. into slices, whose thickness usually varies from 0.7 mm to 7 cm or even more. Slicers basically consist of one or more rotating discs or other kinds of knives, adjusted to cut products to the desired thickness. There are two possibilities: either the knives move toward the products (Fig. 4.8a) or the products move toward the knives (Fig. 4.8b). Products are fed automatically into slots or some other devices, lying below rotating knives that slice them. The thickness of a slice depends on the adjustment of knives. This adjustment can be controlled electronically (photocells, etc.), so that all slices maintain a more or less equal thickness, throughout the cutting of a whole piece. In advanced machines, an automatic correction of the slicing thickness, based on the remaining piece, guarantees little end cut loose.

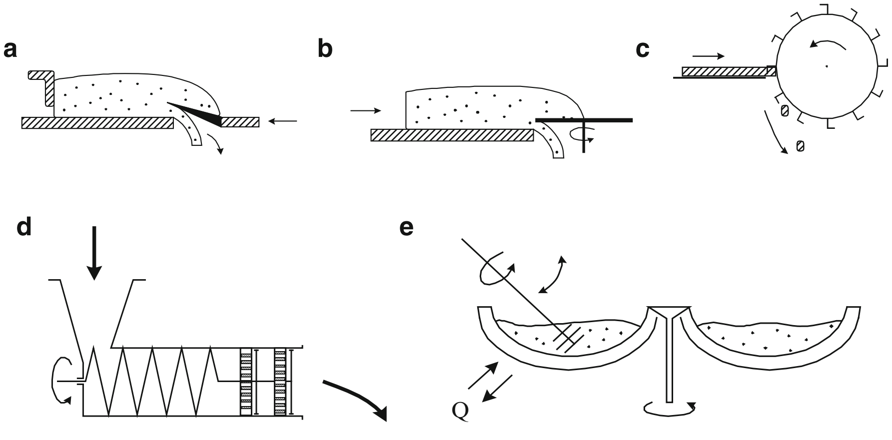


Fig. 4.8 Cutting equipment (see text)

Cutting quality is influenced by the speed of cutting, the product consistency, its temperature, and the quality of knives. The speed can be varied. Excessive speeds do not give good cut. Soft products have to be cooled down, if even and clean cuts are required. In cutting fresh beans by disk knives, a speed of 1500 rpm can be applied. For meat cutting, e.g., the optimal temperature lies between -5 and 5 °C. Sharpness of knives is very important. If knives are not sharp or well adjusted, splintering of bones may take place, when cutlets or chops are cut.

The capacity of slicers may be up to 500 cuts/min. Their power requirement is 2.0–2.5 kW. The overall dimensions may be about $2.0 \times 0.8 \times 1.5$ m and their weight about 300 kg. In dicers, the product is firstly cut into strips and subsequently chopped by bent or inclined knives, mounted around a rotor (Fig. 4.8c). The size and capacity of diced products (e.g., French fries) depends on the type of knives used. The larger the pieces, the larger the capacity. In cubes, e.g., it may vary from about 2 mm to more than 50 mm. The required energy is about 3–4 kW. The overall dimensions of such machines may be $2 \times 2 \times 1.5$ m.

Meat Mincers

The mincing machine is used for fine-“structured” mincing of products and especially for mincing different kinds of meat. It may be also used in the preparation of processed cheese. The machine (Fig. 4.8d) consists of a structured tube in which a work worm rotates, forwarding the material toward the other end of the cylinder, where it is compressed through a system of vertical plates and rotating knives, behind each plate. Usually 4-wing knives are used (Berszan 1986). The pitch of the worm may be larger at the beginning and smaller near its end. Thus, the compression is more intensive as the product draws near the plates. In some versions, a second worm with large pitch, or a shaft with paddles, rotates parallel and above the main worm, mixing the products before mincing. The number of vertical plates depends on the fineness of cutting. Usually 2–3 plates are used. The aperture of perforation of the plates decreases progressively. The rotating knives behind the plates cut the product, as it comes out of them. The capacity of larger machines is up to 10 tons/h. In the case of frozen products, the capacity is reduced to 2 tons/h. The power required for single worm machines is 15–20 kW. Machines with pre-mixer consume about 10 kW more. The length of a meat grinder is about 1.7 m, its width is about 1 m, and its height is about 1.5 m. The weight of a large meat grinder is 1.0–1.5 tons. In some cases, the meat mincers are provided with a refrigerator system, which reduces the heat developed during mincing.

Cutters

Cutters are very versatile machines used mainly in mincing, mixing, and emulsifying meat and added fat, etc., required in the preparation of fillings of salamis and sausages. In meat processing, the size reduction lies between small pieces and colloids (30 mm–5 μm), Berszan (1986). Cutters can be also used in fine cutting of vegetables (e.g., spinach) and cheese. They are made up of a circular bowl (Fig. 4.8e) that rotates around a vertical axis. The product in the bowl is minced by 3–12 concentrically coupled rotating sickle knives (Berszan 1986). The knives rotate as close as possible to the surface of the bowl bottom, with speeds that can be adjusted between 40 and 5000 rpm. The higher the speed of rotation, the finer the cutting. Slow rotation is used for mixing (e.g., meat mash with salt and spices). The progressive addition of ingredients (e.g., spices), ice, or water can be regulated during processing. For processing different types of products, several adjustments are required. These include changing the speed of knives and their distance from the bowl bottom or even replacement of knives by other more suitable. The change of the distance of knives from the bottom of the bowl is progressive and can be automated. Replacement of knives must be rapid and easy. Filling of cutters is achieved by hydraulically elevating and tipping the content of carts, transporting the required material (e.g., meat) to the bowl. The bowl contents are emptied through an inclined rotating disk put sideways in the bowl. Through the combined rotation (bowl disk), the product is pushed out. The disk rests in a swinging arm beside the bowl and comes automatically in the right bowl position, when emptying is required.

Cutters are built in a great variety for meeting different requirements. Often double-jacketed bowls are used, so that cold water, hot water, or steam may flow between the walls, cooling or heating the bowl contents. Furthermore, bowls may be hermetically closed, for processing under vacuum or for using inert gases. If heating during processing is applied (e.g., mixing after mincing), no extra cooking of the processed mash is required. By processing under vacuum or inert gases, oxidation is avoided, thus products have a better consistency and the meat has a better color. For increasing productivity and for quality reasons, air evacuation must be done quickly. Usually, it lasts less than 1 min. The bowl rotates at low speed, adjustable between about 8 and 20 rpm. In most cases of preparing meat mash for sausages, meat at low temperature (−2 to 0 °C) is preferred. This way, cutting is clear and smearing is avoided (Mueller 1991). The capacity of cutters depends on the kind of product cut, the type of mash produced, and the bowl volume. Usually, bowls contain 200–350 L, but there are also 550 L bowls. It is important for the quality of the products and the life of the machine to have a very well-balanced rotation of the bowl, which is achieved easier in smaller bowls. Machines should switch off automatically, if vibration during operation is excessive.

Furthermore, good central lubrication facilitates maintenance. Power requirement of the 200–300 L bowl cutters is 90–100 kW for the rotating knives and 3–4 kW for the rotating bowl, the cart elevator, and the rotating emptying disk. The length (including motor and gear box which is usually located on the side of the bowl) is about 3.0 m. The width is about 2.5 m and the height about 2.5 m (when the bowl cover is open). The weight of such a machine is about 3–4 tons. For smaller capacities (bowl capacity up to 50 L), there are machines combining the cutter—with the grinder functions.

Slicing, cutting, dicing, and shredding equipment is used widely as a preliminary step in several fruit and vegetable processing operations, such as canning, freezing, drying, cooking, and frying. Dicing is achieved by slicing the product and cutting into strips and subsequently into cubes. Shredding is performed in modified hammer mills, in which hammers are replaced by knives. Pulping equipment is used in

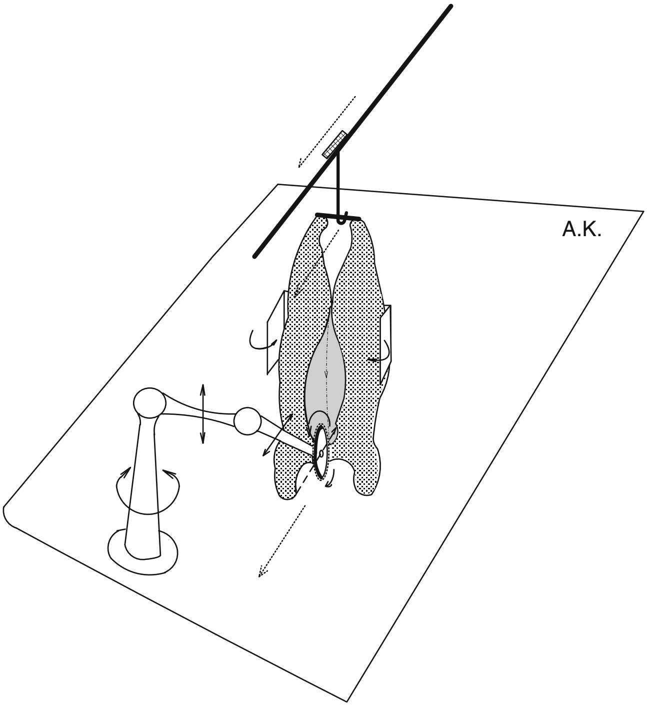


Fig. 4.9 Robot in slaughtering operation

the extraction of fruit and vegetable juices (see sections on Mechanical Expression and Expression of Juices in Chap. 5).

Other Cutting Tools

Robots are also progressively used in cutting applications (Sect. 12.6). Nowadays, this occurs in large food processing units such as slaughter houses (Fig. 4.9), ready food meal preparation, and confectionary/bakery industries. Robots use all prescribed cutting devices, but they also use ultrasonic and water jet cutting devices. The slaughtering capacity of such a unit is up to 650 pigs/h. In splitting and in operations of further cutting of meat, the speed of cutting is about 400 pigs/h. The knives are cleaned by water of 85 °C after each operation.

Ultrasonic cutting devices, besides being used in meat processing operations, are also applied in cutting and slicing cheese, creamy foods, chocolate, confectionary products, and all types of frozen food. They are used for up to 15–20-cm deep cuts. They achieve clean and exact cut. Through vibration, the resistance during cutting is reduced, and little food adheres on the knives. The frequency of vibration is 20,000–40,000 cycles/s (20–40 kHz). Their productivity depends on the object they cut. Usually, it is about 100 cuts/min. Another benefit of ultrasonic cutting devices is that very little food remains on the devices after each action.

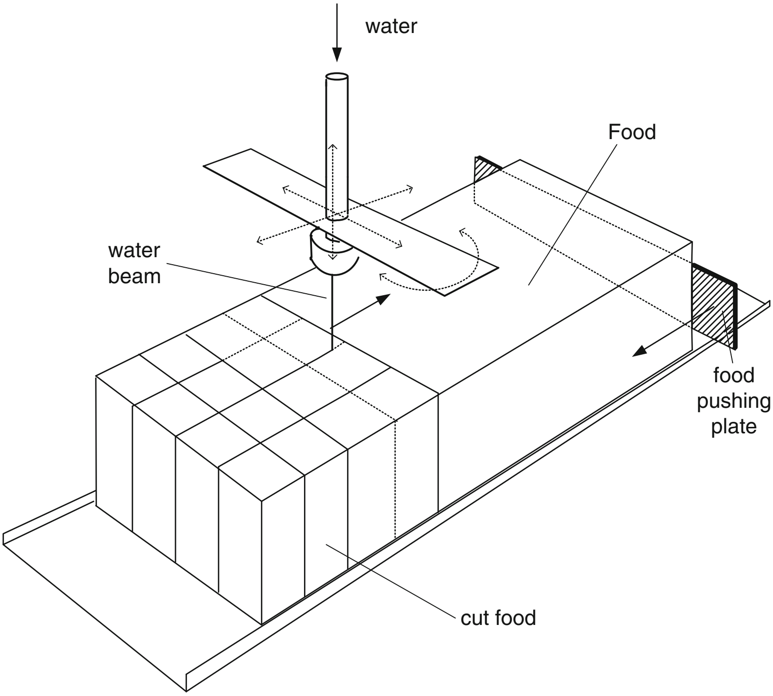


Fig. 4.10 Robot in water jet cutting

Water jet cutting devices use pressurized "water beam." Water is pumped to the product, through adjustable nozzles at max pressures of 620 MPa. They achieve exact kerfs of up to 0.2–0.3 mm, through water beams that are almost as thin as a human hair and flowing at 900 m/s. Therefore, they may be also used in slicing. Besides high cutting speed, further benefits are as follows: (a) their hygienic operation, since contamination of several bacteria is avoided, (b) the "nonthermal" operation of the process does not affect the structure and the consistency of food, and (c) the exact cutting reduces product wastes and is suitable for food portioning operations (Fig. 4.10). Their water consumption is approximately 0.5 gallons/min. In combination with robotic and electronic instrumentation such as laser technology and geodesic-based software, water jet cutting is also applied in *portioning* (Chap. 12).

4.2.2.3 Selection of Equipment

Since there is a quite large variety of cutting equipment, their selection depends on the intended use. Nevertheless, there are some general guidelines in selecting of cutting equipment:

(a) The cutting edge must be sharp, without reducing the firmness of the cutting tool. This requires fine cutting edges and hard material for reduced wear.
(b) The cutting metal must be made of hardened stainless steel, steel containing 5 % chromium and corrosion-resistant tungsten carbide.
(c) Cutting efficiency must be high. This requires exact cutting in relation to adequate cutting speed.
(d) The energy requirements must be as low as possible. In more sophisticated machines, the dead time must be as low as possible (e.g., by automatically switching on or off).
(e) Replacement must be easy and fast.
(f) Safety must be high. All parts that are not directly involved in cutting must be covered. Automatic stopping of operation whenever there are problems. Covering of cutting blades whenever not in use.
(g) Cleaning should be easy and thorough.
(h) Increased versatility. Possibility of using the same machine with different cutting tools.

4.2.3 Crushing and Grinding Equipment

4.2.3.1 Introduction

Figure 4.1 indicates the limits between crushing and grinding. As mentioned earlier, the borders between crushing and grinding are not sharp. Taking into consideration the proposals of several authors and the construction characteristics of equipment (e.g., grindability and range of size reduction), in the present book, it is assumed that the border between crushing and grinding lies at “particle size” 750 μm, taking as particle size the statistical length of particles. There are several quantities that may characterize the “particle size.” Characteristic size quantities of products can be the main dimensions, the statistical length, and the specific surface of a body. The main dimensions can be used only in the case of geometrical bodies, e.g., diameter and height of a cylindrical body. Statistical lengths are projections of certain dimensions of bodies. These are especially important when methods of image analysis of irregular particles are used.

Often, for statistical lengths, the following equivalent dimensions of particles are used (Rumpf 1975; Allen 1990; Stiess 1992): (a) the Feret diameter, (b) the Martin diameter, (c) the longest chord diameter, and (d) the Stokes diameter.

The statistical mean values of the three first diameters are determined usually with microscopic methods. The Feret diameter is the parallel distance in the measurement direction chord, which is perpendicular to two opposite and parallel tangents, drawn at the contour of the particle projection. The Martin diameter is the parallel distance in the measurement direction chord, which divides the projection of a particle into two equal parts. The longest chord diameter is the longest parallel in the direction of measurement chord. The Stokes diameter is the diameter of a sphere that settles in a fluid with the same velocity as that of the real particle (Perry and Green 1997). The Stokes or hydrodynamic (settling) velocity is used in particle separations in fluids.

In estimating the size reduction, several particle analysis methods can be used. These include optical methods, methods based on the velocity of particle settling, measurement of the particle surface, the Coulter counter, and sieving. Sieving is important, not only because it is the relatively simplest and more often method used, but also because screens (sieves) are part of various equipment. This is, e.g., the case, when grinding must last until a certain size reduction is achieved. In this case, instead of wire woven screens, perforated metal screens are employed.

The screens used in determining the size of particles are standardized. For particle analysis, the following standards are commonly used (Allen 1990; Loncin 1969):

France: AFNOR X-11-501
Germany: DIN 4188
UK: BS 410
USA: Tyler and ASTM-E11 series
ISO: TC-24

The DIN series is based on the aperture (opening) and the thickness of wire, in mm. The Tyler series is based on the screen of 200 mesh (wire thickness, 53 μm; aperture, 74 μm). It is emphasized that the mesh number is not equal to the aperture, since in the measured length (1 in.), the wire thickness is also included. The ISO standardization is similar to that of DIN, and the BS and ASTM are similar to that of the Tyler series. Table 4.5 shows some values of DIN, Tyler, and ASTM standards (see also Table 5.1, Chap. 5).

Grindability is a quantity useful in selecting the right grinding or milling equipment (Perry and Green 1997). It indicates the facility of grinding and depends on the texture, the hardness, the moisture content, the water activity, and the degree of agglomeration of the materials and the way it is ground or broken down. An analytical determination of the influence of all these factors on grinding is not easy or possible. Therefore, grindability is determined experimentally in the laboratory, under controlled conditions (energy consumption, size reduction of the material).

Advantages of grinding are as follows: (a) preparation of material for further size reduction (e.g., fine milling); (b) preparation of particles for agglomeration (e.g., producing material for tabletting); (c) preparation of food for processing (e.g., grinding of frozen coffee for freeze-drying); (d) production of final products (e.g., tea) or material disintegration; and (e) use in de-agglomeration (e.g., breakdown of undesired agglomerates, as high humidity milk powder or salt).

Disadvantages of grinding are as follows: (a) high energy requirement; (b) production of heat during grinding, which may damage food quality; (c) production of powder as by-product; (d) the process is often inefficient(e.g., a second grinding is required, if cracking or breaking is not easy); (e) uneven particle distribution is often obtained.

Table 4.5 Comparison among different sieve standards

DIN aperture (μm)	DIN wire (μm)	TYLER (mesh)	TYLER aperture (mm)	TYLER wire (mm)	ASTM-E11 (No.)	BS-410 (mesh)
45	28	325	43	36	325	350
50	32					
56	36					
63	40	250	61	41	230	240
71	45					
80	50					
90	56	170	88	61	170	170
100	63					
125	80	115	124	97	120	120
160	100					
200	125					
250	160	60	246	179	60	60
...	...	...	...	...	...	...
1000	630	16	991	597	18	16
...	...	...	...	...	...	...
2000	1000	9	1981	838	10	8

Factors influencing grinding are (a) product to be ground (consistency, texture, moisture, etc.), (b) product hardness (formation of cracks), (c) initial size of material, (d) final size of particles, (e) rate of feeding the grinding machine, and (f) condition of grinding tools.

Grinding presumes stress of particles. This depends on the contacts between particles and grinding tool, or on the contact among particles themselves. Furthermore, stress is influenced by the number of contacts, their direction, and the frequency of the contacts (Dialer et al. 1984). Stressed material breaks when its deformation reaches certain product-specific limits (Fig. 4.11). Solid material breaks after being deformed (inelastic deformation). Elastic material returns to its original condition when stress is removed (elastic deformation). Brittle material breaks readily by small deformation, while elastic material breaks after significant deformation (Loncin and Merson 1979). However, although brittle materials must be much more stressed than elastic materials up to their break, elastic materials require much more work (W) for the same result (Stiess 1994), e.g., $W_1 > W_2$ (Fig. 4.11).

Breaking is an energy absorption and a release process. The material accumulates elastic energy, which is then released for breaking. The mechanism of breaking is discussed by Rumpf (1965) and Bernotat and Schoenert (1988). The accumulated energy may be due to supply of heat, exothermic chemical reactions, mechanical or corrosive stress, and/or adsorption (Fig. 4.12).

Breaking starts at points of material "defects." The larger the number or significance of defects, the easier the material breaks. Structure deformities and incorporation of foreign substances also count as material defects. Cracks appear in

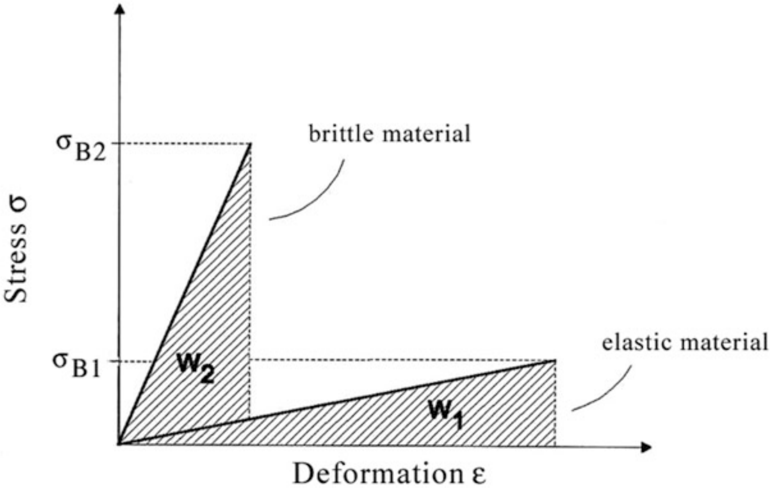


Fig. 4.11 The relation of stress and deformation of materials

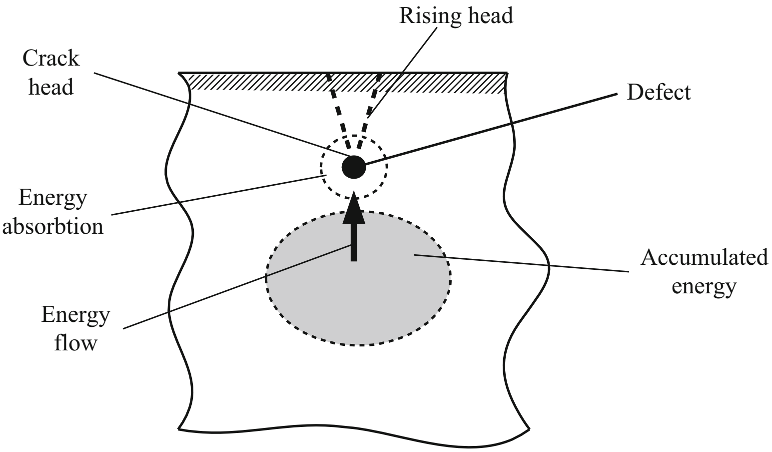


Fig. 4.12 Creation of material crack

defected positions. The further increase and expansion of these cracks depends on the relation between energy absorption and release. The energy released results in irreversible deformations in the micro area of the heads of cracks. Breaking is fast, if the "material resistance to cracking" (*R*) is smaller than the "rate of energy release" (*G*, J/cm^2), which is also called "specific energy for propagation of breaking," indicating the breaking speed of a material (Rumpf 1975):

$$G = -\mathrm{d}W_{\mathrm{el}}/\mathrm{d}A_{\mathrm{b}} \tag{4.3}$$

where W_{el}, the elastic energy absorbed (J) and A_{b}, area at breaking point (cm^2).

The calculation of "*G*" is possible only for very simple bodies (e.g., tension of a very thin plate). If the propagation of a crack is fast ($G > R$), much heat is produced in the head of a crack, deforming even the texture of the material. The rate of energy release "*G*" is then effectively a material constant (Stiess 1994).

The smaller the particles, the lower the number and the significance of defects. Besides that, small particles accumulate less elastic energy, which may be not sufficient for supporting further breaking. Furthermore, in small particles, the number of plastic deformations in the contact positions increases, resulting in a reduction of stress (Dialer et al. 1984). Therefore, breaking of smaller particles is more difficult, and their further size reduction requires more energy. Anyhow, grinding is a very inefficient process, as only 1–5 % of energy input is used for the actual size reduction (Brennan et al. 1990). The rest of the energy is used for elastic deformations before breaking, for creating cracks, or for heat production.

There are several theories for calculating the energy that is required for size reduction (Loncin and Merson 1979), three of which are used more frequently, i.e., the Rittinger, Kick, and Bond "laws" (Perry and Green 1997; Fellows 1990; Brennan et al. 1990; Loncin and Merson 1979). These three laws are based on the following general equation:

$$\mathrm{d}E/\mathrm{d}x = -K/x^n \tag{4.4}$$

where dE, energy for accomplishing a change dx in the size of the material; x, size of the material; K, a material constant (depending on material and equipment); and n, an exponential factor. The energy (E) is usually measured per unit mass of the material to be ground, e.g., kWh/ton.

Rittinger

The Rittinger theory assumes that, for a certain size reduction, the required energy is proportional to the new surface, created after size reduction (Fig. 4.13a), i.e., $n = 2$. Thus, the integrated equation (4.4) becomes

$$E = K(1/x_2 - 1/x_1)$$

where $x_{1,2}$, mean size of feed and final product and E, energy per unit mass required for creating the new surface. The Rittinger law gives better results in the case of fine grinding, since in this case the surface increase is significant.

Kick

The Kick theory assumes that the energy required for a specific reduction of the initial size is proportional to characteristic size of the particle (e.g., longest chord

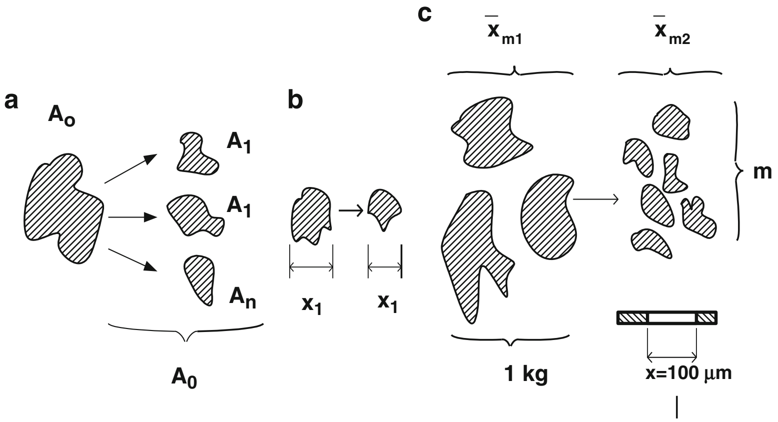


Fig. 4.13 Relations of size reduction in energy laws. (**a**) Rittinger; (**b**) Kick; (**c**) Bond

diameter), before and after size reduction (Fig. 4.13b). According to Kick, $n = 1$, and the integrated equation (4.4) becomes

$$E = K \ln (x_1/x_2) \tag{4.6}$$

where E, energy for reducing the particle size from a certain initial mean size to a new one and (x_1/x_2), ratio of size reduction. The Kick law gives the required energy of size reduction of particles, up to their elastic deformation. The results of Kick law are better for coarse grinding, when there exist already many cracks.

Bond

According to the Bond theory, $n = 3/2$, and the integrated equation (4.4) becomes

$$E = K\left[1/x_2^{1/2} - 1/x_1^{1/2}\right] \tag{4.7}$$

where $K = 10\,W_b$ and W_b, bond work index. It indicates the energy in kWh/ton feed, required for size reduction of the unit mass of particles from a very large initial mean size $\left(1/x_2^{1/2} = 0\right)$ to another size that can be sieved to 80 % by screens of aperture of 100 μm (Fig. 4.13c). The Bond law can be used in size reduction of coarse up to fine particles (grinding and milling).

4.2.3.2 Particle Size Distribution

The size of biological particles usually follows the normal size distribution:

$$f(x) = \left[1/s(2\pi)^{1/2}\right]\exp\left[-(x-\xi)^2/2s^2\right) \quad (4.8)$$

where ξ is the mean size and (s) is the standard deviation of the particles

Most particles, produced in industrial processing, follow the logarithmic normal distribution (Allen 1990; Perry and Green 1997).

$$f(\log x) = \left[1/2\pi^{1/2}\log s\right]\exp\left[-(\log x - \log\xi)/2(\log s)^2\right] \quad (4.9)$$

The industrial particles follow also the Rosin–Rammler distribution:

$$R = \exp(-x/x')^n \quad (4.10)$$

where R, the cumulative distribution of the particles larger than x; x', a characteristic size; and (n), the uniformity index of the particles.

The particle size distribution is usually presented in graphical form, using special diagrams of cumulative distribution versus particle size. Normally, the residue cumulative distribution (R) is used, defined as $R = \int_x^\infty f(x)\mathrm{d}x$, i.e., the fraction ($R < 1$) of all particles larger than (x).

The log normal distribution is represented by a straight line on a diagram which coordinates the logarithmic probability (R) versus log (x). The Rosin–Rammler distribution is represented as a straight line in a diagram of log [log (1/R)] versus log (x).

4.2.3.3 Crushing and Grinding Equipment

General Aspects

Grinding equipment used in the food industry has been adopted from the chemical industry. However, there are cases in which this equipment is either not used for foods or used in a quite modified form. This is especially the case of equipment of the chemical industry engaged in large size reduction as, e.g., in crushing of large pieces or minerals, in shredding, and in size reduction of very hard materials. On the other hand, there are cases in which equipment often used in size reduction of foods, such as the strainers, are not very common in the chemical industry. In food processing, most crushing and grinding concern sizes between a few cm and 0.5 mm. Furthermore, in food processing, the quality of the final product is more important than the exactness of its size. Therefore, since in many crushing/grinding

Table 4.6 Food crushing and grinding equipment

Type of size reduction	Equipment		Size of end product	Reduction ratio (initial/final size)	Main force applied
Stress between two grinding tools	Roll crusher		>10 mm	4–6	Pressure and shear
	Roll mill		5–100 μm	>20	Pressure and (shear)
	Pan mill		0.05–1.0 mm	10	Pressure and shear
	Strainer			5–10	Shear and (pressure)
	Hammer mill		50 μm–10 mm	10	Impact (and shear)
	Hammer crusher		>8 mm	5	Impact
Stress by one grinding tool	Disc	Pin disk	2–50 μm	>50	Impact (and shear)
	Grinder	Colloidal mill	5–20 μm	>50	Shear
		Disintegrator	>100 μm	>20	Impact and shear
	Rotary grinder		20–100 μm	10–25	Shear (and impact)
Stress due to relative motion of particles	Impeller attritor		20–300 μm	>30	Shear and impact
	Jet mill	Counter jet mill	1–100 μm	>50	Impact
		Spiral jet mill	1–100 μm	>50	Impact and shear
		Oval jet mill	5–100 μm	10–50	Shear

methods the temperature during grinding is high, they are not applicable to foods, unless special measures are taken, such as freezing the product before grinding, cooling it, or using inert gases during processing. Another example is the undesirable damage of food texture that may occur during size reduction. This may result in sensory changes and loss of valuable ingredients.

The crushing and grinding equipment (Table 4.6) is classified here according to the scheme proposed by Rumpf (1975), in which grinding of the material is done by two tools (e.g., two surfaces), by only one tool, or by attrition of moving particles (e.g., attrition between particles or between particles and the surrounding fluid).

Equipment using two tools for grinding includes machines that are primarily used in crushing/breaking relatively large, hard materials, such as (a) jaw crushers, (b) cone breakers (gyrators), (c) roll crushers, (d) roll mills, and (e) strainers.

In jaw crushers, the material is crushed between reciprocating plates, whose distance is larger in the upper part. In cone breakers, the material is crushed in the space between a ring with inclined inner sides and a cone rotating eccentrically.

In roll crushers, the material size is reduced in the gap between two rolls counterrotating. Almost all equipment of the first two categories (jaw crushers and gyrators) is used in breaking/crushing large or very hard materials, which are not encountered in the food industry. Therefore, in the following presentation of equipment, only roll crushers, roll mills, and strainers will be considered.

Product Between Two Crushing/Grinding Tools

Roll Crushers

Roll crushers are used in size reduction of larger pieces, in coarse grinding (e.g., grinding of maize, coffee, frozen products), and in pre-grinding. Usually roll crushers have two counterrotating rolls that may either be smooth or have ripples, pins, or teeth (Fig. 4.14). The forces applied to the product crushed between smooth rolls are compression and shear. Toothed rolls exercise additional bending forces. In the case of smooth rolls, the angle of the nip is important. The surface of steel rolls is hardened to withstand wear. In using toothed rolls, ground materials should not be very hard. This type of crushers, besides brittle materials, can also crush or grind softer plastic or viscoelastic materials. Toothed roll crushers can be used for producing sizes down to 10 mm. Their advantage is relatively low energy consumption and very little dust production. The energy consumption of toothed rolls of 30 cm diameter is about 8 kW. The theoretical capacity of roll crushers (m, cm^3/min) based on the discharge of continuous solid ribbon of material, according to Perry and Green (1997), can be calculated as

$$m = slv/2.96 \qquad (4.11)$$

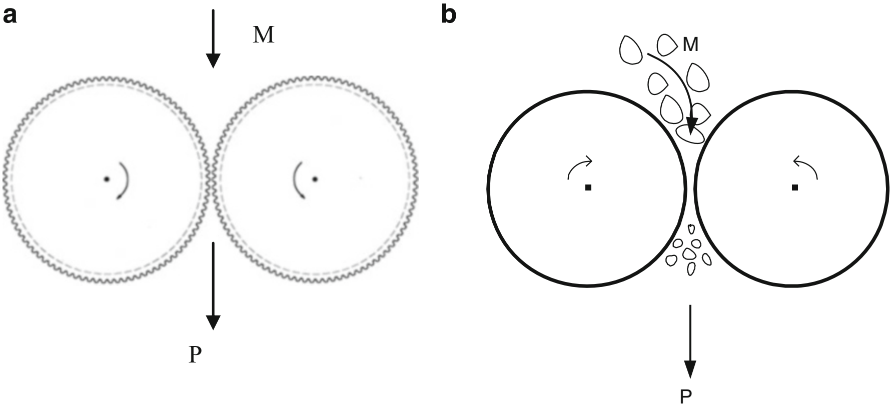


Fig. 4.14 Roll crushers. (**a**) Teethed; (**b**) smooth. *M* feed material, *P* product

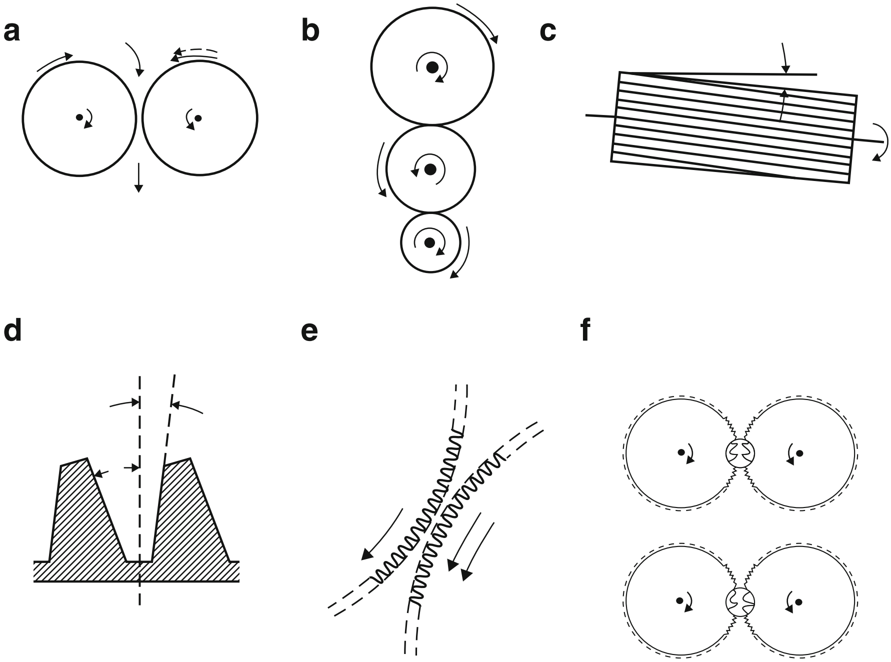


Fig. 4.15 Roll mills. (**a**) Two roll; (**b**) multiple roll; (**c**) corrugated; (**d–f**) grooved

where *s*, distance of rolls (cm); *l*, length of rolls (cm); and *v*, peripheral velocity (cm/min). The actual capacity is 25–75 % of the theoretical, depending on the roll diameter, feed irregularities, and product hardness.

Notice: Secondary force applied is put in parenthesis.

The advantages of roll crushers are (a) little dust production (especially for toothed rolls), (b) versatility through changing of rolls, (c) application to wide range of products (brittle, ductile, dry, moist), and (d) wide range in pre-grinding size reduction.

The disadvantages of roll crushers are (a) high wear, (b) grinding teeth vulnerable to hard materials, and (c) high energy consumption.

Roll Mills

The roll mills are the main type of milling equipment used in the fine grinding of cereals (5–100 μm). They consist of counterrotating roll pairs (Fig. 4.15a) or, in some cases (e.g., wet fine milling), of a system of rolls (Fig. 4.15b) (Leninger and Beverloo 1975). After each grinding operation, sifting follows, separating oversize product, that is further ground. However, there are mills in which the product is ground twice (passes through two pairs of rolls) before it is sifted.

Grinding with roll mills depends on (a) product (kind, consistency, texture), (b) dimensions of rolls (length and diameter), (c) condition of roll surface (smooth, grooved, corrugated), (d) kind and number of flutings (if roll has flutings), (e) speed of rotation of rolls, (f) gap between rolls, and (g) moisture content of the product.

Usually the diameter of standardized rolls is 220–315 mm and their length 315–1500 mm (Macrae et al. 1993). The rolls may be smooth or grooved (fluted) or have corrugations. The corrugation runs along the axis of the whole length of the rolls, but inclined at slight angle (α) with respect to the axis (Fig. 4.15c). This inclination is 2–4° for the first rolls and increases to 8–10° in the last rolls of the mill. The number of grooves is 4–16 per cm of roll (Tscheuschner 1986). The first rolls have less grooves. The grooved or corrugated rolls are used for coarse grinding. The diameters of grinding roll pairs are equal, but their speed is different. The roll grooves have nips whose basic construction is indicated in angles in Fig. 4.15d. Each flute has a V-form of non-equal sides. One side is steeper than the other. The angles formed (β, γ) depend on the type of rolls. According to Kent (1984), the angles in the USA and Canadian rolls are different from the UK rolls. The approximate values of these angles are $\beta = 64–69°$ and $\gamma = 30–35°$. The rotation velocity of the faster roll of each pair is about 6–9 m/s. The difference of the speed of the rolls depends on the fineness of grinding and may be 2.5–2.7 for coarse and 1.5–1.8 for fine grinding (Macrae et al. 1993; Tscheuschner 1986). The difference of rotation speed of rolls depends also on the type of product ground. For wheat grinding, e.g., it is 1/2.5, while for rye grinding, 1/3. The gap between the rolls can be adjusted accurately. The gap depends on the type of product and the fineness of grinding. In the last stages of grinding (usually the wheat passes 4–7 times through the rolls), the gap becomes narrower. The following gaps (Table 4.7) are given by Kent (1984):

The burdening and abrasion of rolls requires their frequent replacement. Wear is especially high, when the gap between rolls is small and the speed of rotation high. The “indicator of abrasion” gives the metal loss of rolls in relation to unit power used (e.g., g/kWh) and depends on the material and method applied (wet or dry grinding). The kind of forces exercised during grinding depends on the type and the relative speed of the rolls (Bollin 1991) (Table 4.8).

As indicated in Table 4.8, the forces during grinding of grains depend on the position of the rolls (Fig. 4.15f). The position of rolls is sharp (S) when their “teeth” face downward during rotation (sharp angle) and dull (D) when facing upward. When grinding is started with new rolls, they are assembled in the dull–dull (D–D) position. As wearing of rolls goes on, the position is changed to the D–S or S–D systems (Kent 1984). In most cases, the speed of rolls is different, and therefore, besides compression, shear forces act as well. However, in the case that both

Table 4.7 Gaps in roll mills

Break stage	Roll gap (mm)
First	0.50
Second	0.15
Third	0.09
Fourth	0.08

Table 4.8 Forces exercised during roll grinding

Left		Right			
Condition of roll	Speed of roll	Condition of roll	Speed of roll	Forces	Remarks
Grooved rolls					
S	H	D	l	Cut-press-shear	S: Sharp
S	H	S	l	Cut-shear	D: Dull
D	H	D	l	Press-shear	h: High
D	H	S	l	Press-shear-cut	l : Low
Smooth rolls					
–	L	–	l	Press	
–	H	–	l	Press-shear	

smooth rolls have the same speed of rotation, especially in grinding soft products, plate-like particles are produced. In the case that the front or cutting angle is small (Fig. 4.15d), the cutting effect of the groove predominates, favoring the production of grits. In flour production, larger front angles are preferred (Macrae et al. 1993). In compressing a product, difficulties are caused by the liberated air in it. Therefore, in many machines, air sucking systems are provided. Furthermore, in roll milling, a high amount of energy lost is transformed into heat, elevating significantly the temperature of the rolls. Therefore, in some equipment, cooling mechanisms (e.g., circulation of water in rolls) are also provided.

In grain milling, there are two basic methods, i.e., dry and wet grinding. In dry grinding, the moisture content of the grains is about 16 %, while in wet milling it is higher. Wet grinding is especially applied to corn grinding in connection with wet processing, used in removing the oil-containing corn germ. The corn, in this case, remains in water for 20–40 h for absorbing the required moisture (Heiss 1991). Both methods (dry and wet) have advantages and disadvantages (Table 4.9).

The capacity of new roll mills depends on the product (e.g., kind and condition of product), loading of the mill, the differential speed of the rolls, and the stage of grinding (product fineness). It is expressed as cm/100 kg/24 h. There is a quite large variation of milling systems and capacities. An indicative value for mills with low specific roll lengths is 2 cm/100 kg/24 h (values for wheat grinding). The energy consumption is about 35–45 kWh/ton. A traditional milling unit has about 14 roll mills. Recently, this number is lower, since there are machines with more roll pairs. The dimensions of a single pair roll mill is about (2.5–3.0) × (0.6–1.0) × (1.5–2.0) m and the weight is 4–6 tons.

Pan Mills

Pan mills consist of 2–4 heavy rolls rotating around an axis in the center of a pan, in which the product to be ground is fed (Fig. 4.16a), or rolling while the pan rotates (Fig. 4.16b). This type of mills, which are used in grinding minerals, is not any more common in the food industry, because of their inadequate capacity in the required

Table 4.9 Comparison of dry and wet milling

Kind of milling	Advantages–disadvantages
Wet milling	Advantages
	• No dust problems
	• Better efficiency in some cases as, e.g., in corn grinding in connection to starch production
	• Combination with water transport
	Disadvantages
	• Greater wear of machines
	• Formation of lumps, if moisture is too much
Dry milling	Advantages
	• Less machine wear
	• No lumping
	• Easier milling
	Disadvantages
	• Danger of explosion
	• No possibility of combined water transport

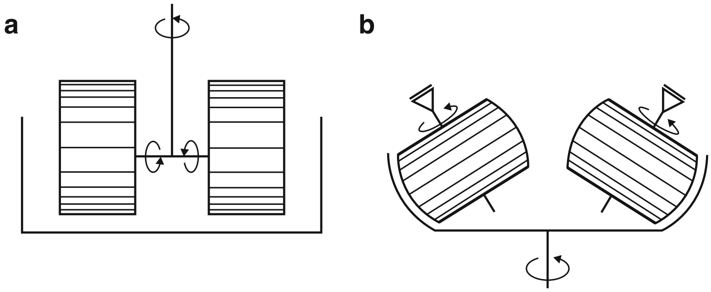


Fig. 4.16 Pan mills. (**a**) Rotating rolls; (**b**) rotating pan

application. Nevertheless, they were used in crushing and grinding products such as olives and other oil containing seeds. The rolls were made of granite, for reducing wear, increasing pressure on material by their weight, and not influencing the material ground. The forces of rolls on the product during grinding are compression and shear (due to steady change of direction during processing). An indicative capacity for olives is 2–3 tons/h. Their main advantage is gentle processing (low temperature and speed). The energy consumption of the machines is related to the pan volume, e.g., a machine with two rolls and 500 L pan requires 22 kW.

Strainers/Pulpers

Strainers are used in pulping fruits and in separating the flesh of fruits and vegetables from their skin and seeds (Fig. 4.17). There are two main types, the extractor and the disintegrator. Both consist of tools (paddles) rotating near the

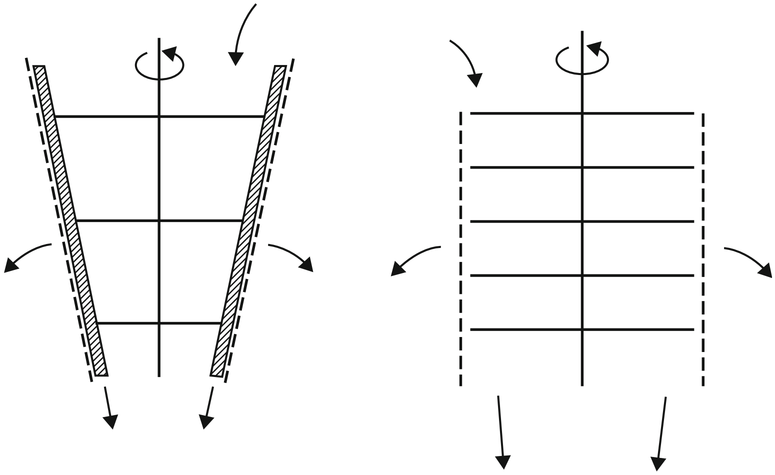


Fig. 4.17 Strainers

surface of a cylindrical or conical screen. In the first type, the rotating paddles compress the product on the screen. In the second type, many rotating tools grind and compress the material through the screen. In both cases, the solid waste is rejected downward, while the soft part and the liquid pass through the screen. The fineness of the product depends on the screen used and the clearance between the screen and the rotating tools. This clearance is controlled by axial adjustment of the rotor. The rotation of the rotor in the extractor (1500–2000 rpm) is slower than in the disintegrator (up to 10,000 rpm). The minimum particle size of the extractor is 750 μm and that of the disintegrator 75 μm. The capacity of the strainers, depending on the processed product and the construction, can be 2–140 tons/h. The energy requirement of an extractor for tomato processing (capacity, 30 tons/h) is about 45 kW. The dimensions of such machines are about 2.5 × 1.5 × 2.5 m, and their maximum weight is about 3 tons.

Product Impact

Hammer Mills

The hammer mill is one of the most commonly used equipment for food size reduction by impact forces. It is used for producing a wide range of medium to fine particles. The ground product can be dry, moist, or even lumpy, soft, brittle, crystalline, or fibrous. Hammer mills consist of a rotor, including axially assembled metallic rods, rotating in a chamber (stator), whose the lower part has a replaceable screen (Fig. 4.18). Depending on the product fed and its final size requirement, different tools, called hammers or beaters (e.g., chip hammers, blade beaters, etc.), may be hung on the rods and swing. Some machines may have up to 20 tools hung

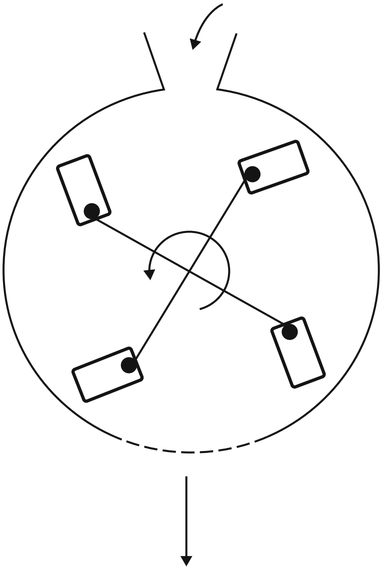


Fig. 4.18 Hammer mill

(in the chemical industry, there are machines with >60 tools). The product fed in the chamber is hit by the quickly rotating hammers, and it leaves the chamber, when it can pass through the sieve at its bottom. The fineness of the ground product depends on the product (consistency, moisture, etc.), the rotor speed, the type of tools used, the aperture of the sieve, and the clearance between rotating tools and chamber/sieve. Chip hammers, e.g., are used for grinding wheat straws for animal feed, roots, and fibrous material. Swing plates are used for grinding bones and lumpy materials. The end size of particles may vary from 10 mm to 50 μm. The hammers/beaters usually rotate at 500–3000 rpm. Nevertheless, in some cases, as in micro-pulverizing of sugar, they may rotate faster (e.g., 6500 rpm). The faster the rotation, the finer the grinding of the product, if all other parameters remain constant. In some applications, temperature increase during grinding is prevented by air (e.g., 200–400 m^3/h) or other cooling method (e.g., using cooled jacketed walls).

The energy requirement of hammer mills in the food industry is usually 5–35 kW. Their specific energy consumption is about 0.2–2 kWh/ton (Dialer et al. 1986). The main external dimensions of hammer mills vary according to the number of hammers used. An indicative value for overall dimensions of a 20-hammer mill is 1.7 × 1.2 × 1.3 m. The weight of such a mill is about 0.6 tons (without the motor).

Advantages of hammer mills are that they (a) have relatively small volume, (b) can be used in the production of a wide range of particles that are of interest to food processing, (c) can be used in a great variety of foods (fibrous, moist, dry), and (d) have relatively reasonable energy requirement.

Disadvantage of hammer mills are as follows: (a) wear out (e.g., life of material is 7–8 weeks grinding 300,000 tons of sugar cane); (b) fines (powder) produced as by-product; (c) pre-grinding is required, if pieces are larger than 4 cm; and (d) temperature must be controlled, if high speed grinding is applied.

Hammer Crushers

Hammer crushers, like most other large-scale crushers, are not often used in the food industry. Their use is restricted in pre-crushing of material that will be subsequently ground further. The machine is similar to the hammer mill. Its difference lies in the range of size reduction employed (>8 mm). The hammer crusher is used for coarser grinding, and therefore, it is larger and more robust. Screens are firmer and hammers are also more compact. In some variations, no screens are used. The speed of rotation of the hammers is lower but their capacity high, since less thorough grinding is required. The capacity of the hammer crushers is higher than that of jaw or cone crushers (gyrators) of the same machine volume (Dialer et al. 1986). Indicative values of hammer crushers are size of particles, 50 cm–8 mm; speed of rotation, half of that of hammer mills; capacity, 50–140 tons/h; and dimensions, 2.5 × 1.5 × 1.6 m.

Disk Grinders

Disk grinders are used for fine grinding of soft up to medium hard brittle materials. Furthermore, they can be used for dry as well as moist slurry materials. Some foods that are ground by disk grinders are starch, dry fruits, sugar, spices, and cocoa. There are two main categories of disk grinders, those with molded surfaces and those with flat surfaces (Fig. 4.19). Equipment of both categories consists of round discs parallel to each other. Material is fed continuously in the gap between the rotating discs. Depending on the type of the machine, one or both discs can rotate. In the case that both discs rotate, the second disk rotates in counter direction (Fig. 4.17b, c). Feeding of the product is usually done by means of a chute, shifting the product in the hole center of one of the two discs. For reducing the temperature increase, air is blasted during grinding or, in some constructions for avoiding oxidation, cooled inert gas is used.

In pin mills, the disk has several metallic pins, placed symmetrically and concentrically on the disk surfaces (Figs. 4.19a, b). The flat disk grinders may be vertical (Fig. 4.19d) or horizontal (Fig. 4.19f). In propeller equipment (Fig. 4.19e), half of the grinding chamber rotates in counter direction to that of the propeller in the center. Disk grinders are used for fine or very fine grinding. The forces during grinding in molded discs are impact and shear. When one disk rotates, the size of the ground particles is 50–5 μm. If both discs counterrotate, the particle size may be reduced down to 2 μm. Size reduction is controlled by adjustment of the gap between the discs and by screens placed on the lower part of the mill. Pin mills may grind, 0.05–6 tons/h. Depending on the product, end size of particles, and capacity, the energy consumption may vary from 3 to more than 100 kW.

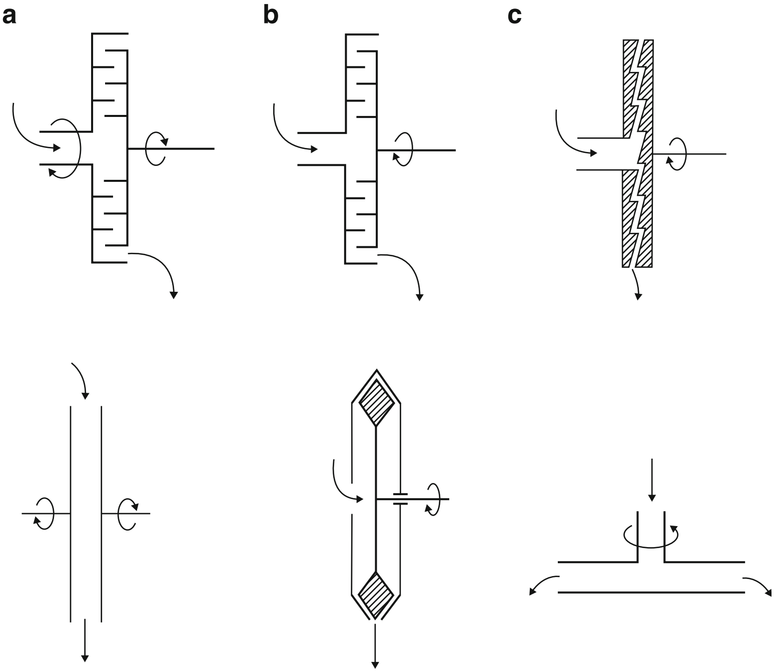


Fig. 4.19 Disk grinders (see text)

The specific energy consumption of impact grinders is 10–100 kWh/ton, at peripheral velocities 100–200 m/s (Stiess 1994). Usually, the peripheral velocity of the pin grinders is 80–160 m/s, and the diameter of the discs is up to 1 m.

Advantages of pin mills are as follows: (a) very fine grinding at relatively reasonable energy consumption, (b) little floor space required, and (c) wide range of application (dry, moist, slurry materials).

Disadvantages of pin mills are as follows: (a) low capacity, (b) high wear, and (c) narrow range of size reduction.

Colloid mills (Fig. 4.19d, f) are a variation of the flat discs and may be used in disintegration of viscous products and in fine grinding of grains. They are also used in the homogenization of fluids. Some applications are manufacturing of mustard, mayonnaise, and salad dressings, very fine grinding of animal or plant tissues for manufacturing baby foods and soups, and homogenization of milk, chocolate drinks, and juices. Furthermore, they are used in rice hulling and rice polishing and in confection grinding. Both or only one disk may rotate. The gap between the discs can be adjusted automatically down to less than 25 μm. In the case one disk is stationary, this can be jacketed for cooling the mill during grinding. When using discs for fluids, their speed can be 1500–3000 rpm. The forces exercised on products are shear forces. For reducing wear, plates are made of toughened steel or corundum. The product is fed in the hole center of the upper disk and is discharged from the sides. If there is no product between the discs, the machine stops automatically. The size reduction achieved is usually 20 –5 μm. In using a colloid mill for oat or rice hulling and polishing, usually only one disk rotates at about 18–20 m/s. At this speed, the rice is readily hulled after 1/3–1/2 turn of the disk (Tscheuschner 1986). The energy consumption depends on the viscosity of the product, the feed rate, and the temperature during processing. For 2000 L/h, about 30 kW is required. In equipment of the first category, impact forces during grinding dominate.

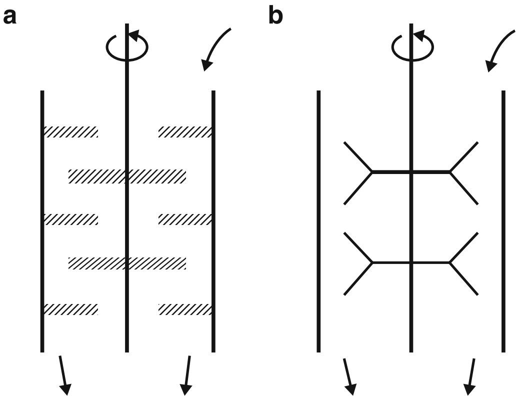
Advantages of colloid mills are as follows: (a) wide range of use (slurry-fluid materials), (b) no pressure required for homogenization, (c) simple construction, and (d) easy adjustment.

Disadvantages of colloid mills are as follows: (a) no wide application in solids, (b) wear of rotating plates, and (c) no fine grinding.

Disintegrators

In disintegrators, the material is disintegrated coming in chambers in which several concentric blades or rods rotate with a peripheral velocity of 4–20 m/s. In some equipment, the tools simply rotate in cylinders (Fig. 4.20a) or they rotate between tools (e.g., bars) that are parts/extensions of the walls of the cylinders (Fig. 4.20b). This kind of equipment is often used in disintegrating packaging or other kind of waste material. For disintegrating lumps, food by-products, or products containing high amount of fatty substances down to 100 mm, there are machines rotating at 4000 rpm. The product flows along the vertical axis of the rotating tools. This way, feeding and discharge are facilitated, due to gravity. The average size distribution of particles may be influenced by the speed of the rotor and the type and number of rotating tools.

Fig. 4.20 Disintegrators (see text)



Stresses Due to Relative Particle Motion

Rotary Grinders

This kind of equipment grinds soft products, such as potato and other roots (final size of ground particles, 2–100 μm). They are also used in wet size reduction of products down to 1 μm, suitable for dispersing and emulsifying. Such machines consist of concentric rolls or discs, rotating fast in cylindrical chambers or rings. The cylinders are grooved or provided with adjustable inclined or vertical knives. The periphery of the discs is engraved or curved, forming sometimes a kind of propeller. The product is fed into the gap between chamber and rotating devices (Fig. 4.21). Size reduction is done by shear/attrition. Attrition occurs among particles and between particles and chamber surface. Shear forces are also exercised by the rotating tools. Rotary grinders are used to produce small random-shaped pieces, which thereafter are directly used in further processing (e.g., sugar production from sugar beets, or starch from potatoes). Feed is usually smaller than 5 mm. In the case of sugar beets, rotors of 2 m diameter with 20–24 knives are used. The cutting speed is 4–10 m/s and the peripheral velocity of rotors, 7 m/s (about 67 rpm) (Tscheuschner 1986). Rotating grinders may process 15–35 tons/h potatoes. Indicative values of such equipment are as follows: dimensions, 1.7 × 2.0 × 2.5 m and weight, 2–2.5 tons. Small units may have rotors of 0.3–1.0 m diameter. Their peripheral speed may be about 5–30 m/s (50–500 rpm). Rotors can also rotate inside perforated cylinders (sieves). Their specific energy requirement is in the range of 20–180 kWh/ton.

Advantages of rotary grinders are (a) high capacity; (b) relatively low wear of moving parts, due to slow rotation; and (c) grinding versatility through adjustment/change of knives/rotating discs.

Disadvantages of rotary grinders are (a) significant wear of knives/discs and channel wall/ring and (b) high specific energy consumption.

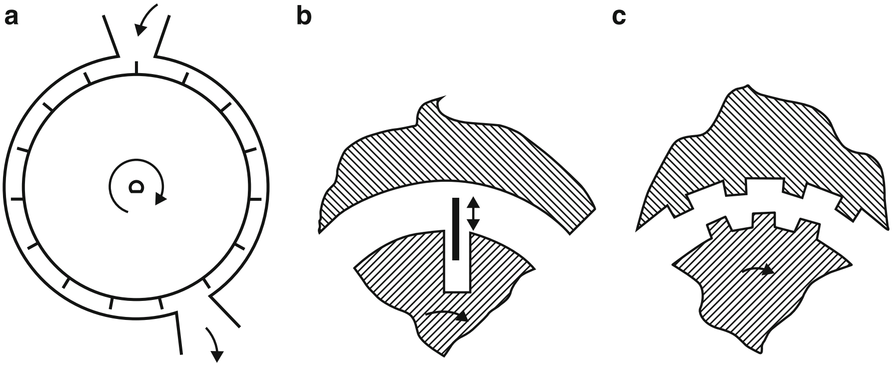
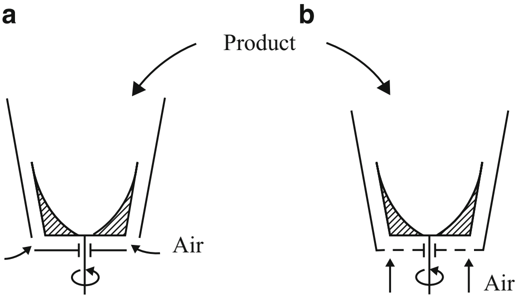


Fig. 4.21 Rotary grinders

Fig. 4.22 Impeller attritors



Impeller Attritors

Impeller attritors are used in fine grinding of a great variety of soft and medium hard products. Some examples are chocolate crumb, powder coatings, baking mixes, fish meal, milk-sugar mixes, etc. They consist of a cylindrical or conical chamber and tools (e.g., anchor like blades), rotating on a perforated plate at the bottom of the chamber, while air may be blasted upward through the plate for reducing the temperature arising during grinding (Fig. 4.22). Tools rotate at 600–4500 rpm (the speed of smaller units can be even higher). Speed can be adjusted linearly. Particles are fed at the top. Size reduction is achieved through attrition among particles and by attrition of particles with the wall of the chamber and impact with the rotating tools. In some constructions, the wall is perforated, or screens control the final size of particles, which can be from 20 μm to more than 100 μm. Large particles (>30 μm) are produced by collision between particles and chamber wall. The size and amount of fine particles depend on their average free path in the chamber, which is a function of the rate of feeding (Dialer et al. 1986). The larger the average free path, the more often collisions occur. Examples of capacities of impeller attritors are 120 kg/h (fish meal, particle size 100 μm) and 140 kg/h milk powder with sugar (particle size: 20 μm). Air flow is 1000–4500 m^3/h. The maximum energy requirement of impeller attritors is 50 kW. The dimensions of larger units are 2.5 × 1.8 × 1.8 m and their weight is about 2 tons.

Advantages of impeller attritors are (a) particle size comparable to those produced by jet grinding, using relatively less energy; (b) easy control of particle size through linear adjustment of speed of rotation; (c) low product temperature; (d) simple construction; and (e) easy cleaning.

Disadvantages of impeller attritors are (a) additional screening required for better size distribution; (b) low capacity; (c) high specific energy consumption; and (d) high wear, if products are relatively hard.

Jet Mills

In jet mills, particles of feed collide, as air sweeps them along. Three basic variations are (1) the counter jet mill, (2) the spiral jet mill, and (3) the oval jet

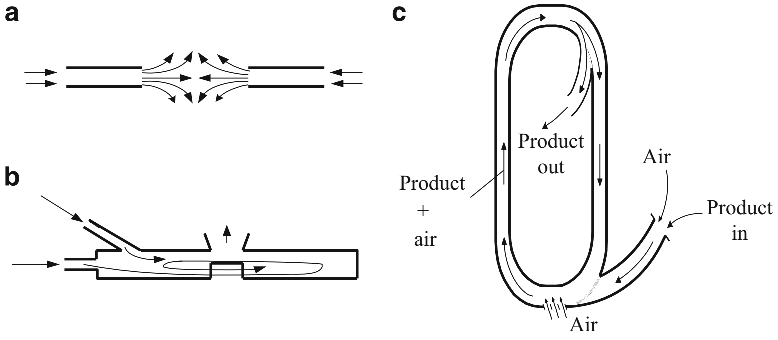


Fig. 4.23 Jet mills (see text)

mixer. The jet mills are used for very fine grinding of hard or medium hard, temperature-sensitive particles. Their capacity varies from 0.05 up to 10 tons/h. In the counter jet mill, particles are ground as two air jets containing them impact when they meet. Both jets flow on the same axis, but they are blown from exactly the opposite directions (Fig. 4.23a). Both jet streams have the same velocity (500–1200 m/s). The consumption of compressed air (7 bar) can be up to 10,000 m^3/h. Particles can be reduced down to 1–3 μm. If the particle size lies in the range of 5–10 μm, 98 % of particles fall in this range. The maximum size of counter jet mills (including a particle classifier) is about 5.5 × 5.5 × 8.0 m. In the spiral jet mill, the product is "injected," by means of compressed air, in another high-speed air stream, rotating in a circular channel (Fig. 4.23b). Size reduction of 1–20 μm is achieved, through intensive attrition among particle and between particles and channel walls. The oval jet mixer (Fig. 4.23c) consists of a vertical oval channel in which air and particles circulate. New product is continuously fed into the lower part of the channel, where it meets high-pressure air or steam of 1.5–20 bar (Loncin 1969). The incoming particles are size reduced by the pressurized air/steam at the lower part of the channel and collisions with each other, as they circulate in the oval channel. In the upper part, the larger particles continue their way through the channel downward, while the smaller particles are sucked away. This method can combine drying with grinding.

Advantages of jet mills are: (a) production of very fine particles possible; (b) relatively little space required; (c) grinding of hard products with reduced equipment wear; (d) low operating temperature; (e) contamination-free processing possible; and (f) no moving parts and no extra foundation required.

Disadvantages of jet mills are (a) small capacity, (b) high energy requirement, and (c) high wear (especially in spiral jet and oval jet mixes).

4.2.3.4 Selection of Equipment

Factors influencing the selection of crushing and grinding equipment are:

1. The texture and condition of the product to be ground
2. The temperature and oxidation sensitivity of the product
3. The production of fine by-products during grinding (wet and dry grinding)
4. The capacity required
5. The wear resistance of grinding tools

4.3 Size Enlargement

4.3.1 Introduction

Any solid can agglomerate, if it is in particulate form and the particles are small enough. In food technology, enlargement of food may take place with or without significant mass changes. No significant mass change is observed when only change of volume of food, due to processing, takes place, as in puffing. Nevertheless, in all other cases, the mass of the new enlarged product, which may be created by coating or agglomeration, is different from that of each of its components (Schubert 1987a, b).

Agglomeration is used in producing several foods. Some examples are baking and pudding powder, aroma substances, ready to eat soups, compressed soup cubes, glazes, ready to cook mixtures, vegetable combinations, spices, instant drinks, vitamin drinks, production of chocolate, and further processing of milk powder. Agglomerates can be a final consumer food (e.g., powder for drinks) or products that are used in further food processing (e.g., starch for food consistency).

In agglomeration, solids come together to form new products, mainly through physical forces (not chemical reactions). The principal objective of agglomeration is to produce aggregates of particles of appropriate size and porosity, which are strong enough to withstand handling and can be dispersed readily, when used in liquids (Wollny and Schubert 2000). In food technology, the desired size of aggregates is usually about 100–250 μm. Because some terms in agglomeration are not clear (e.g., granulate/agglomerate, pelletizing/granulation), the terms used in this chapter are listed in Table 4.10. The numerical limits of each type of agglomerate are indicative, since no accurate quantitative definitions are available.

Agglomeration (enlargement) depends on adhesion forces between similar or different materials, by compression or extrusion. These forces are desirable or not desirable (Pietsch 1967). Desirable forces contribute to the formation of large granules or pieces for direct consumption (e.g., instant products, candies, pastas, and flakes) or for use in further processing (e.g., crust for coating frozen fish and poultry, spice combinations, cocoa). Undesirable forces form clumps, deteriorate the homogeneity of products, or have negative influence on the flowability of

Table 4.10 Agglomeration terms

Term	Explanation
Agglomerates	Solids created through methods of agglomeration, i.e., enlargement of fine solids, through physical methods
Fine solids	Solids: 0.001–10 mm that can be dispersed
Particles	The smaller fine solids
Powders	The next larger to particles solids
Granules	Grain-like products. Dimensions between powders and tablets Irregular or near irregular spherical shapes
Tablets	Compressed solids of certain shape with max. effective diameter <40 mm
Briquettes	Compressed solids of certain shape that are larger than tablets
Pellets	Solids created by pressing substances through holes or dies
Free structuring	Creation of agglomerates without pressure, including rolling agglomeration, spray drying, fluidized bed, and mixing methods
Key substances	Materials, besides binders, used in forming agglomerates

powders and grains. Undesirable forces also contribute to scaling and fouling; blocking valves, pipes, and filters; and falsifying measurements based on particle analyses. In using photometry instrumentation for particle analysis, falsified measurements due to agglomeration of investigated samples are significant, when the diameter of particles is smaller than 10 μm (Pahl 1989).

Agglomeration can be achieved through free structuring and compression. In free structuring, the adhesion forces between solid particles are due to (a) material association, (b) nonmaterial association, and (c) form-related association. In material association, "bridges" between solids, such as crystallized substances or "fluid bridges," are built, due to adsorption film or capillary forces (Schubert 1974). In nonmaterial association, van der Waals and electrostatic forces keep substances together. Form-related association exists in the case of fibers or other plaited materials (Rumpf 1975; Stiess 1992; Perry and Green 1997). The role of these associations is important for the strength of agglomerates. Furthermore, in agglomeration through free structuring, the granulation mechanisms (layering, coalescence, etc.) are important to the size distribution of granules (Perry and Green 1997). Compression may be carried out in different types of presses and extrusion devices. In compression, the adhesion forces between solid particles are also due to the prementioned associations, except the electrostatic ones.

In most cases of food agglomeration, binders are indispensable. Besides an increase of strength, homogeneity of granules depends also on the control of the quantity and rate of binder supply. A formulation of agglomerates may furthermore include flow aids, wetting agents, surfactants, and substances determining the final characteristics of the products, such as flavor modifiers and colors. Properties that determine the quality of agglomerates are the size and the porosity of powders or granules, their wetting ability, and their strength. For food, water is the most common binder. In most cases, it forms bridges between particles when crystallization of dissolved solids occurs. If the moisture of agglomerated material is high and agglomeration lasts relatively long, porous granulates are produced. If moisture is low and agglomeration lasts relatively long, high-density granules of insignificant size variation are produced (Hemming 1991).

For foods, besides water, the following binders can be used: carbohydrates (several sugars such as glucose, lactose, etc.), polypeptides (e.g., powder of milk and cocoa, soy flour, etc.), and starches or starch derivatives, e.g., cornstarch or amylopectin (Heinze 2000). The binders used for food must not contain impurities and must meet the requirements of the food laws. In several cases of subsequent storage and final use of agglomerates (e.g., dissolution in preparation of drinks), combinations of binders and other additives are used. Such additives can be emulsifiers and antioxidants and substances that produce CO_2 when dissolved in water, which accelerates the dispersability of the agglomerates, when released. In instantized cocoa, emulsifiers added usually make 0.8–1.0 % of the total blend.

If no water is used, the other kinds of binders are usually more expensive than the key materials, and they are added in the lowest possible quantity. Their content does not exceed 2–10 % (Heinze 2000). If water is used as a binder, the high water content increases the moisture of the granules, requiring more energy for the subsequent drying. On the other hand, in agglomeration processes through free structuring, relatively high water content is required for increasing the size and porosity of the granules. In agglomeration of powders using low viscosity liquids, granulation occurs very close to the saturation of the mixture, and every agglomerate has its typical optimal moisture content (Perry and Green 1997). Key substances may be powders, or moist substances combined with dried or ground solids, filter cakes, or even ductile or slime materials, all in combination with fine dry solids (e.g., powder).

Advantages of agglomeration are:

(a) Possibility of creating new solid substances through mixing solids (powders and granules) and/or liquids. This is important in adding ingredients like vitamins, aroma substances, taste materials, etc.
(b) Influence on the porosity of solid materials. This way the capability for absorption of further substances may increase or decrease.
(c) Influence on the product density. It helps in the separation of particles in liquids or influences the sinkability of granules in liquid.
(d) Utilization of by-products and reduction of pollution. Powders arising during comminution may be further processed into granules, reducing also the pollution they cause.
(e) Creating by-products of certain shape and form. This is done, e.g., by compression or extrusion of powder materials.
(f) Influence on the solubility of food, through the production of *instantized products*.

Disadvantages of agglomeration are:

(a) The strength of agglomerate created through mixing is low. If agglomerates are not properly processed (e.g., small size distribution, right humidity), rubbing-off may take place in packaging the material or during handling and transport.

(b) Fouling and scaling during processing may occur if material is not properly agglomerated or humidified/dried.
(c) Dependence of agglomerate production on binding substances may cause additional technical problems or even increase the cost of production.
(d) Special storage conditions of agglomerates and their raw materials are required.
(e) Difficulties in keeping the original properties, when products of significant stickiness are used.
(f) Relatively high energy is required, especially when compression is applied.

4.3.2 Agglomeration Equipment

4.3.2.1 General Aspects

Any solid mixer can be used for agglomeration of small amounts of solids, if proper binders are used. The two basic methods of agglomeration are free structuring and compression. The products of all free structuring methods have a low strength and a nearly spherical or irregular shape. The strength of compression products is much higher and their form depends on the molds or dies used. These processes are further distinguished according to the type of free structuring: (a) roll processes, (b) mixing processes, and (c) drying-related processes.

In roll processes, the initial agglomeration nuclei are enlarged during rolling in rotating pans or drums. Enlargement of particles through mixing can be done through intensive mechanical agitation or in fluidized beds. Combination of mechanical agitation and fluidized bed is also possible. In drying-related processes, such as spray drying and fluidized bed drying, fine particles build agglomerates with granules, before granules get completely dry (Table 4.11).

Compression processes are distinguished into (a) tableting processes, (b) roll-press processes, and (c) pelletizing processes.

In tableting processes, the agglomerates are fabricated through pressing of powders or granules in special molds, until the consistency of the agglomerate is achieved. In roll presses, two identical rolls run reversely. Powders or granules fed at the upper side between the rolls are carried along and compressed between the two rolls, whose clearance is adjustable. The surface of the rolls may be smooth or structured. In pelletizing processes, materials are pressed through perforated surfaces or dies, which determine the final shape of the pellets.

Agglomeration processes may be continuous or in batch. Main advantages of continuous processes are (a) high capacity, (b) constant quality, (c) low labor requirements, and (d) less skilled personnel required.

Table 4.11 Methods and equipment of agglomeration

Main type of process	Type of machines	
Free structuring agglomeration		
Rolling	Rotating apparatus	Rotating pan, rotating drum
	Agitators	Oscillating, swinging, and slowly moving agitators
	Vibration	Specially formed vibrated surfaces
Mixing	In apparatus	High-speed agitators
	In air/gas stream	Fluidized beds
	Combination: apparatus-air/gas mixing	Air/gas steam, centrifugal and high-speed agitators
Drying agglomeration	Drying-related processes	Spray drying, fluidized bed drying
Compression agglomeration		
Tableting	Piston and molding press	Single punch press
		Rotary press
Roll press	Smooth roll surface	Double roll press
	Structured roll surface	Briquetting roll press
	Circularly perforated surface	Ring roll press
Pelletizing	Hollow rolls	Pellet mill

The advantages of batch process are (a) flexibility in product variations, (b) flexibility in often-changing of formulas, (c) high precision in mixing of small compounds, and (d) less sensitive to process changes.

4.3.2.2 Free Structure Equipment

General Aspects

The agglomerates of structuring methods are almost spherical with a diameter of 0.3–2.0 mm. Binders are much more important in producing granules by these methods, than in compressed agglomerates. Water is the most important binder in food agglomeration. Furthermore, since moisture influences agglomeration time, further processing of agglomerates and strength of granules, especially for products created by structuring methods, it is very important in adjustment of moisture content to the right level for each product. Here, knowledge of the water activity and diffusivity properties of products is necessary. Since the strength of agglomerated granules, produced by free structuring methods, is low, it is possible to increase it by subsequent drying. In all cases of agglomeration, the basic aim is to bring in contact the appropriate new key substance (usually a powder) with the main material. In this procedure, further granulation depends very much on the granulation nuclei formed.

Agglomerates produced by structuring methods have the following advantages: (a) large external surface of granules; (b) good for processes in which fast heat exchange is required; (c) large overall heat transfer coefficients; and (d) possibility of mechanical transport in fluidized bed agglomeration, using methods applied to fluids.

Factors influencing the structuring methods are (a) the kind and quantity of binders, (b) the size of droplets when the binder is a liquid (water), (c) the position binders added, (d) the position of key substances (e.g., powders) added, (e) the temperature of binder and granules, and (f) the particle or granule size.

Advantages of structuring methods are (a) characteristics of instantized products; (b) give good results, when used in mixtures; (c) stability of granules; and (d) need less energy than press methods.

Disadvantages of structuring methods are (a) low strength of granules, (b) not very uniform size, (c) shape variation not possible, and (d) large-sized equipment.

Among agglomerates, instantized products are very important in food processing of soups and drinks and in several manufacturing methods, in which dried food in the form of powders or granules is used (e.g., in chocolate manufacturing). Instantized products are manufactured by intensive mixing of powders or during fluidizing and drying processes. Instantization of a powder usually does not change its equilibrium solubility. It only decreases the required time to be dissolved.

Basic properties judging the quality of instantized products are:

(a) Dispersability. Instantized agglomerates must be dissolved easily and quickly in smaller units. This depends on the binding forces between the particles, their size, and porosity.
(b) Wettability. When very fine particles stick together, liquids cannot penetrate in the granules easily. If the affinity of particles to liquids is low, elevated temperature of the liquid or pretreatment of the powder (e.g., coating with emulsifiers) helps.
(c) Sinkability. Agglomerates should not float, sink, or stick on the surfaces of vats, cups, etc., in which they are being dissolved. Thus, dissolving of granules can be enhanced. Sinkability depends on the density/ porosity and size of the particles.
(d) Flowability. This is important in weighing/filling, packaging, and storage of the instantized products. Furthermore, it is important with respect to vending machines of drinks (e.g., cocoa, coffee), in which instantized products are used.

As indicated in Table 4.11, free structuring equipment may be classified as rolling, mixing, and drying systems.

In *rolling agglomeration* (Fig. 4.24), the distinction of equipment is based on the way key substances (powders, particles) are brought into contact with the already existing bed of material.

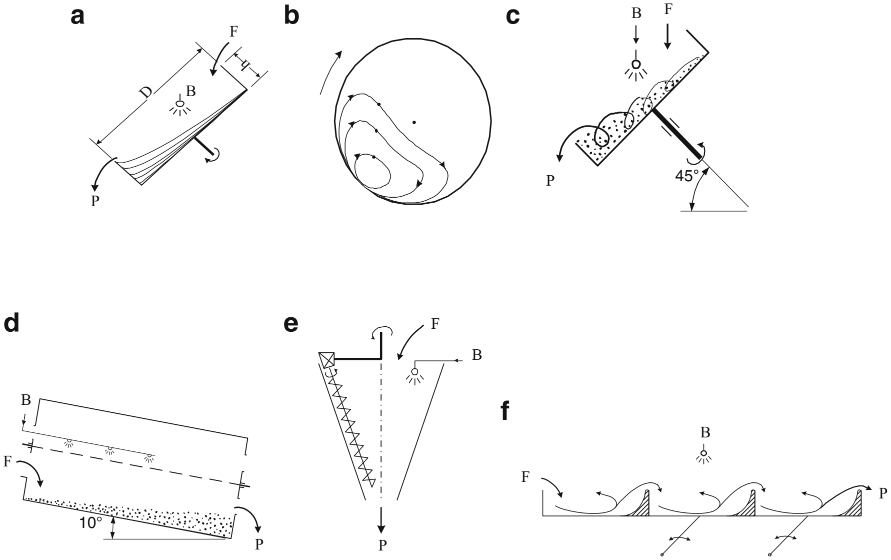


Fig. 4.24 Rolling agglomeration equipment (see text)

Rolling agglomeration is achieved by means of:

(a) Rotating walls that roll up the material, which subsequently falls down, before being taken upward again by the moving wall. Rolling up is done in rotating pans or drums (Fig. 4.24a–d).

(b) Agitators which move up granules and then leave them roll or fall back. This may be done in drum or vat equipment, in which helical coils or paddles rotate or swing slowly to moderately (Fig. 4.24e).

(c) Vibration. Equipment consisting of vibrating inclined beds forces granules to hop up and fall down continuously, while, due to the inclination of the vibrating bed, granules get rolling motion as well (Fig. 4.24f).

In *mixing agglomeration* (Fig. 4.25), key substances are enlarged by bringing them into contact by means of:

(a) High-speed rotating agitators, which mix the content of vats several times a minute (Fig. 4.25a).

(b) Fluidization of small granules in a gas stream. Particles come in contact with rotating small granules, forming agglomerates (Fig. 4.25b).

(c) Combination of the above two methods. Agglomeration takes place while the product is agitated in a gas stream (Fig. 4.25c).

In *drying agglomeration* (Fig. 4.26a, b), subsequent drying of the product is not necessary. Drying is required in other processes, when the moisture content, due to wetting with binders, is high. Agglomeration is achieved by bringing into contact already dried-out small granulates with the key substance, which is a wet powder of the same material (dried-out small granules).

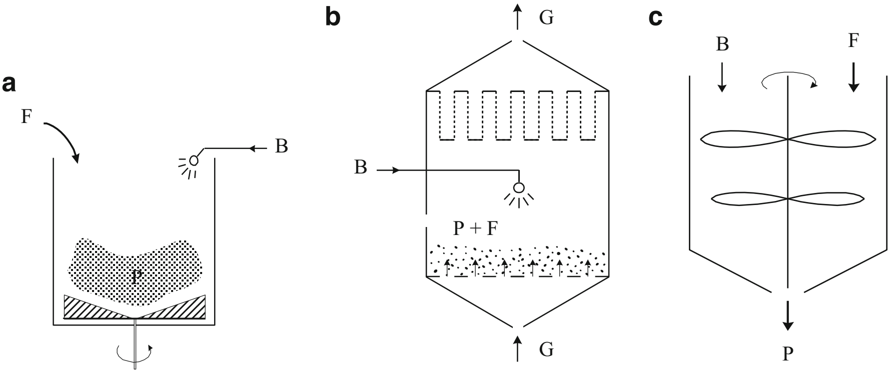


Fig. 4.25 Mixing agglomeration (see text). *F* feed, *P* product, *G* gas, *B* binder

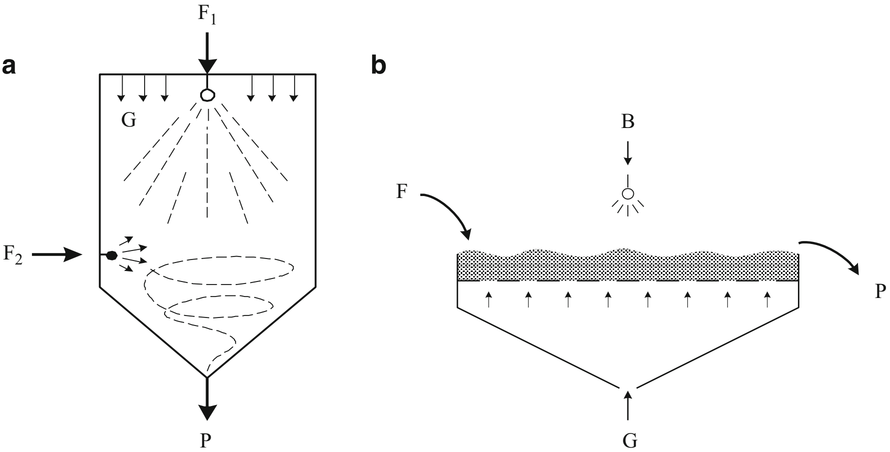


Fig. 4.26 Agglomeration in drying equipment (see text). *F* feed, *P* product, *G* gas, *B* binder

Rolling Agglomeration

Rotating Pans

This granulating equipment (Fig. 4.24a–c) consists of a round pan that rotates around its inclined axis. The diameter of the granules can vary between 0.5 and 2.0 mm. New material and binder are fed at the upper part of the pan in different positions from each other. Blades scrape any material sticking on the wall.

Factors influencing the efficiency of pan agglomeration are (a) inclination of the pan; (b) speed of rotation; (c) position of addition of binder; (d) position of addition of key material; and (e) relation (*D*/*h*), where *D* is the diameter and *h* is edge of the pan.

The method can influence the following agglomerate properties: (a) size, (b) porosity, and (c) moisture.

The size distribution in the pan is not homogeneous. As indicated in Fig. 4.24c, smaller granules and particles rotate on the upper part of the bed. As they become larger, they move toward the lower part near the bottom of the pan. Finally, when they reach the appropriate predetermined size, they move to the surface of the pan, from which they are discharged.

The critical speed of rotation of the pan (n_c, 1/s) is very important in the rotation of granules:

$$n_c = 1/\pi \sqrt{} g(\cos\alpha)/2D \tag{4.12}$$

where α, angle of inclination of pan; D, diameter of pan (m); and $g = 9.81$ m/s^2

If the rotation exceeds n_c, the relative motion between particles of the product in the pan stops. Another size, characterizing the limits of rotation is the Froude number (Fr). At speeds of rotation $n = n_c$, $\mathrm{Fr} = 1$. Since in agglomeration processes by rotation, $n < 1$, the Froude number is also <1:

$$\mathrm{Fr} = R\omega^2/g(\cos\alpha) = (\omega/\omega_c)^2 = (n/n_c)^2 \tag{4.13}$$

where R, radius of pan; (m) $\omega = 60n$; and speed of rotation, (rpm).

The specific power (N_s) required to agglomerate the mass m (kg/h) using a rotating pan is (Stiess 1994)

$$N_s = N/m\ (\mathrm{kW/kg}) \tag{4.14}$$

where: m, mass in the pan; (kg), N; power required, (kW)

$$N = \pi^2/4\ \cos\alpha\psi\varphi\rho_b gD^3hn \tag{4.15}$$

ψ, drift factor (for small D, $\psi = 0.4$, for large D, $\psi < 0.4$)
D, diameter of pan (m)
h, height of side wall (m)
α, angle of pan inclination
n, speed of rotation of pan (1/s)
$\rho_{b,}$ bulk density of material in pan (kg/m^3)
f, degree of pan filling ($f = 0.1$–0.3), $f = 4/\pi\ V_b/D^2\ h$
φ = filled fraction of pan (0.10–0.30)

The speed of rotation of a pan is $n = (0.50–0.75)\,n_c$. The pans rotate at an angle of 45–55°. The pan dimensions depend on the capacity requirements. In food processing, the diameter of pans usually does not exceed 2–3 m. The ratio (h/D) can be fixed experimentally (Heinze 2000), and it may vary from 0.08 to 0.15 (shallow pans), up to 0.5 (deep pans). Depending on the type and quality of the raw material and the quality requirements of the final agglomerate, the capacity and the required power of a pan apparatus may vary up to 25 %. Usually the capacity of a rotating pan (m) is proportional to the square of its diameter (D^2). For a rotating pan of 0.7 m diameter, and capacity of about 0.5 tons/h, the specific power requirement may be about 1 kWh/ton. The granules leaving the pan are spherical of about the same diameter.

Advantages of rotating pan are (a) easy handling, (b) good control, (c) versatility, (d) easy cleaning, and (e) continuous or batch processing.

Disadvantages of rotating pans are (a) many moving parts, (b) inclination mechanism complicates construction, (c) relatively large dimensions, and (d) open system (environmental effects).

Rotating Drums

Agglomeration in a rotating drum is very similar to that of a rotating pan. The main difference is the homogeneity of agglomerates. The size of the pan agglomerate for a certain process is more or less constant, while the size distribution in a rotating drum varies. Therefore, the granules produced by rotating drum agglomeration are subsequently screened out, and the fine agglomerates are fed back to the drum for getting the desired size (Fig. 4.24d).

Drums are mainly used for large capacities and heavy duty materials. As in the case of rotating pans, binders are spayed continuously over the rolled product during processing. They are slightly inclined at an angle up to 10° for facilitating emptying of granules formed. The speed of rotation is $n = (0.30–0.55)\, n_c$ (usually $n = 8–20$ rpm). The length to diameter ratio (L/D) of drums is 2–5, and the degree of filling is low (2–3 %) (Heinze 2000). In the chemical industry and in metallurgy, there are drums with maximum dimensions of up to $D = 3$ m and $L = 15$ m and capacity of up to 100 tons/h. Similar capacities are achieved with rotating pans of $D = 10$ m. The capacity of a rotating drum depends on the properties of the product and agglomerates processed. As a guide value, in processing 7.5 tons/h of fertilizers, a power of 11 kW is required (Walas 1988).

Advantages of rotating drums are (a) robust construction, (b) versatility in use, (c) large capacities in gentle mixing possible, (d) relatively good control, and (e) they may be used in batch and continuous processing.

Disadvantages of rotating drums are (a) relatively high energy required, (b) large dimensions (space), (c) inefficient use of total volume, and (d) nonuniformity of agglomerate size.

Slow Agitation Equipment

In this category belongs batch equipment in which the product (mostly powder) is rolled by slowly moving agitators. An example of such equipment is the conical planetary mixer that is still being used in processing small quantities of agglomerates in the pharmaceutical industry (Tscheuschner 1986; Dialer et al 1986). In some cases, a double-walled mixer is useful for controlling the temperature of the processed product (Fig. 4.24e): indicative values, 100–200 kg/batch; batch time, 20–40 min; and required energy, 10–20 kW (Perry and Green 1997). Such equipment may be used also in other kinds of processing as, e.g., mixing of pasty materials.

Vibration Equipment

This type of continuous processing equipment consists of vibrating beds through oscillating movement of the supporting mechanism. Through vibration, small granules leap over hurdles until they leave the bed (Fig. 4.24f). However, they roll back quite a few times before the next hurdle, being enlarged this way through mixing with new key material under binder support (Tscheuschner 1986).

Mixing Agglomeration Equipment

High-Speed Agitation

These processes, with some exceptions, are mainly batch operations. In all cases, high-speed rotating agitators bring into contact the material which agglomerates. Equipment is made up of a vat in which the product is mechanically fluidized by means of vigorously rotating agitators. This ensures short time of processing and mixing homogeneity, independent of particle/granule density and size. Variations in high-speed agitation equipment are basically due to differences in the agitating systems. Typical forms of agitators are angular paddles, plows, and helices. In all cases, the material is moved toward the ends of the vat and backward, while the binder is spread over it continuously. Agglomeration takes place in a fluidized zone. In some cases, additional agitators are used for breaking lumps that may be built, when the product becomes quite moist.

Factors influencing the size of agglomerates of this method are (a) construction of the equipment, (b) mixing intensity, (c) mixing time, and (d) moisture of the product.

Some typical equipment in this category is given below (Fig. 4.25). They are all used for batch processing, but variations have been developed for continuous use as well. The data given for each type of equipment are only indicative information, since exact values depend on the agglomerated product and the particular method of processing, e.g., binders used, length of process, etc.

1. Twin Shaft Paddle Equipment (Forberg)
   This equipment consists of one or two adjoined vats, in which two shafts with agitators rotate in opposite direction. Additional agitators are used for increasing the effectiveness of binders and reducing accumulation of lumps (Fig. 4.27a). Agglomeration lasts about 1 min and energy requirement is 0.2–2.0 kW/100 L (installed power, 15–30 kW). For 2000–3000 L vat volume, the ground space required is 4–7 m^2 and the weight of the machine is 3–5 tons. Advantages of the

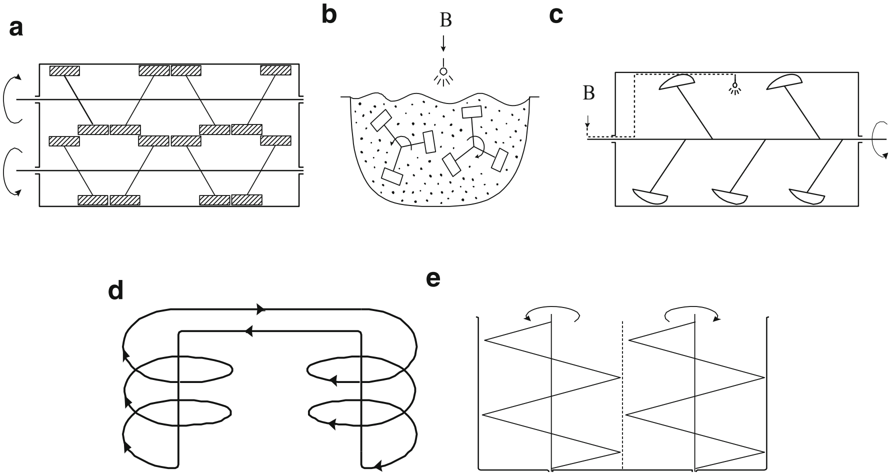
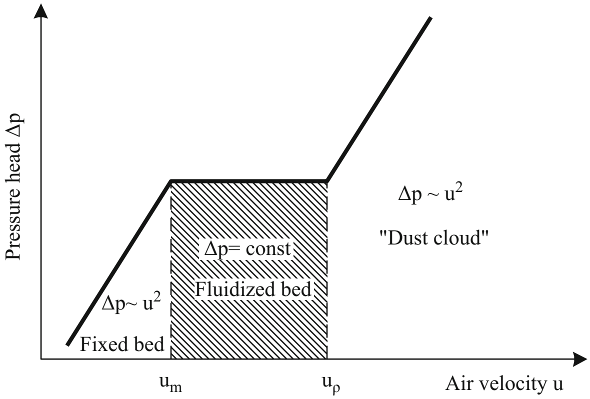


Fig. 4.27 High-speed agitation agglomeration (see text). *B* binder

system include independence of size and density of product and versatility in use. By proper type, number, and position of agitators, it is possible to achieve mixing, even at relatively low agitation speed (<100 rpm).

2. Plow Equipment (Loediger)
   This equipment has plow-type agitators mounted on a single shaft, rotating in the middle of a cylindrical vat at 60–800 rpm (Fig. 4.27b). Different types of choppers, rotating vertically to the main product stream, are placed for reducing the formation of lumps (when the moisture of the product is high), or for increasing the distribution effect of key substances or binders. These choppers can rotate at high speed (>3000 rpm). Volume of vats is up to 15,000 L and operational filling is about 50 %. The required ground space for about 3000 L vat volume is 8 m^2. Agglomeration lasts 1–4 min. The number of charges depends on formulation and quantity and can be 2–12/h. Power required is up to 2 kW/ 100 L. Advantages of the system include versatility in use, wide application (size of products 1–1000 μm), and simple construction.
3. Two-Helix Equipment (Ruberg)
   This type of agglomerator consists of two identical cylindrical vats adjoined to each other (Fig. 4.27c, d). Along the axis of each vat, a helical agitator, almost as wide as the diameter of the vats, rotates. The material moves along the first shaft downward and continues following spirally upward around the wall of the first vat. Subsequently, the same flow procedure is repeated in the second vat, starting from the top of the shaft of the second vat. Agglomeration is intensive in counterflow between the two vats, and it lasts up to 3 min. Required ground space, motor power, and machine weight of a 3000 L vat are about 5 m^2, 30 kW, and 4 tons, respectively. Advantages of the system include low speed of rotation, gentle mixing, and simple construction. Good mixing occurs readily by filling only 10 % of the vats.

Fig. 4.28 Influence of air velocity on fluidization pressure head



4. Fluidized Bed Agglomeration

Agglomeration takes place while key materials and small granules are both whirled in a gas stream, which is usually air. Fluidization is achieved at operating air velocities (u) between the minimum air velocity (u_m) and the air velocity at which solids are pneumatically conveyed (u_p) (Perry and Green 1997; Fig. 4.28).

For fluidized beds of granules, $1.5\,u_\mathrm{m} < u < 5\,u_\mathrm{p}$ (Perry and Green 1997). A fluidized bed exists when the pressure drop (Δp) across the bed balances the weight of the bed. The bed remains uniform if $\mathrm{Fr} < 1$, where (Fr) is the Froude number. Δp depends on the thickness of the bed, its porosity, and the density difference between granules and air.

The air velocity (u, m/s) for achieving fluidization of a bed of granules is given by the equation

$$u = [(\rho_s - \rho)g/\eta]\left[\left(d^2\varepsilon^3\right)(180(1 - e)\right] \tag{4.16}$$

where

ρ_s, density of solid particles (kg/m^3)
ρ, density of air (kg/m^3)
g, acceleration due to gravity (m/s^2)
η, viscosity of the fluid (Pa s)
d, diameter of particles (m)
ε, porosity of the bed (void fraction)

Agglomerates produced in fluidized beds have less strength than those created by rotating methods; nevertheless they have better instantization properties. High humidity supports agglomeration. However, if the moisture content of agglomerates is high, then drying of granules is required. In fluidized bed agglomeration, significant powder may be produced due to attrition between particles. Therefore, in many cases, screening and recycling of powder is applied.

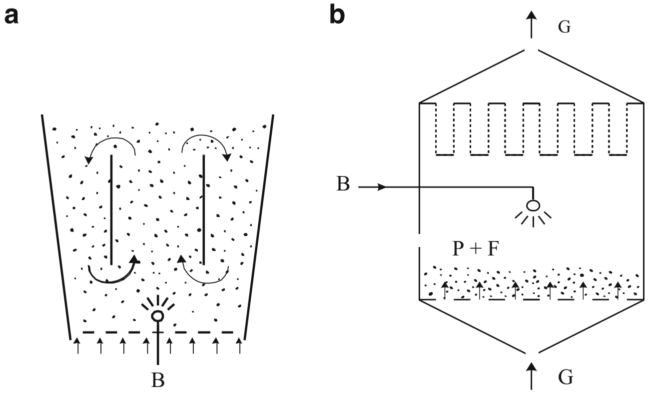


Fig. 4.29 Fluidized bed agglomeration (see text). *B* binder, *F* feed, *P* product, *G* gas

Factors influencing agglomeration in a fluidized bed are (Perry and Green 1997) (a) liquid (binder) rate, which increases size, density, and strength of the granules; (b) liquid droplet size, which increases size and homogeneity of the granules; (c) air velocity, which increases attrition rate and initially decreases and later increases the granule growth; (d) bed height, which increases strength and density of the particles; and (e) bed temperature, which decreases strength and density of the particles.

There are several methods of fluidized agglomeration (Fig. 4.29). They vary mainly in the way materials are fluidized.

Fluidized Bed-Spray Agglomerators (Vometec, Glatt)

Fluidization of granules takes place in a bed that is formed in a cylindrical or conical vat (wider at its upper part), as the material that comes in the equipment is blown by air, coming from the bottom of the vat (Fig. 4.29a). At the same time, binder is sprayed in the dispersed material. On the top of the vat, there are filters collecting dust or any other fine particles, which are then recycled. Capacity of such equipment in batch processes may be up to 2000 L. The floor space required is about 4–5 m^2 and the height may be up to 10 m. The required energy for air blasting and spraying of liquids is about 80 kW.

(a) Recycling Fluidized Bed Agglomerators (Wurster)
This type of equipment is similar to the fluidized bed-spraying agglomerator. Its main difference lies in a tube (in some cases a Venturi pipe), placed concentrically above the bottom of the conical vat (Fig. 4.29b). The fluidized bed is divided into two parts: the upward streaming bed in the central tube and that around it, flowing downward (similar to a spouted bed dryer, Chap. 8). The bed in the tube is formed as both air blown upward through the perforated bottom of the vat and binding fluid and also sprayed in the same direction,

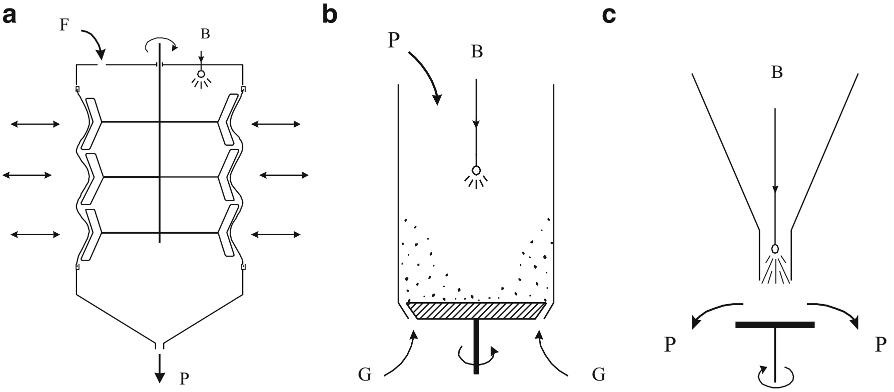


Fig. 4.30 Combined fluidized bed agglomeration

flowing through the central tube. The material falls then back to the lower part of the vat, through the gap formed between the central tube and the wall of the conical vat, creating the external part of the bed. There it is recirculated, as it is carried along by the air that is continuously blown through the perforated bottom of the vat. The larger granules are removed at the side of the vat. Agglomerates are formed after 3–5 recyclings. The volume of such equipment is up to 700 m^3 (Dialer et al. 1986).

(b) Combined Fluidized Bed Agglomeration

Systems combining air flow with agitation belong to this category (Fig. 4.30). Mixing is very intensive and very short (1–3 s). Therefore, the dimensions of such equipment are small. However, since the residence time of granules in such equipment is extremely short, control of particle size is difficult, and good dosing of the key materials is indispensable. Main benefits of such equipment are the little space required and the very short time of agglomeration.

Factors influencing the efficiency of such equipment are (a) pre-dosing of components, (b) binder quality, (c) properties of solids to be agglomerated, and (d) speed of rotation.

(c) Shugi Agglomerator

This equipment consists of a cylindrical vat/tube, in which agglomeration takes place, as air is blown by impellers installed in it, and sprayed binders are mixed, while moving downward. Air velocity and mixing are controlled by changing the type, number, and angle of impellers. The adjustable speed of rotation is 1000–3000 rpm. The volume of the cylindrical vat/tube is up to 400 m^3 and its height up to about 4 m. The capacity depends on the product agglomerated and on the size of the equipment. Since processing lasts only a few seconds, the cylindrical vat/tube has a small product hold up. The volume of air flowing is 10–30 m^3/ton and its pressure 10–40 bar. Usual processing time is 3–10 s, capacity may vary between 0.3 kg and 30 tons/h, and energy consumption is about 1–100 kWh/ton. In a variation of this machine, the wall of the processing chamber/vat is flexible, and it is moved by means of a mechanism, in which rolls press the wall externally as they move up and down.

(d) Centrifugal Agglomerator

In centrifugal agglomerating equipment, agglomeration is achieved by mixing key components of different density on a rotating disk. In another machine, mixing and agglomeration take place as key components are supplied on a rotating disk, heated and tumbled on a stator, which is a cylindrical wall surrounding the rotating disk. Disk and wall form effectively a high-walled pan, whose bottom is rotating, leaving a slit between it and the stationary wall. Air blown upward through the slit increases the mixing intensity of the material concentrated around the edge, where the disk meets the wall. This machine is also used in the manufacturing of pharmaceuticals (forming globular drugs).

Drying Agglomeration

Drying agglomeration is accomplished during spray, or fluidized bed drying. In both cases, granules come in contact with powder that is whirled with them. High humidity in the agglomeration chamber is helpful. Binders may not be required, if either the granules are not completely dry or the powder and particles added flow through a moist environment, before contacting the dried granules. The agglomerates are instantized products.

(a) Spray Drying Agglomeration

In the spray drying tower, recycled powder of the already dried material is radially sprayed toward the center of the tower. In the whirling that takes place, agglomeration of the spray-dried granules occurs. If the additive powder is dry, it is added to the phase of the product which is not very dry. Otherwise, the powder must be wetted, e.g., by steam, before contacting the dried granules.

The stability and size of agglomerates depend on the (a) agglomerated material, (b) moisture and temperature of powder and spray-dried granules, (c) contact time of powder with granules, (d) size of the sprayed granules, and (e) relation of powder/granulate quantities.

The size of the granules may be controlled by proper spraying. The smallest droplets are produced, when pressure nozzles of a single material (product) are used. Two-media nozzles (product/air) produce larger droplets. Rotating discs, dispersing liquid that falls on particles, produce even larger droplets (Chap. 8).

(b) Fluidized Bed Agglomerators

This type of equipment is often used for subsequent drying of moist agglomerates. The fluidized granules come in contact with recycled powder of the dried material, and usually, for enhancing agglomeration, "atomized steam" is sprayed near the position that the powder is fed. The fluidized bed is divided in compartments by weirs. The position and size of compartments depend on the type of drying. The flow of granules of the desired size is controlled by the height of the last weir at the end of the equipment.

Requirements of an effective fluidized bed agglomeration are (a) narrow size distribution, (b) low dust emission, (c) no size limitations because of static design (no adjustable moving parts), (d) avoiding post agglomeration, (e) continuous removal of larger agglomerates from the fluidized bed, and (f) no blockage of the air distribution plate by moist (therefore heavier) granules.

4.3.2.3 Compression Agglomeration

General Aspects

In food processing, compression agglomeration is less important than free structuring agglomeration. It is mainly used in confectionery (chocolate processing, sugar further processing, production of candies, etc.) and in extrusion (production of flakes, pellets, pasta, etc.). Compressed agglomerates usually are produced by compression of powders. In all cases, compression agglomeration requires more energy (2–4 times) than structuring agglomeration. Usually, the compressed products have less moisture and an amorphous structure. As indicated in Table 4.11, compression agglomeration equipment may be classified into tableting, roll press, and pelletizing systems.

Factors influencing pressure agglomeration are (a) raw material used (form, structure, stickiness, moisture content, etc), (b) power applied, (c) duration of compression, (d) temperature of the product during compression, and (e) binders used.

Advantages of compression agglomeration are (a) increased strength of agglomerates, (b) utilization of products that cannot be agglomerated otherwise, (c) variety of shapes and sizes, and (d) exact dosage of components.

Disadvantages of compression agglomeration are (a) high energy requirement, (b) low processing capacity, (c) wear out of equipment and tools, and (d) cost of auxiliary tools (molds, dies) used.

Compression Agglomeration Equipment

Tableting Equipment

Tableting equipment may be further distinguished into machines in which the filling funnel changes position, moving from mold to mold, while pistons and molds are fixed (Fig. 4.31a), and machines in which the filling funnel is fixed while the pistons with molds change position periodically (Fig. 4.31b). In the first case, reciprocating movement of the filling funnel occurs, stopping each time

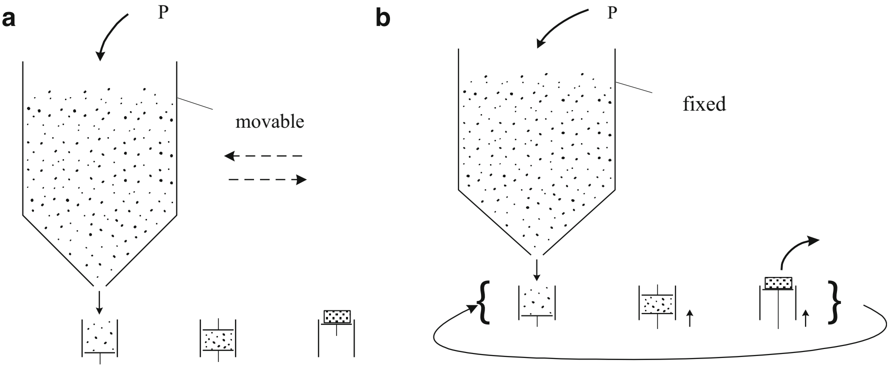


Fig. 4.31 Tableting agglomeration (see text). *P* product

exactly above the mold that has to be filled up. In the second case, molds are placed on a round table, which rotates and stops every time molds reach the funnel.

Advantages of tableting machines are their accuracy in making products of good strength, certain shape, and density. They can also guarantee precise dosing of constituent materials, which makes them indispensable in pharmaceuticals.

Tableting machines are used in the production of compressed products of exactly defined specifications (density, shape, form, etc.). Powder is filled in molds and compressed by reciprocating pistons. Often, two pistons are used, one forming the bottom of the mold, in which the material is compressed, and the second exerts the pressure required. After compression of the material between the two pistons, the upper piston removed and the lower pushes out the compressed agglomerate. Such machines are mainly used in the pharmaceutical industry, while in food processing they are used for producing candies.

The capacity of tableting machines depends on the type of material compressed and on the size of the tablets produced. Capacity is reduced as size is increased. The capacity of the rotating table machines is larger than that of the reciprocating machines. For about the same pressure on products and the same dimensions of products, the capacity of a rotating table machine can be 30 times larger (with 3–5 times more energy input).

Modern tableting machines are fully automated, and large ones can produce up to 1 million pieces per hour for tablet diameter of 11 mm and height of 8–9 mm. The depth of the cylinder that has to be filled with powder and compressed between the two pistons is 18 mm. The compression force depends on the capacity of the machines and is 50–100 kN. The speed of rotation of the round table with the molds is 30–100 rpm. Such machines do not require much space (1–2 m^2). Their weight is 2–5 tons and the required power 10–15 kW.

Factors influencing tableting are (a) flow properties of material, (b) binders used, (c) adhesion of tablets on the compression pistons, and (d) facility of tablet removal after compression.

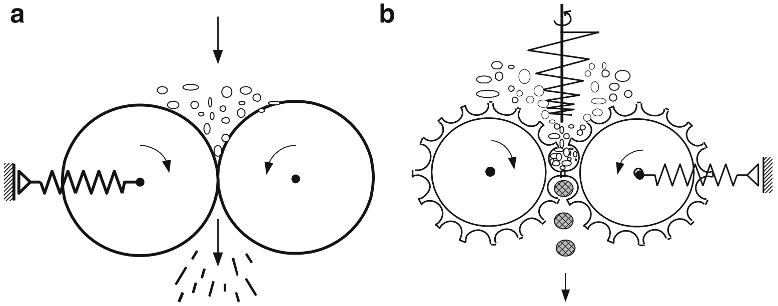


Fig. 4.32 Roll pressing agglomeration. (**a**) Smooth; (**b**) structured rolls

Roll Pressing Equipment

Roll pressing agglomeration equipment may be further distinguished between (a) smooth (Fig. 4.32a) and (b) structured pressing rolls (Fig. 4.32b). In both cases, two reversely rotating cylinders are used. In the first case, the surface of the cylinders is smooth, while in the second it may have structures depending on the shape the compressed products must get, or may have gear-wheel structure. Their main advantages are the utilization of relatively low value materials (e.g., by-products), transforming them economically to easy to handle useful products.

Roll press machines can produce large quantities of uniform products. However, these products are less uniform than those produced by tableting machines. Rolling machines consist of two metallic cylinders, one roll is fixed while the other is adjustable, so that the gap between the two rolls can be controlled. In calculations of roll systems, processing pressure, torque, and angle of nip are important. Processing pressure is needed for calculating the load on the bearings and fastening/support of the shaft of the cylinders. The torque is needed for calculating the required power consumption. The angle of nip determines the ability of rolls to grip material and drive it through the rolls. Larger angles of nip increase the time of compression. If the product to be compressed is very fine, then a snail gear moves the material toward the rolls. For forwarding granules/particles through the rolls, the force $F_s > F_v$ or $\mu > tg\alpha$. For smooth rolls, $\mu = 0.3$ which corresponds approximately to an angle $\alpha = 30°$ (Fig. 4.33).

$$F_s = F \sin \alpha \tag{4.17}$$

$$F_s = F_r \cos \alpha = \mu F \cos \alpha \tag{4.18}$$

Common dimensions of rolls are diameter, $D = 0.8$–1.5 m, and width, $b = 0.6$ m (Perry and Green 1997; Stiess 1992). Both cylinders rotate at the same speed. Rotation must be moderate, since very high speeds will increase the amount of air released during pressing. This air causes some kind of fluidization of the material waiting above the compression zone to be processed. Especially in the

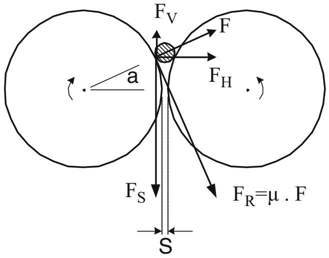


Fig. 4.33 Angle of nip in rolling processes

case of structured rolls (briquetting) and fine powder, this reduces the homogeneity of the compressed material (Stiess 1994). Speed of rotation is usually 5–40 rpm (Heinze 2000). Pressure (*P*) depends on the type of machine and the product compressed. For compressing dry material by smooth rolls, $P = 1$–14 kbar, and for compressing moist materials, $P = 1$–100 bar (Rumpf 1975).

Factors influencing roll pressing of briquettes are (a) type of machine, (b) size of feed material, (c) size distribution of feed material, (d) shape and surface of feed material, (e) temperature of processing, (f) moisture content of products, (g) type and quality of binders, and (h) hardness and brittleness of product.

Pelletizing Equipment

Pelletizing agglomeration machines are further subdivided into (a) screen pelletizers, (b) hollow rolls, and (c) extruders. In the first case, the material is agglomerated as it is pressed through screens. In the second case, rolls are perforated and the product is agglomerated as it passes through holes inside the rolls. In the third case, a screw drives and compresses the material against a perforated plate or through special dies. Extruders are discussed in the last part of this chapter (forming equipment).

Advantages of pelletizing machines are the possibility of yielding products of relatively high variety of constituents and solubility and processing of relatively moist materials. The different types of compression machines are analyzed in the following section. The data for equipment given are only indicative and may vary according to the material compressed.

In pelletizing machines, the key material is compressed through screens which determine the shape of the pellets formed. There are two basic variations: (a) fixed screens, while rollers or blades force the material to pass through them, and (b) material is pressed through perforated hole cylinders.

In the first category, screens are stationary while rolls or blades rotating over material press it through screens underneath (Fig. 4.34a, b). Pellets formed are cut to the desired length through scrapers lying on the internal or external surface of the whole cylinder. The capacity of such machines may vary significantly according to the kind of compressed material and the type of pellets produced. Indicative examples are product throughput of 1–300 kg/h and power requirement up to

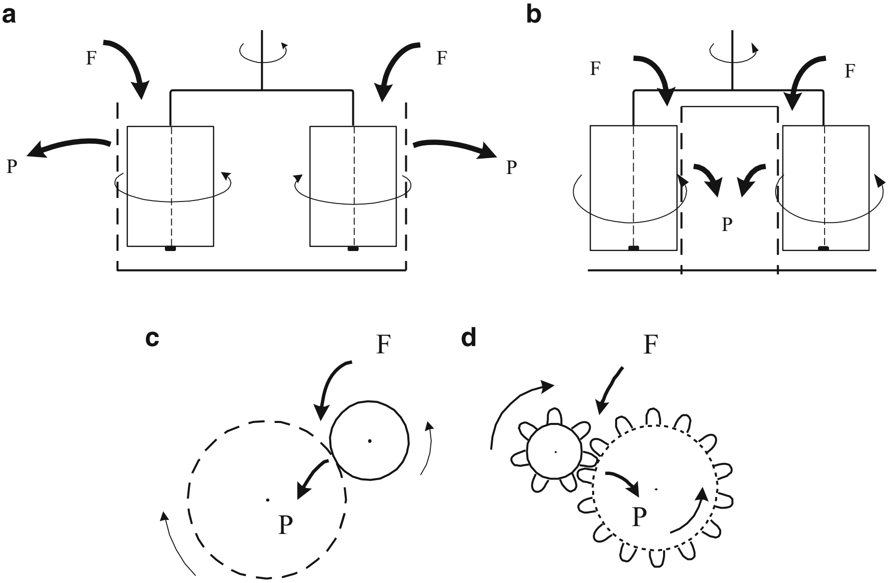


Fig. 4.34 Pelletizing equipment (see text)

3 kW, or product throughput of 2.5 tons/h and power requirement up to 22 kW. Pellets are usually cylindrical, and their diameter may vary between a few mm (e.g., 1–3 mm) and a few cm (e.g., 5 cm or even larger). The blades or rollers rotate at about 2 m/s, and the energy required for pressing may be around 10–20 kWh/ton. Slow rotation is beneficial as it keeps wear and noise below the acceptable limit of 80 db and facilitates the release of air of compressed material.

The second category of pelletizing machines is often used for producing pellets from moist materials. In this case, the material is pressed through a perforated cylinder by a counterrotating non-perforated cylinder (Fig. 4.34c). The diameter of such pellets is usually up to 5 mm. The capacity of such a machine may be up to 3 tons/h, and its energy requirement is about 5 kW/ton. A variation of perforated cylinders is that in which perforated gear wheels are used. This system is used for pelletizing hard materials which are pressed through nozzle bores situated between the teeth, along the whole width of the pitch of the gear wheels (Fig. 4.34d).

In the Hosokawa Bepex machines of this type, it is possible to influence the shape and dimensions of the pellets by placing different dies in the holes. Such machines may produce pellets of 1–10 mm. The diameter of gears is about 30 cm, their width is 4–10 cm, and the power requirement to drive such a system is 4–11 kW.

Factors influencing pelletizing are (a) resistance in forwarding the material through holes, (b) residence time of material in the holes, (c) pressure exercised, (d) moisture of material, binders used, and (e) dimensions of final product.

4.3.3 Selection of Agglomeration Equipment

In selecting agglomeration equipment, besides the general selection criteria of processing equipment, mentioned in Chap. 2, the following economic and technical criteria must be fulfilled:

(a) Economic criteria: (1) Cost of equipment must be consistent with its capacity and quality; (2) price of binders or other additives must not be excessively high; (3) the relation of energy consumption to production capacity must be low; (4) wear of machine must be low; and (5) spare parts must be easily replaced and not expensive.
(b) Technical criteria: (1) Capacity must be coherent with the type of processing requirement (batch/continuous processing); (2) quality of products, including texture, solubility, precision of composition, and shape, must be fulfilled; (3) noise of machines must not exceed 85 dB, and since in most cases raw material is in powder form, agglomeration equipment must be airtight; and (4) foundations should absorb vibrations, especially when reciprocating or fast running machines are used.

4.4 Homogenization

4.4.1 Introduction

In homogenization, uneven particles of liquid foods are reduced into smaller, more uniform units. Homogenization retards the separation of mixed liquids into separated groups and eliminates consistency variations. Homogenization enables better viscosity control, and it supports jelling at low temperatures. It facilitates cell rupture and comminution of fibrous materials dispersed in liquids.

Homogenization is a further step of emulsification. Homogenizers and emulsifiers are often used interchangeably with respect to equipment of emulsification (Fellows 1990). In emulsification of liquids, one or more liquids forming the internal phase are dispersed in another liquid, which forms the external continuous liquid phase, provided the liquids are immiscible (Fig. 4.35). Due to surface tension, the liquid droplets (internal phase) tend to form spheres. Subsequently, the small spheres tend to get together supporting the disintegration of the emulsion in separate continuous liquid phases. The physical properties and stability of an emulsion depend on the relation and type of the internal to the external phase. If the interfacial tension is high, the formation of emulsions is difficult, and furthermore, when these are formed, they are not very stable (Brennan et al. 1990).

Emulsification is governed by droplet disruption, due to energy input and re-coalescence of unstabilized droplets (Schubert and Karlstein 1994). The formation of such emulsions requires work input for overcoming the resistance to creation

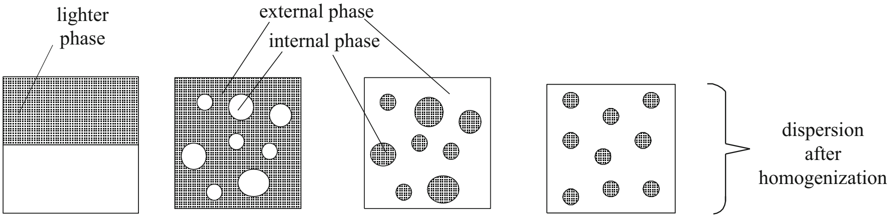


Fig. 4.35 Forms of emulsification and dispersion in a two liquid system

of new surfaces, caused by interfacial tension. This is accomplished in several ways. If the product has a very high viscosity or if the dispersed particles are quite large (e.g., fibrous particles), homogenization can be achieved by agitation. However, in most cases homogenization concerns low viscosity liquids. In this case, fluid droplets are broken down into smaller units by methods such as pressure, rotor stator, and ultrasound homogenization (Treiber 1978).

Some examples of application of homogenization to food processing are pulps, fruit and vegetable juices, vegetable oil, ketchup, baby food, salad sauces and creams, milk and milk products, liqueurs, gelatin, starch production, dispersion of gases in fermentation processes, dispersion of hops in beer production, and homogenization of cocoa in candy manufacturing.

The type of equipment used depends on the final size of particles and the output required. The higher the pressure, the smaller the particles. Pressures may vary from about 120 to 600 bar. If low pressure is applied, two-stage homogenization may be required. In high-pressure homogenization, the final particle size can be lower than 1 μm.

4.4.2 Homogenization Equipment

4.4.2.1 Pressure Homogenization

Pressure homogenization is applied to liquids whose viscosity is less than 0.2 Pa s (Brennan et al. 1990). Pressure homogenizers consist of two main parts, the high-pressure pump and the homogenization valve, which is the most important element of the equipment (Fig. 4.36). The emulsion is fed at 1–2 bar pressure into a reciprocating pump, consisting of 3 or more plungers. The larger number of plungers secures constant product feeding and reduces machine vibration. Subsequently, the emulsion flows through the suction valves of the pump cylinders, during the withdrawal of the plungers, which follows each compression. The suction valves close, while each plunger moves forward again, compressing the contents of the corresponding cylinder through the discharge valves, to the homogenization valve. The pressure applied depends on the product and the final size of particles required. With respect to the product, it is noted that in liquids, consistency

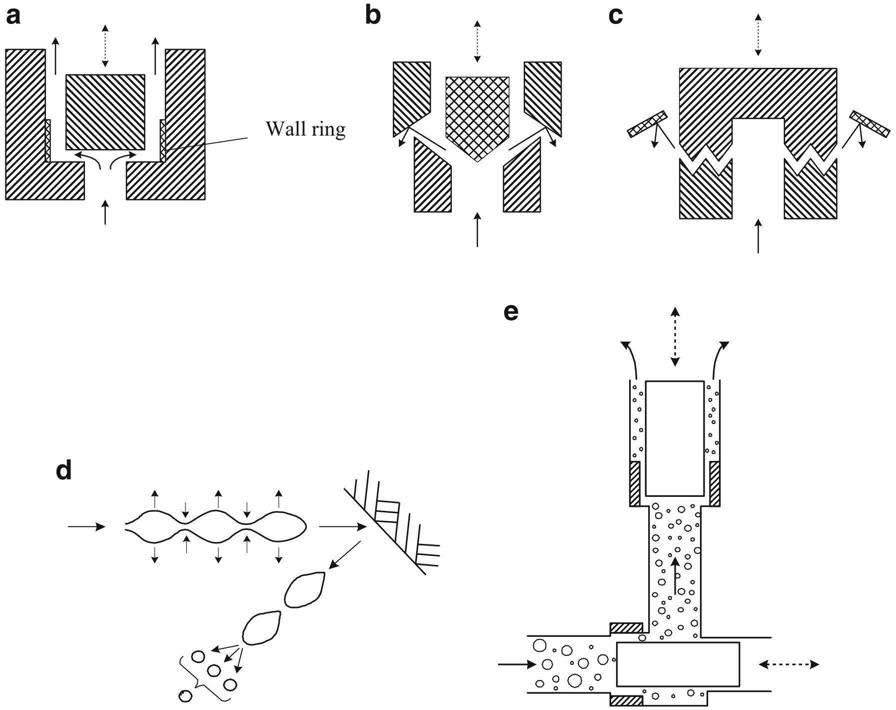


Fig. 4.36 Pressure homogenization valves (see text)

influences the process through the physical properties. In milk, e.g., the efficiency of homogenization decreases if the fat content increases, since fat increases the viscosity of the product. The pressure in homogenization may be 130–500 bar. Figure 4.37 indicates the influence of pressure on the mean particle of milk globules (Kessler 1981). The mean diameter of fat globules (d_m, m) in homogenized milk is given by the equation

$$d_\mathrm{m} \sim (w/u_\mathrm{o})(\sigma/\rho\nu)(1/\mathrm{Re})^{1/3} \tag{4.19}$$

where

w, width of valve gap (m)
u_o, velocity at gap aperture (m/s)
σ, interfacial tension (N/m)
ρ, density of the continuous phase (kg/m^3)
ν, kinematic viscosity of the continuous phase (m^2/s)
Re, mean Reynolds number in the valve gap

The type of homogenization valve is very important for the efficiency of homogenization. It consists basically of a plunger and a valve seat (Fig. 4.36a–c).

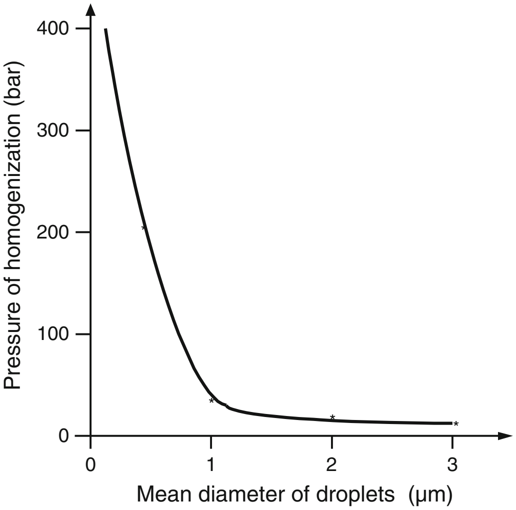


Fig. 4.37 Influence of pressure on the mean diameter of milk globules

Between the plunger and the valve seat, a ring gap is formed. As compressed material arrives at the plug valve, it flows radially through the narrow ring gap and is then impacted on the surrounding wall ring. Valves with a sloped seat (Fig. 4.36b) need higher pressures than flat-seated valves. The valve efficiency increases (i.e., less pressure for the same result is required), if a flat-seated valve has grooved surface (Fig. 4.36c) (Kessler 1981). In this case, the droplets are compressed and expanded as they flow along the peaks of each groove. This probably facilitates the subsequent breaking when the droplet impacts on the wall (Fig. 4.34d). If the droplets are not small enough (which happens at relatively low pressures), the emulsion is not very stable. In this case, a second stage of homogenization is required (Fig. 4.36e). In a two-stage homogenization system, the pressure of the first stage can be 150–200 bar and that of the second stage about 20 % of it. In milk homogenization, one stage is enough, if fat globules are <0.7 µm and no clusters, due to casein subunits, are formed (Kessler 1981).

The ring gap can be adjusted by controlling the position of the valve plunger. The adjustable gap can be 15–300 µm (Brennan et al. 1990). The product velocity in the ring is very high (200–300 m/s). According to Bernoulli's law, this high velocity causes a rapid pressure reduction and initiation of cavitation, which contributes to weakening the coherence of the droplets and finally to size reduction (disruption). Several efforts have been made to interpret the mechanism of particle size reduction (Treiber 1978; Kieffer 1977; Kurzhals 1977). Mulder and Walstra (1974) have summarized the forces that may act in homogenization. In pressure homogenization, the most important are shear, impact, cavitation, pressure gradient, and turbulence forces.

The energy loss during pressure homogenization is significant. As measurements on milk have shown, although the residence time of the product in the homogenization valve is extremely short, its temperature increases by about 4–5 °C

(Klostermeyer 1991). However, this temperature increase is welcomed, since the "degree of homogenization" (i.e., the ratio of the volume of particles of the internal phase that is reduced below a certain size limit to the total volume of the internal material of the emulsion) increases when products are preheated (Kessler 1981) (Fig. 4.38). The preheating temperature depends on the product. Milk, e.g., is preheated to 60–70 °C and essential oils for lemonade to 25–40 °C. In the case that the equipment is used to treat aseptically processed food, homogenization valves and pressure pump are constructed in such a way that no contamination of the processed food occurs. In most constructions, this is achieved by using live steam around the vulnerable contamination points.

In some cases, such as in the homogenization of primary or intermediate food products (e.g., milk for cheese, fruit pulps for marmalades, citrus pulp for drinks), low-pressure homogenization (<70 bar) is enough. Besides reduced energy cost, this increases also the capacity, since the capacity of equipment depends on the pressure applied (Fig. 4.39).

Some indicative data of pressure homogenizers are given in Table 4.12. The size of a pressure homogenizer is determined by its motor and pump, since the volume

Fig. 4.38 Influence of preheating on the degree of homogenization

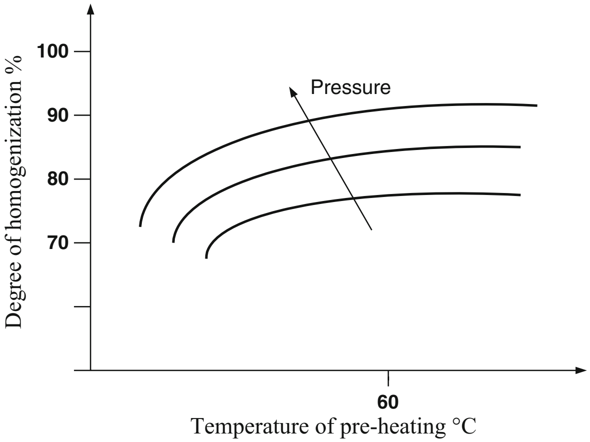


Fig. 4.39 Influence of pressure on the capacity of homogenization

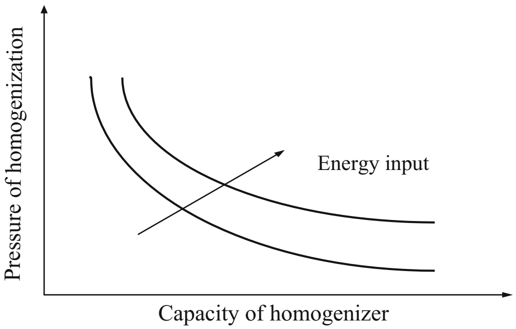


Table 4.12 Indicative technical data of homogenizers

Pressure (bar)	Capacity ×1000 (lit/h)	Power (kW)	Dimensions (m)	Weight[a] (tons)
100–550	28–14	95–225	2.0 × 1.5 × 1.5	5.0
140–550	13–5	75	1.5 × 1.5 × 1.5	2.5
200	10–25	110	1.5 × 2.0 × 2.0	3.0
350	0.5–5	35	1.0 × 1.5 × 1.0	1.0
200–300	5–3	43	1.0 × 1.0 × 1.5	3.0

[a] Without motor

of the homogenization valve is not more than 0.5–0.7 m^3. The relation weight (tons)/volume (m^3) is almost linear and can be approximated by the equation: (weight) = (0.7) × (volume) + 0.2. The power requirement of pressure homogenizers is 30–250 kW. High pressure reduces the equipment capacity.

4.4.2.2 Colloid Mills

As mentioned in b, the description of crushing and grinding equipment (Fig. 4.19f), colloid mills can also be used in homogenization of liquids. In liquid homogenization, colloid mills are used when the viscosity of the product is relatively high (>1 Pa s) (Brennan et al. 1990). This kind of equipment is discussed in the Sect. 4.2.3 of this chapter. When a colloid mill is applied to homogenization, the disk rotates at 3000–15,000 rpm. The more viscous a product, the slower the rotation of the disk. The gap between the discs may be adjusted between 0.1 and 1.0 mm. The pressure during homogenization lies between 1.5 and 3.0 bar. At relatively high constant homogenization pressures, the influence of the gap between the discs on the capacity of the mill is not important. It becomes significant at low pressures (e.g., <1.5 bar). The capacity and power requirement of a colloid mill in homogenization depends on the processed product. It may be 2 to more than 30 m^3/h, and the required energy may lie between 5 and 100 kW. In homogenization, e.g., of oil, capacities of 4000–40,000 kg/h and power consumption 6–75 kW have been reported. In using the same colloid mill in the homogenization of more viscous products, such as mayonnaise, containing about 80 % of oil and meat paste, the production is reduced to 1000–1200 kg/h and the power consumption can rise to 90 kW.

4.4.2.3 Rotor-Stator Homogenizers

The construction of this homogenizer is very similar to the rotary grinder, described in the Sect. 4.2.3 (Fig. 4.21). The machine consists of a rotor assembled horizontally or vertically very near to a stator. Both are usually cylindrical or conical. The rotor can be also made of concentric discs. Both the stator and the rotor surfaces that face each other are "structured" (usually grooved). In the case of discs, their periphery, as indicated in Fig. 4.21, is either toothed or has a turbine-like construction. The product is size reduced by shear, impact, and cavitation forces, developed in the structured gap between the stator and the fast turning rotor (2000–8000 rpm). Such equipment is used in *homogenization* of products in the viscosity range, 1–30,000 mPa s (Treiber 1978). The particle size is controlled through the type of rotor used and its position with respect to the stator (width of the gap). The motor power of rotor-stator homogenizers is 8–100 kW for equipment with capacities 10–60 m^3/h, and it can be up to 500 kW for capacities of 120 m^3/h.

4.4.2.4 Ultrasonic Homogenizers

In ultrasonic homogenizers, the homogenization of low viscosity liquids is carried out by alternative compression and tension, caused by high-frequency sound waves (18–30 kHz) (Fellows 1990). The particles formed by cavitation forces have size 1–2 μm. There are two main categories of ultrasonic homogenizers, the electrically created and the mechanically induced. An example of electrically created size reduction is that produced by piezoelectric systems. A quartz, e.g., vibrates on the surface of water, producing very fine particles (Fig. 4.40a). This method is used for increasing the humidity in cold stores, since water particles in such rooms must be as fine as possible for reducing the formation of condensate and mold on the product. Another possibility is to produce sound waves through vibration of electromagnetic devices in the liquid (Fig. 4.40b). The mechanically induced ultrasound can be, e.g., created through metal blades vibrating at their resonant frequency as small particles (e.g., globules) fall on them, while flowing through tubes (Fig. 4.40c). Since the size distribution of particles created this way is wide, the homogenization process must be repeated if a more even size distribution is required. Products homogenized by these methods are oil emulsions, salad creams, ice creams, and baby food.

4.4.2.5 High-Pressure Homogenization

See Chap. 12, Sects. 12.2.5 and 12.5.

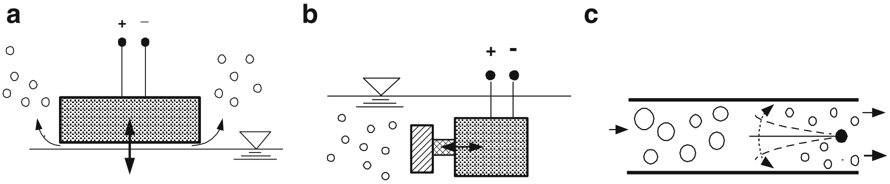


Fig. 4.40 Systems of ultrasound homogenization. (**a**) Quartz vibrator; (**b**) electromagnetic; mechanical vibrator

4.5 Mixing and Forming Equipment

4.5.1 Introduction

Mechanical mixing operations are used widely in the food processing industry to give new physical, rheological, and organoleptic properties to food products, to disperse components in multiphase mixtures, to improve heat and mass transfer, and to develop new food structures (Rielly 1997). The design and operation of mixing equipment depends on the physical and rheological properties of the initial components and the final products. Entirely different mixing systems are required for gas–liquid, liquid–liquid, solid–liquid, and solid–solid mixing. The theory of mixing is more developed in fluid (liquid–liquid) systems, while solid mixing is treated mostly empirically.

4.5.2 Fluid Mixing Equipment

The primary engineering characteristics of fluid mixers are the power (energy) requirements and the efficiency (uniformity) of mixing. Mixing of gases or liquids in a liquid is based on the mechanical agitation to disperse a component or a phase into another phase. Factors influencing mixing of liquids in agitated tanks/vessels:

1. Mixing efficiency
   - (a) Viscosity of liquid
   - (b) Type of mixing device (propeller, paddle, etc.)
   - (c) Position of mixing device (e.g., eccentricity, etc.)
   - (d) Mounting of mixing device (e.g., angle of immersion)
   - (e) Form of tank (e.g., cylindrical, parallelogram, etc))
   - (f) Form of bottom of tank (e.g., flat, inclined, etc.)
   - (g) Baffles
2. Additionally, factors that have to be considered in selection are:
   - (a) Facility of cleaning
   - (b) Required space
   - (c) Construction (e.g., stability, materials used, open or closed type, filling and emptying, etc.)
   - (d) Possibility of heat treatment (heating, cooling of liquid)

4.5.2.1 Agitated Tanks

The basic mixing unit is the agitated tank, i.e., a vertical cylindrical vessel equipped with one or more impellers and baffles with specified dimensions for a given application. Various types of impellers are used, depending on the volume of the vessel and the viscosity of the liquid. High-speed agitators include propellers, turbines, and hydrofoils, while anchors, paddles, ribbons, and screws are used for low-speed applications.

Mixing of low-viscosity liquids is improved by baffles on the walls of the vessel, which prevent the creation of vortices in the center of the tank. Baffles are ineffective in mixing very viscous or non-Newtonian fluids. Figure 4.39 shows diagrammatically a typical agitated tank, equipped with a propeller agitator and 4 wall baffles. Typical geometries of agitated tanks for fluid mixing are:

$$(H/D) = 1, (d/D) = 1/3, (h/D) = 1/3, \quad \text{and} \quad (B/D) = 1/10 \tag{4.20}$$

The mixing in agitated tanks is expressed by the Reynolds (Re) number, which is defined by the equation (Newtonian fluids)

$$\mathrm{Re} = N d \rho / \eta \tag{4.21}$$

where (N) is the impeller rotational speed ($1/s$), (d) is the impeller diameter (m), and (ρ, η) are the density (kg/m^3) and viscosity (Pa s) of the liquid, respectively. In agitated tanks, the following flow regimes are distinguished: laminar flow ($\mathrm{Re} < 10$), intermediate flow ($10 < \mathrm{Re} < 10{,}000$), and turbulent flow ($\mathrm{Re} > 10{,}000$). In liquids of low-viscosity liquids, turbulent flow ($\mathrm{Re} > 10{,}000$) can be obtained at high speeds. For non-Newtonian fluids, the (Re) number is estimated from the equation

$$\mathrm{Re} = \left(\rho d^2\right) / \left(K \beta^{n-1} N^{n-2}\right) \tag{4.22}$$

where (K, Pa s^n, and n) are rheological characteristics of the fluid, defined by the power law equation

$$\tau = K \gamma^n \tag{4.23}$$

(τ) is the shear stress (Pa), and (γ) is the shear rate ($1/s$) of the fluid (Saravacos and Maroulis 2001).

The characteristic constant (β) is defined by the empirical equation (Holland and Brugg 1995)

$$\gamma = \beta N \tag{4.24}$$

The empirical constant (β) is characteristic of the agitated system, with typical values of 10–13.

The shear stresses and shear rates vary widely within agitated tanks. The apparent viscosity of pseudoplastic (non-Newtonian) fluids decreases significantly ($n < 1$) as the speed (N) is increased (see Chap. 3). Thus, the mixing will be faster close to the agitator blades (propeller or turbine) than away from it, creating a well-mixed volume of liquid, within a surrounding volume of unmixed liquid. For such systems, paddle of anchor agitators are more efficient, since they can mix the whole volume of the liquid.

4.5.2.2 Power of Mixing

The power of mixing in an agitated tank is given by the empirical equation

$$\text{Po}/\text{Fr} = c\text{Re}^m \tag{4.25}$$

where

$$\text{Power number Po} = P_\text{A}/\left(\rho N^3 d^5\right) \tag{4.26}$$

$$\text{Froude number Fr} = N^2 d/g \tag{4.27}$$

(P_A) is the agitator power (W), $g = 9.81$ m/s^2 is the acceleration of gravity, and (c) is a characteristic constant of the agitated system and the flow regime. The Froude (Fr) number is a measure of the vortex, formed in the center of unbaffled agitated tanks. For baffled tanks and laminar flow, Fr = 1.

In laminar flow, Eq. (4.25) yields

$$P_\text{A} = c_\text{L} N^2 d^3 \eta \tag{4.28}$$

Thus, the power is proportional to the viscosity, but independent of the density of the liquid. In turbulent flow, the power is proportional to the density, but independent of the liquid viscosity. In the intermediate flow range, the agitation power is estimated from empirical equations or diagrams of log(Po/Fr) versus log(Re) for both Newtonian and non-Newtonian fluids (Perry and Green 1984; Walas 1988; Holland and Brugg 1995). The scale-up of mixing in food processing is discussed by Valentas et al. (1991).

4.5.2.3 Industrial Mixers

Various types of industrial mixers are described by Dietsche (1998). In addition to the batch agitated mixers (Fig. 4.41), continuous in-line mixers are used, such as the static in-line (low shear) and the rotor-stator mixers for high shear, high viscosity, and particle disintegration. Colloid mills and pressure homogenizers, discussed earlier in this chapter, can be considered as continuous in-line mixers. Figure 4.42 presents some types of agitators.

Important factors in agitated tanks are their main dimensions (H, D), the diameter of the agitator (d), its distance from the bottom of the tank (h), and the

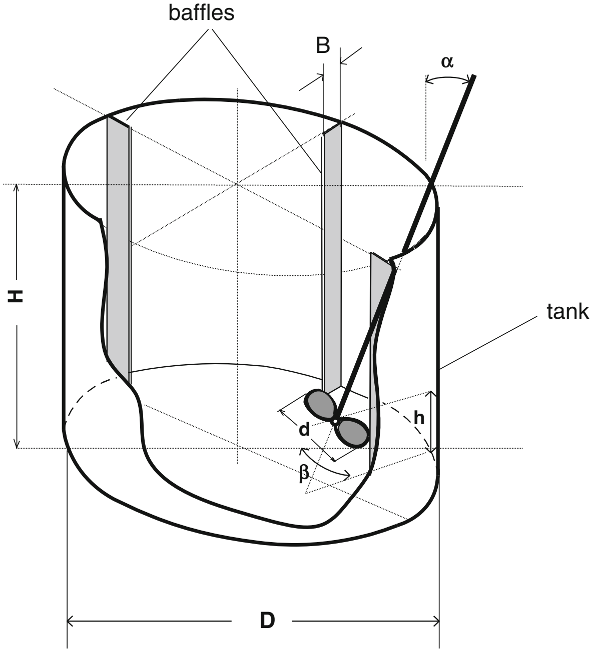


Fig. 4.41 Agitated baffled tank; *B* baffle width, *d* impeller (propeller) diameter

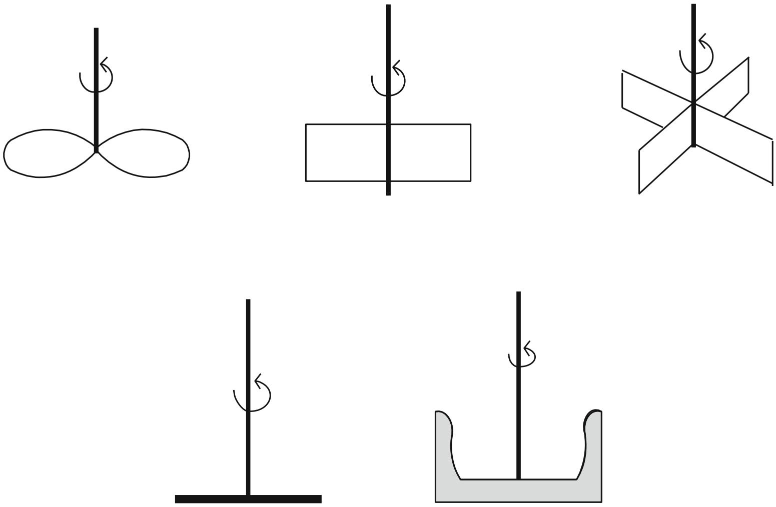


Fig. 4.42 Types of agitators

inclinations of the axis holding the agitator (α and β). In case of using baffles, important are also their number and their width (B) (Fig. 4.42).

Mixers of suspended solids in aqueous systems are operated at speeds high enough to prevent the settling of the particles. The suspension of solids in liquids is achieved by proper selection of the impeller type and the impeller/tank diameter ratio (Shaw 1992). High-shear mixers, suspension mixers, and colloid mills are described by Myers et al. (1999).

Gas–liquid mixers are used to absorb oxygen in aerobic fermentations. The absorption rate of oxygen in water solutions is controlled by mass transfer (see Chap. 11). High impeller (usually turbine) speeds are required to transfer the gas from the surrounding atmosphere, and the absorption is enhanced by supplying the gas through spargers at the bottom of the tank. Mechanical agitators are used on the surface of wastewater treatment tanks and pools to transfer oxygen from the atmospheric air into the water.

4.5.2.4 Food Mixers

Food mixers are carried out, in addition to chemical process mixing, for improving food quality, e.g., for texture and color development. Food mixtures involve many ingredients, including liquids, powders, gases, and granular (particulate) solids. Some important ingredients are present only in minor quantities, which should be dispersed evenly and efficiently in the final mixture.

High viscosity and non-Newtonian fluids require special mixing equipment. Mixing patterns and product characteristics are related in complex manner. Scale-up of food mixers is based more on constant food properties than constant power/volume ratios.

Multistage or staged mixing of a minor ingredient may improve product quality. Efficient dispersion of minor expensive ingredients is essential.

High shear stresses, induced by agitators, are required for making fine dispersions and emulsions, while low shears are used for mixing solid particles/pieces in solid or liquid phases. Undesirable segregation of particles from mixed products should be considered.

Mathematical modeling, e.g., lamellar model mixing, can elucidate the mixing mechanism of complex food mixers, such as the Brabender Farinograph (Prakash and Kokini 1999).

4.5.2.5 Selection of Mixers

The selection of appropriate fluid mixing equipment for a given application depends primarily on the viscosity of the liquid and the volume of the mixing vessel (Fig. 4.43). The mixing of viscous fluids requires large diameter impellers (e.g., paddles), which sweep a large portion of the tank volume. Large diameter impellers ($d/D > 0.5$), operated at speeds $N > 20$ rpm, are also needed for mixing non-Newtonian fluids, preventing the formation of a cavern (cavity) around the propeller. The power requirement is about 2 kW/m^3 of liquid (Rielly 1997).

The power requirements of the agitated tanks range from 2 to 100 kW. The impellers can be top or side entering, depending on the volume of the vessel.

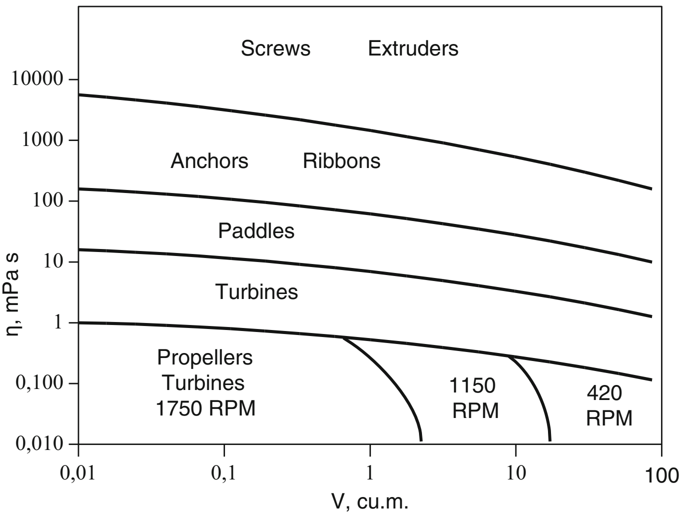


Fig. 4.43 Selection of fluid mixing equipment

The superficial liquid velocity near the impeller depends on the viscosity, varying in the range of 0.1–0.3 m/s. Technical data on agitated tanks (volume, superficial velocity, and power) are given in the literature (Walas 1988) and by suppliers.

4.5.3 Paste and Dough Mixing Equipment

The mixing of food pastes and doughs is accomplished in specialized equipment, developed empirically by equipment manufacturers and industrial users (Uhl and Gray 1966; Bhatia and Cheremisinoff 1979; Walas 1988; Levine and Behmer 1997). Double planetary mixers are used for highly viscous fluids and pastes. The revolving stirrers may be raised hydraulically and immersed in another mixing tank, while the first tank is emptied. Dough mixing and processing are important operations in the baking, pasta, and cereal process industries. Doughs are more solid-like and viscoelastic than usual pastes. Protein (gluten-based) doughs are basic for bakery and pasta products (Levine and Behmer 1997). The two other food doughs are the starch based (cereals) and the fat based (cakes and pies).

Mixing of protein doughs increases their viscoelasticity and gas-holding capacity, essential requirements for bread making. Gluten development during dough mixing (kneading) is based on the alignment, uncoiling, extension, and folding of the protein molecules. Dough mixers are usually batch units, and they can be vertical (most common), horizontal, and high speed. For small capacities (110 kg material, 3.7 kW), the vertical double hook/paddle mixers are preferred. For capacities up to 350 kg (22.4 kW), the double spiral mixers are used. The power requirement of these mixers is in the range of 0.35–0.70 W/kg of mix.

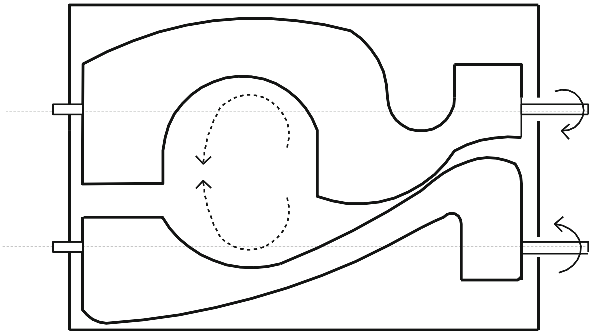


Fig. 4.44 Diagram of a Z-kneader

Spiral horizontal mixers, operating at speeds 35–70 rpm, have capacities of up to 1500 kg and power requirements of up to 100 kW. High-speed mixers (300–1200 rpm) are used for obtaining better quality products by faster mixing. A cooling jacket may be needed to remove the heat produced.

Kneaders or Z-blade mixers are used for doughs and pastes, which cannot be handled by anchors and helical ribbons. They are mounted horizontally and have two counterrotating blades. The blades have very close clearances with the walls of the trough for preventing buildup of sticky material on the wall. The kneaders achieve mixing by a combination of bulk movement and intense shearing as the material passes between the two blades or between the wall and one blade (Rielly 1997). Energy consumption per unit mass of doughs depends on the composition of the wheat (protein content) and the type of mixing equipment, e.g., 5–20 W h/kg. Figure 4.44 shows diagrammatically a Z-kneader.

4.5.4 Extrusion and Forming Equipment

4.5.4.1 Extruders

Extrusion is a complex food process combining several processing operations, such as mixing, cooking, kneading, heating, shaping, and forming. It is related to the palletizing agglomeration processes, discussed earlier in this chapter.

Extrusion is accomplished in a special screw conveyor, operated under controlled speed, pressure, temperature, and product flow. The shape of the extruded product is formed by forcing it through a specific die. Single or twin-screw extruders are used. Extruders have operational elasticity and versatility and do not affect environment. They act basically as positive displacement pumps, operating at high pressures and relatively low rotational speeds. In addition to the positive action of the screws, the product is also transported by drag flow, caused by friction with the barrel surface. The net flow is the difference between the forward drag flow and the backward pressure flow. The extruder screws are designed with decreasing pitch, or with a constant screw pitch but with conical barrel, so that the product is compressed as it is conveyed from the entrance to the exit of the barrel (Levine 1992; Heldman and Hartel 1997).

Extrusion is divided into low-temperature (isothermal) and high-temperature or cooking extrusion. Low-temperature (cold) extrusion is actually a forming (shaping) operation, used in the processing of pasta, cereal, and special food products, e.g., coextruded food and confectionery products (Heldman and Hartel 1997; Fellows 1990). Extruders operate continuously and efficiently, and they can replace some other shaping equipment, if the higher investment can be justified for a given application. Pasta extruders operate at about 50 % moisture, 50 °C, and 50 rpm.

Extrusion cooking is more widely applied than low-temperature extrusion. It is operated at higher temperatures and pressures, producing several starch-based food products (Harper 1980; Mercier 1989; Riaz 2000; Guy 2001). Extrusion cooking, operated at high temperatures, can be considered, in addition to forming, as a HTST thermal process, reducing microbial contamination and inactivating spoilage enzymes.

Extrusion science and technology is based on the application of food chemistry and food process engineering to physical, chemical, and mechanical changes of food materials subjected to the flow, pressure, shearing, and temperature conditions of the continuous food extruder (Kokini et al 1992).

The physical properties (density, texture) of the extruded products can be designed by controlling the operating conditions of a given extruder (Weipert, Tscheuschner, Windhab 1993; Paulus and Cheftel 1989).

In the *single screw extruder* of Fig. 4.45, the extruder is divided broadly into three sections: conveying (feed charge zone A), kneading (compression zone B), and pressurizing (transport zone C). In the die (b), the influence of elasticity of the product is large. The elasticity energy is liberated as soon the product exits the die. The pressure drop Δp, (a), is a function of the elasticity properties of the extruded product. In zone A, the product usually consists of a humid heterogeneous mixture. In zone B, a homogenous paste-like, easy to flow matrix arises. Here the condition of the product is influenced by its viscosity, while the influence of its elasticity properties is reduced (Weipert, Tscheuschner, Windhab 1993).

Twin-screw extruders because of their advantages are usually preferred in the food industry over the single-screw units. The material to be extrusion cooked is usually a cereal powder (e.g., corn, wheat) at moisture content of 15–20 %, which is compressed and heated above the gelatinization temperature and then expanded through a die to puffed (porous) product of desired shape. They can operate at higher speeds, providing higher flow rates, higher shear rates, and better mixing as they are also effective in a backward mixing. In case the humidity of the product during extrusion is too low, water is added along with the product input. Additional benefits of the twin-screw extruders are:

- The product flow in the extruder is independent of the feeding charge.
- The heat distribution during processing is more even.
- Processing of even fatty and sticky products, or even high humidity products, which glide in the single-screw extruders, is possible.

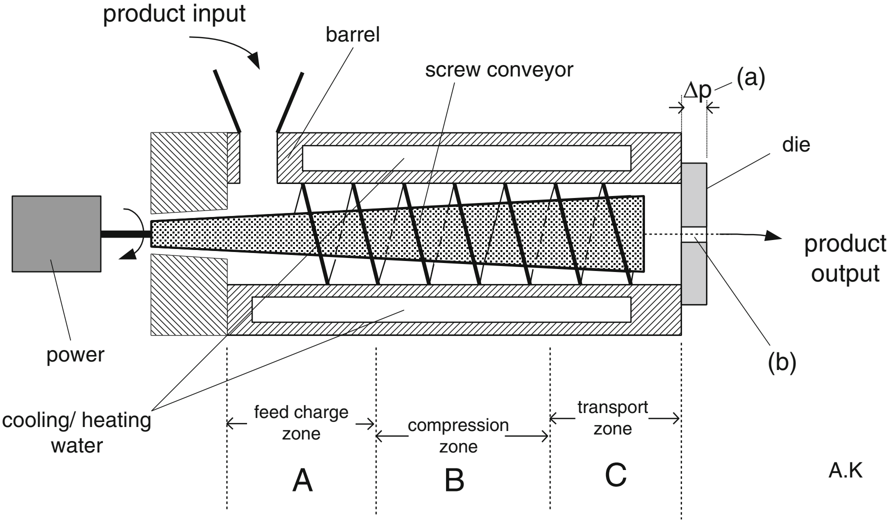


Fig. 4.45 Single-screw extruder

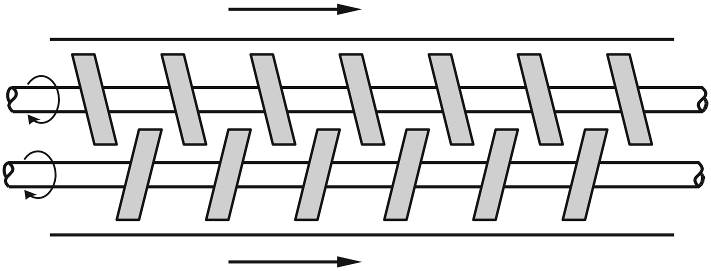


Fig. 4.46 Principle of twin-screw extruder

- Enables the post addition of substances by a provisory reversing operation of the screw conveyor rotation.
- Reduced length of the equipment.
- Possibility for an effective application even to powders.

Figure 4.46 shows diagrammatically two intermeshing corotating screws of a twin-screw extruder. The extruder is divided broadly into three sections: (1) conveying, (2) kneading, and (3) pressurizing. The extruder screws are designed with decreasing pitch, so that the product is compressed as it is conveyed from the entrance to the exit of the barrel (Levine 1992; Heldman and Hartel 1997).

Most extruders operate with no external heating, utilizing the heat produced by mechanical dissipation of the viscous forces in the pressurized particulate food material. However, if more accurate temperature control is required, the extruder barrel may be foreseen with external water circulation (Fig. 4.45).

The relative effect of external heat transfer to heast developed by heat dissipation of mechanical energy is characterized by the Brinkman number (Br), defined by the equation

$$\mathrm{Br} = (\text{mechanical energy})/(\text{heat energy at wall}) = \left(\eta u^2\right)/(\lambda \Delta T) \tag{4.29}$$

where (η) is the viscosity of the material, (Pa s), (u) is the velocity of the material in the extruder (m/s), (λ) is the thermal conductivity (W/m K), and (ΔT) is the temperature difference between the barrel wall and the product in the extruder (K).

In most food extrusion processes, using low moisture particulate materials, the mechanical heat dissipation is higher than the heat transferred through the wall, i.e., $\mathrm{Br} \gg 1$.

The development of food (mostly cereal) shaping and extrusion equipment is discussed by Kokini et al. (1992), and the application or extrusion to various food products is described by Frame (1999) and Guy (2001). Twin-screw extruders can be used to produce various extruded foods of improved quality (Wiedmann 1992). The scale-up of extruders from pilot plant to industrial scale is outlined by Yacu (1992). Chang and Wang (1999) discuss the application of extrusion technology to the production of feeds. In scaling-up of extruders, the residence time distribution (RTD) and the specific mechanical energy (SME) should be kept constant.

Typical capacities of commercial extruders are 300 kg/h (snack foods), 1200 kg/h (cereals), and 9000 kg/h (pet foods). Normal operating conditions of extrusion cookers are pressure, 15–70 bar; temperature, 120–170 °C; rotational speeds up to 500 rpm; specific energy requirement, 0.02–0.1 kW/kg; total power, 5–200 kW; shaft torque, 70–2500 N m; and residence time, 20–90 s. Overall dimensions of the extruders are length, 2–4 m; width, 1–1.5 m; and height, 1.2–1.5 m.

4.5.4.2 Forming Equipment

The forming equipment into various shapes and sizes is achieved by using various types of apparatus developed, in general, empirically. Figures 4.47, 4.48, and 4.49 present examples of equipment, used in connection with the prementioned three first types that are used in forming of food.

The forming equipment may be classified in four main categories:

(a) Equipment modulates the product by cutting it to desired shapes and dimensions.
(b) Using friction forces to achieve a differentiation in forming the initial product mass (e.g., in creating “dough balls” in the bread and candy industry).
(c) Equipment shapes the product by pressing it through rotating rolls, by extrusion, and by pressing it using pistons. In the last two cases, the task is done in

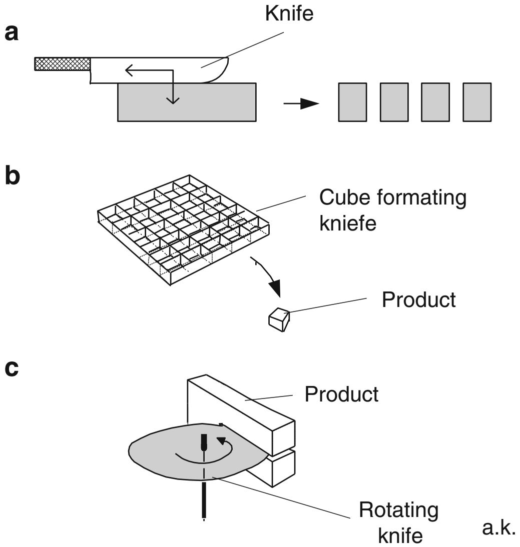
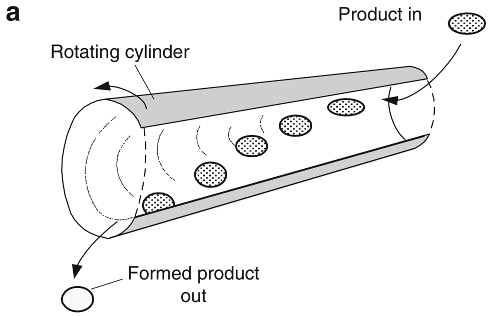
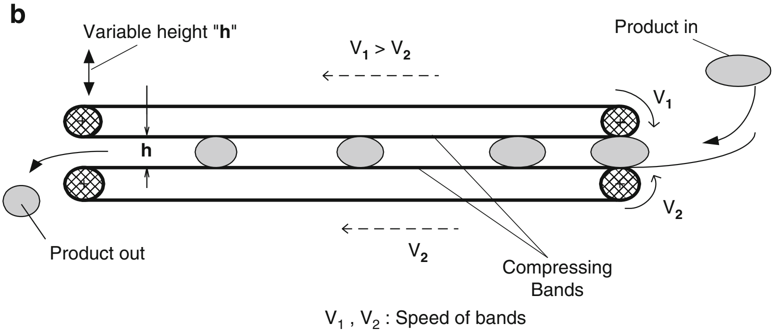


Fig. 4.47 Cut forming



Forming by rotating cylinder cut off image)



Forming by moving bands

Fig. 4.48 Forming by friction

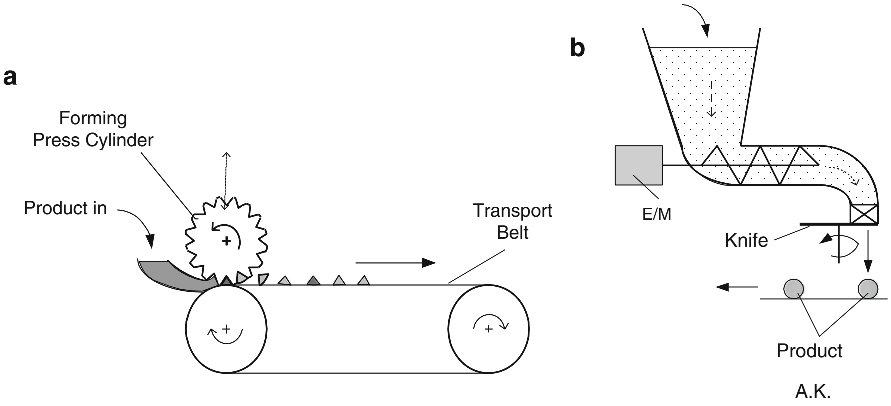


Fig. 4.49 Forming by pressing

connection to special dies put at the end of the compressing instrument (e.g., extruder) giving it the desired shape and form.

(d) Using molds in which the initially low viscous product (e.g., dough, chocolate mass, etc) is put to fill certain molds.

Figures 4.47–4.49 present examples of equipment, used in connection with the prementioned three first types that are used in forming of food.

The description of using forming equipment in the processing of bread and other baked products, biscuits, pies, and confectionary products is described by Fellows (1990) and Levine and Behmer (1997). Bread rolls that will expand to the required bread loaf shape when proofed are prepared in three stages, i.e., sheeting, curling, and sealing.

The engineering aspects of the sheeting operation are discussed by Levine and Behmer (1997). The conventional sheeting equipment (sheeters) is based on the reduction of dough thickness, by passing a slab through 2, 3, or more sets of rolls of varying distance between them. Sheeting can also be accomplished by mechanical extrusion. Laminated dough products consist of dough layers, interspersed with a separating agent, usually a shortening (fat) layer. Lamination is obtained by passing two or more dough sheets through sheeting rolls several times.

Pie coatings are formed by depositing a piece of dough into aluminum containers or reusable pie molds and pressing it with a die. A filling is then deposited into the casing, and a continuous sheet of dough is laid over the top, and the lids are cut by reciprocating blades. Biscuits are formed by pressing the dough in a shaped molding roller, cutting biscuit shapes from a dough sheet with a cutting roller, extrusion though a series of dies, or cutting biscuit shapes from an extruded dough sheet.

Equipment for forming bakery products is described by Matz (1989). Such equipment includes sheeters, laminators, loaf molders, and special forming and enrobing machines for cookies, crackers, pies, doughnuts, and cakes.

Confectionery products are formed into various shapes and sizes using individual molds, which are carried below a piston filler, depositing accurately the required hot sugar mass into each mold. The product is cooled in a cooling tunnel and ejected from the molds, using special ejection devices.

Coating and enrobing of food products with batter, chocolate, and other components are used to improve the eating quality of foods and to protect the product from the environmental effects (oxygen or moisture transfer). Chocolate is used to enrobe confectionery, ice cream, and baked goods. Corn syrup, flavorings, colors, and emulsifiers are also used. The thickness of a coating is primarily determined by the viscosity of the enrobing material. Enrobing is achieved by passing the product on a stainless steel conveyor beneath a curtain of hot liquid coating. The coating is applied by passing the product through a slit in the base of a vessel or by coating rollers. The coating is cooled by air in a cooling tunnel, and the coated foods are held at 22 °C for 48 h to allow fat crystallization. Batters are applied to fish, poultry, and potato products. A single layer of viscous batter is applied by passing the product through a bath of batter between two submerged mesh conveyors. Seasonings are applied from a hopper over a conveyor, followed by passing the product through a rotating drum, fitted with internal flights. Fluidized beds are also used for coating flavors on food particles (see section on Agglomeration in this chapter). Coating of fruits and vegetables for protection against moisture loss and microbial contamination is practiced by dipping, spraying, or brushing of paraffin and beeswax dispersed in an organic solvent (Krochta et al. 1994).

4.5.5 Butter and Cheese Processing Equipment

Depending on the final product, the operation of some butter and cheese equipment combines several mechanical processes, such as mixing, agitating, cutting, liquid–solid separation, forming, and even "partial extrusion."

In *Butter drum processing*, the milk cream is battered as the drum containing it rotates (Fig. 4.50). It follows kneading through rotating gear wheals.

In *automated butter processing*, the milk cream is initially mixed before it is successively forwarded in a tube with screwdriver which compresses the product to its end, from which butter comes out through a relative narrow die (Fig. 4.51).

In several batch *cheese processing methods*, milk with additives (e.g., the enzyme rennet, etc.) is agitated in the cheese processor, up to the production of cut crude (Fig. 4.52). After draining of the liquid whey, the remaining product is put in forms, and it is compressed before being stored for ripening. This process can be also automated. The processing of milk and crude on a moving belt is done automatically (e.g., agitated and cut by instruments lying above the belt) until the crude is ready to be put in containers for pressing and final storage (rippening) (Fig. 4.53).

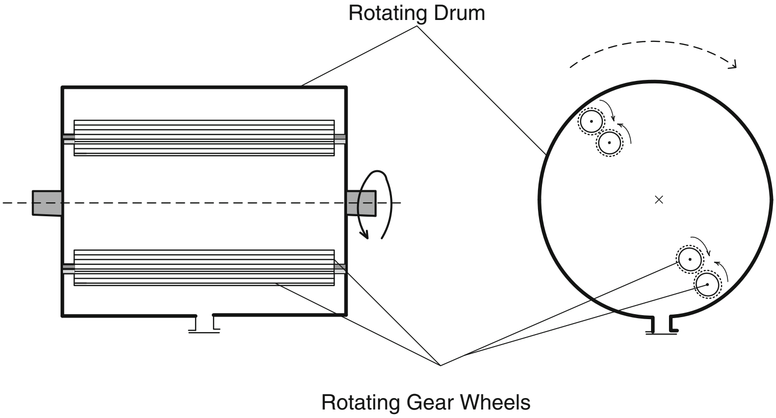


Fig. 4.50 Rotating butter drum

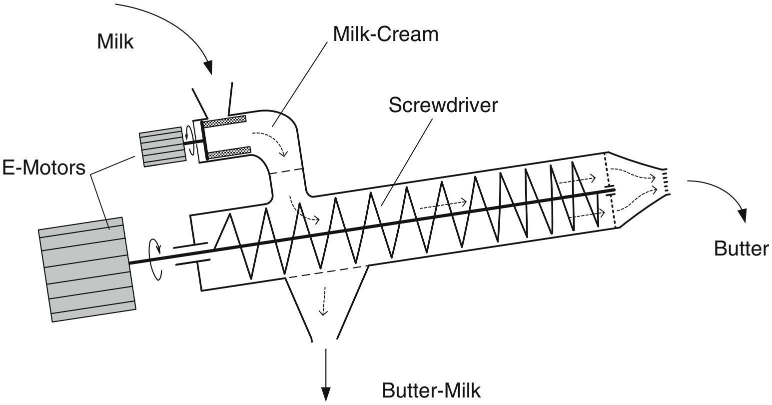


Fig. 4.51 Fritsch automated butter processor

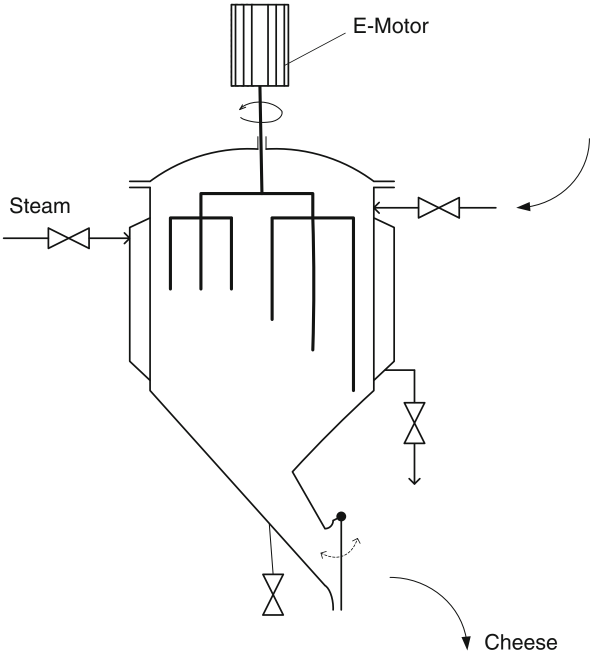
4.5.6 Solid Mixing and Encrusting Equipment

Various types of equipment are used for the mixing and blending of solid particles and pieces, described in the technical literature (Bhatia and Cheremisinoff 1979; Walas 1988; Perry and Green 1997) and in suppliers' literature. Uniform blending of solid particles is very important for the quality of the food products. The blended product should be stable, and de-mixing and agglomeration should be prevented during storage and use (Johanson 2000).

The following are typical examples of solid mixers/blenders:

(a) The ribbon mixers consist of helical blades, rotating horizontally, which can mix and covey particles in an horizontal U-shaped trough. Dual helical

Fig. 4.52 Cheese processor



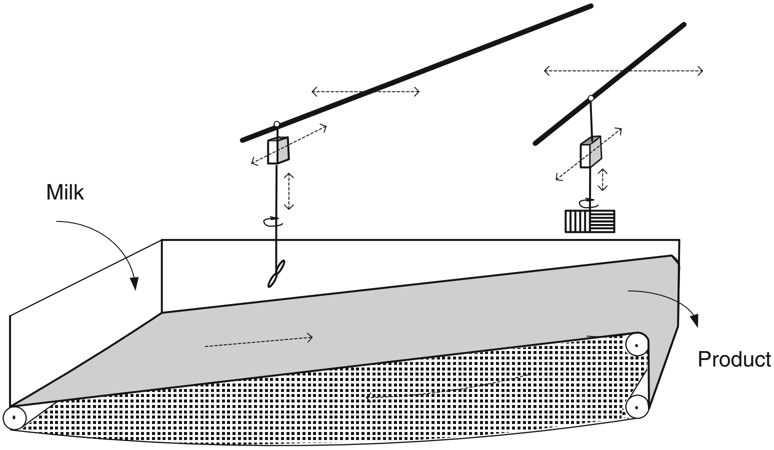


Fig. 4.53 Automated cheese processor

ribbons, rotating slowly at 15–60 rpm, can mix particles of bulk density about 500 kg/m^3 and capacities up to 50 m^3.

(b) The tumbling mixers consist of drum, double-cone, V-cone, or Y-cone blenders, rotating at 20–100 rpm. The particulate material splits and refolds in the legs of the blender as it rotates. The capacity of these mixers varies from 0.1 to 7 m^3.

(c) The conical screw blenders are large inverted cone vessels of capacity 35 m^3, filled with particulate material, which is mixed with a vertical screw, orbiting around the periphery (epicyclic path) at about 3 rpm.

(d) Two-cone screw blenders, operating on the same principle, can have a capacity of 78 m^3. The conical screw blenders are suitable for incorporating small amounts of a component into a larger mass of another material.

(e) The mullers are used to blend intimately minor amounts of liquid into a major solid carrier. They consist of a circular pan with a central shaft in the bottom of the pan. Attached to the shaft are horizontal extensions that hold free-turning wheels, which rotate at slow speed around the periphery of the pan. Plows are attached to the shafts and directed the flow of the material to the wheels, which then pass over the materials in the pan. The mullers prevent the agglomeration of small particles during the mixing with the liquid. Small units have capacities of 0.5–0.7 m^3 and require 5 kW power, while larger units have capacity of 6 m^3 and power requirement 45 kW.

The description of using forming equipment in the processing of bread and other baked products, biscuits, pies, and confectionary products is described by Fellows (1990) and Levine and Behmer (1997).

Manufacturing of products consisting of separated different foods (e.g., jam or chocolate encrusted in dough as in croissants) or which consist of different layers or components (e.g., layers varied in color) is done by guiding the different components simultaneously as indicated in Fig. 4.54.

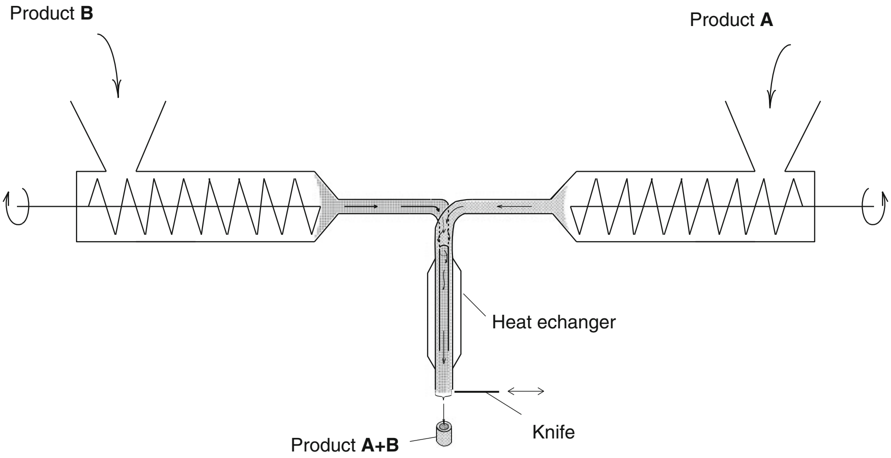


Fig. 4.54 Encrusting

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