Chapter 5
Mechanical Separation Equipment

5.1 Introduction

Mechanical separations in food processing include two main operations, i.e., the removal of material or substances and their classification (Table 5.1). Removal is distinguished between removal of undesired parts (cleaning) and desired parts (separation).

Mechanical separation equipment is used extensively in the food processing industry, either in preparatory operations or in the main manufacturing and preservation operations. Mechanical processing operations such as size reduction, size enlargement, agglomeration, homogenization, and mixing, treated in Chap. 4, may involve some form of mechanical separation. Membrane separation processes, treated in Chap. 12, include micro-, ultra-, and nanofiltration, which are related to mechanical separations.

The basic materials involved in mechanical separations are discrete particles and solids, which behave differently than solutions or suspensions of dispersed materials. The mechanical equipment used in handling and processing particles has been developed empirically from practical experience, contrary to the fluid and gas handling equipment, which is based on fundamental physical and engineering principles. However, engineering principles and materials properties are used increasingly in the design and operation of solids handling equipment.

Mechanical separations are based on differences of density and size/shape of the food particles/pieces. They include solid/solid, solid/liquid, liquid/liquid, and solid/air operations. Solid/solid separations involve screening (sieving) of particulate foods (e.g., flour), cleaning and sorting of food pieces/particles (e.g., fruits, vegetables), and peeling, pitting, and dehulling of various plant foods (e.g., fruits/vegetables and cereals).

Solid/liquid separations are based on the size/shape of the food particles/pieces and the rheological (flow) properties of the liquid suspension. They include

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Table 5.1 Mechanical separations in foods

Removal								Classification		
Undesired parts					Desired parts			Sorting		
External parts			Internal parts							
Own parts			Own parts		External parts		Internal parts			
Animal products	Plant products	Foreign parts	Animal products	Plant products	Plant products	Animal products	Plant products	Grading	Solids	Liquids
Skin	Peel	Dust	Bones	Kernels	Extracted soya	Guts	Juice	Based on: Physical features	Based on: Physical properties	Based on: Physical properties
Hoof	Hair	Metals	Intestines	Seeds	Bran	Collagen	Starch			
Horn	Stem	Stones	Excrement	Stones	Peel	Blood	Oil	Quality standards	Shape	Composition
Shell	Husk	Dirt					Nuts		Composition	
Feather	Hull	Insects								
		Other organic material								

sedimentation (clearing of wastewater effluents), filtration, and centrifugation (juices, oils, milk).

The mechanical liquid/liquid separations are based on differences of the liquid densities (e.g., oil–water separation). The solid/air separation is based on different densities of the materials (e.g., particles in cyclone) and on the fact that solids, unlike gases, cannot pass through fine-meshed (woven) textiles.

The properties of solid particles, related to mechanical processing, are discussed in Chaps. 3 and 4 (storage and transport of solids, size reduction, and size enlargement). The properties of solid foods are discussed by Lewis (1990), Mohsenin (1986), Peleg and Bagley (1983), and Jowitt et al. (1983, 1987). The characteristics of particles were reviewed by Schubert (1987a, b), and their analysis is described by Allen (1990). Appendix B gives some typical physical properties of foods.

Physical properties of solid particles of importance to separation processes are particle shape, size, and size distribution; particle density, bulk density, and porosity; elastic, plastic, and viscoelastic properties; wetting and flow properties; and electric, dielectric, and optical properties.

The particle size distribution is usually expressed as percent undersize (R), i.e., the percent of particles that are smaller than a given size (x). The data of particle (e.g., sieve) analysis are recorded in the following diagrams (Walas 1988): (a) cumulative (R) versus $\log(x)$, (b) differential bar $f(x)$ versus $\log(x)$, (c) differential histogram $f(x)$ versus $\log(x)$, (d) logarithmic normal $\log(R)$ versus $\log(x)$, and (e) Rosin–Rammler–Sperling diagram $\log\log(1/R)$ versus $\log(x)$. Most of the food particles, produced by industrial processes, like size reduction and size enlargement, follow the logarithmic normal distribution, from which the mean particle size and the standard deviation can be estimated, as shown in Eqs. (4.9) and (4.10) (Chap. 4).

The particle (solids) density of dry food materials is about 1500 kg/m^3. The density of "wet" foods varies in the range of 560 kg/m^3 (frozen vegetables) to 1070 kg/m^3 (fresh fruit). The bulk density of food particles varies from 330 kg/m^3 (instant coffee) to 800 kg/m^3 (granulated sugar). The porosity of solid foods varies from about 0.1 to near 0.95 (freeze-dried and extruded products).

The flowability of food powders is characterized as: very cohesive, non-flowing, cohesive, easy flowing, and free flowing. The hydrodynamic properties of food particles are characterized by the Stokes equation, which describes the fall (settling) of a particle of given diameter and density in a fluid of known density and viscosity.

5.2 Classification Operations

The classification of raw food materials is very important before any further processing takes place. Two main categories in classification are (a) grading and (b) sorting. Grading is the separation of the products in quality categories, indicating the grade of their acceptability. In sorting, acceptable products are further classified according to predetermined physical or other characteristics.

5.2.1 Grading

Grading is the classification of food materials on the basis of commercial value, end usage (product quality), and official standards. Grading is necessary, e.g., for avoiding the further processing of blemished or spoiled products or products not meeting the quality requirements. Grading is done mostly by hand (e.g., inspection of fruits after washing), but when the physical characteristics are also indicative of product quality, grading can be done through machinery. In, e.g., rice, the white kernels are separated from the spoiled or from foreign matter optically, and the lighter unripe tomatoes can be separated from the ripe, according to their specific weight.

The effectiveness of hand grading depends on the following factors: (1) quality of the product, (2) quantity per inspector and min, (3) experience and physical condition of the inspector, (4) kind of inspection, (5) the ergonomics during work, and (6) the speed at which products move in front of the inspector.

The inspectors can assess a number of quality factors simultaneously and separate physically the product into certain quality categories, using sets of comparison standards, e.g., color cards or plastic models (Brennan et al. 1990). Fruits and vegetables are graded on the basis of state, federal, and international standards. Quality classifications, such as "free from damage" or "free from serious damage," are used. Higher tolerances are used for minor rather than serious defects (Salunkhe et al. 1991).

The products should be properly illuminated and they should move relatively slow in front of the inspectors. Bad quality and large quantities result in bad grading. Tired or less experienced workers cannot inspect products efficiently. If, e.g., bottles or eggs pass in front of an illuminated plate or if the products steadily rotate such as in the case of fruits that are moved on conveyors, consisting of rotating rolls, the inspecting personnel gets quickly tired. The workers that inspect food must work comfortably. The products, e.g., must not exceed a distance larger than 80 cm from the worker, because an additional effort is needed to reach them. The speed of products moving in front of the workers inspecting them is product specific (Table 5.2).

Grading of larger quantities of food or products, such as grains, is based on testing of smaller quantities. The lots are taken out randomly and are subsequently evaluated in the laboratory, using proper instrumentation.

Table 5.2 Speed of products (fruits) moving in front of inspecting personnel

Product	Speed of product (m/min)
Apples	35–45
Apricots	28–35
Berries	15–19
Cherries	20–25
Peaches	35–44
Plums	28–34

Besides skilled personnel, special machines are used increasingly for grading. The trend is to develop quality control methods that enable a continuous and quick estimation of the products. Nondestructive optical and physical methods, such as color measurements and use of X-rays, lasers, IR rays, and microwaves, are new promising methods (Knochel 2001; Clerjon and Damez 2001; Alderman et al. 2001). Most of the machines that are used in grading can be also used in sorting of food. The X-rays are also used in detecting foreign matter, such as glass splits and stones in even packed food. Machines having dimensions of $1.3 \times 1.5 \times 2.5$ m can control 500 jars/min, detecting glass splits as small as 3 mm. Machine grading of a food product should be based on a representative index of quality, e.g., color, firmness, and pH, or a reasonable combination of these properties.

5.2.2 *Sorting*

Sorting, like grading, facilitates subsequent processing operations, such as peeling, pitting, blanching, slicing, and filling of containers. It is beneficial in heat and mass transfer operations, where processing time is a function of the size of the product (e.g., heat conduction, mass diffusion).

Sorting is done by equipment specific for each product or product category. It is based on the criteria indicated in Table 5.3.

Most of the mechanical sorters are based on the size of the materials, but some equipment utilizes differences in shape, density, and surface properties of the food pieces and particles.

Screens (flat or drum type) are used extensively in sorting various grains, seeds, crystals, and other food pieces/particles of relatively small size. Inclined screens, one on top of the other with horizontal and vertical oscillations, are effective in grain and seed sorting.

Sorting of fruits and vegetables may be related to quality classification, e.g., small-sized peas and okra are considered more tender and desirable than larger sizes, large potatoes are desirable for long French fries, the length of corn on the cob should not be higher than 150 mm, etc. (Salunkhe et al. 1991).

The shape of fruits and vegetables should be suitable for mechanical harvesting, handling, and processing. The size and shape of some fruits presents problems in processing operations, e.g., apples, mangoes, and papayas.

Table 5.3 Criteria for sorting of foods

Category	Criteria
Physical criteria	Size, weight, shape
Technological criteria	Processing suitability or compatibility to existing equipment
Organoleptic	Texture, color, aroma, taste, ripeness, or freshness
Commercial	Attractiveness, tradition, variety, utility, price

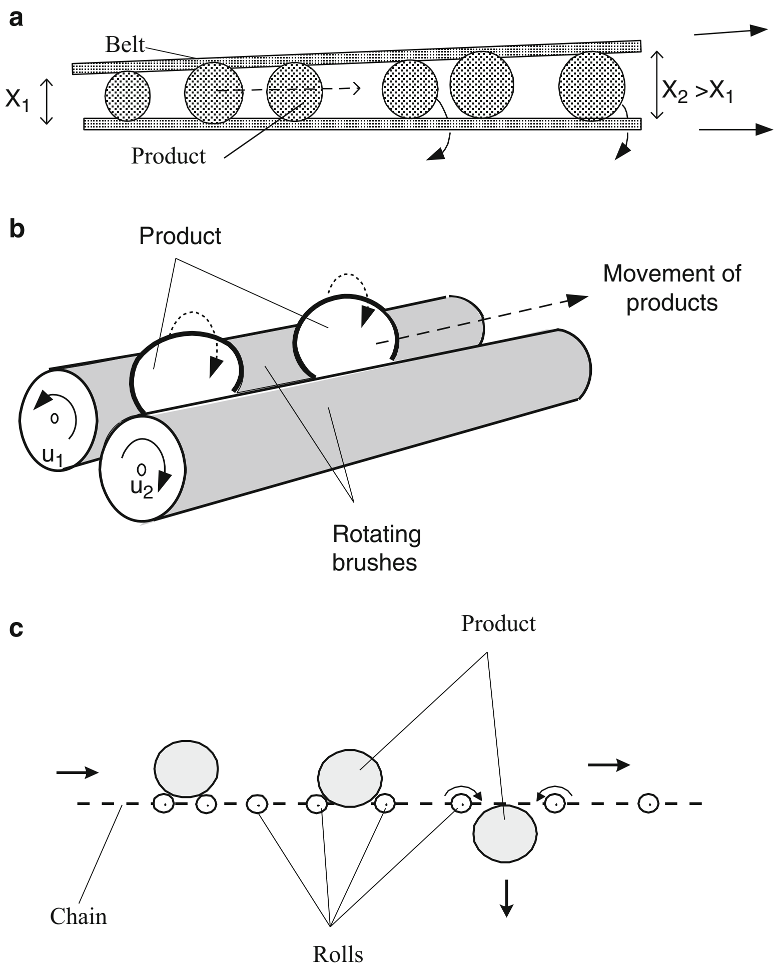


Fig. 5.1 Principles of size sorting machines. (**a**) Parallel belts and cables, (**b**) brush rollers, (**c**) roller sorter

Figure 5.1 indicates the principle of sorting of food, based on size. Products like several kinds of fruits can be sorted in diverging belt/cable sorters (Fig. 5.1a), diverting rollers (b), or roller sorters (Fig. 5.1b), which separate the fruits into various sizes by allowing them to pass through an increasing slot (opening). In the case shown in Fig. 5.1b, the rollers are brushes. This way the product (e.g., eggs) may be also round and round dry-cleaned during sorting as the rotation speed of two of the brush rollers may vary (e.g., $u_1 > u_2$).

The fruits move slowly through two parallel belts or cables, the distances of which increase in the direction of flow. The small fruit will fall first through the opening, followed by the next size. The various sizes of fruit are collected in padded chutes, placed under the separator. The two belts may be driven at different speeds, subjecting the fruit to a more efficient separation.

The roller sorters are installed on a roller conveyor, so that the gap between them increases in the direction of flow of the food pieces. Thus, the fruits are separated in progressively increasing sizes, and they are collected in padded chutes under the conveyor. In many cases it is possible to combine classification/ sorting with computers, for the registration of the results of the classification automatically.

The spiral separators separate grains and seeds on the basis of shape. They consist of a vertical double helix through which the food particles fall by gravity. The round particles speed up as they roll down the internal helix, and they are thrown into the outer helix by the developed centrifugal force. The nonspherical particles are separated, as they move down through the internal helix at a lower speed.

Cylindrical and disk separators are used to separate nearly round grains (e.g., wheat) from long grains or particles (Fig. 5.2). The cylindrical unit consists of horizontal cylinder with hemispherical indents on the inside surface. The mixed grains are picked up by the indents and they are separated on the basis of their length, as they move up the cylinder. The longer grains fall down first, leaving the smaller grains, which fall in a different compartment. The fineness of the separation is controlled by the speed of rotation and the adjusted position of the separation edge in the cylinder. As in the following disk separator, the capacity of the cylindrical separator depends on the product to be separated. For sorting out, e.g., 10 % broken rice, the capacity of a cylindrical separator with dimensions 3.5×1.5 m and which weighs 1 ton and consumes 3 kW is 5 tons/h. The equipment capacity is reduced to 3 tons/h, if the broken rice is 25 %.

The disk separator operates on the same principle with the cylindrical unit. The disk contains slightly undercut pockets, which can pick up and retain short grains, but long grains fall out. Thus, wheat grains can be separated from rye, oats, barley, etc. A number of different separations can be made in a single machine by installing banks of disks with different characteristics. The capacity of a relatively large disk separator may be up to 14 tons/h. Such units rotate with 100–135 rpm and require up to 3.5 kW.

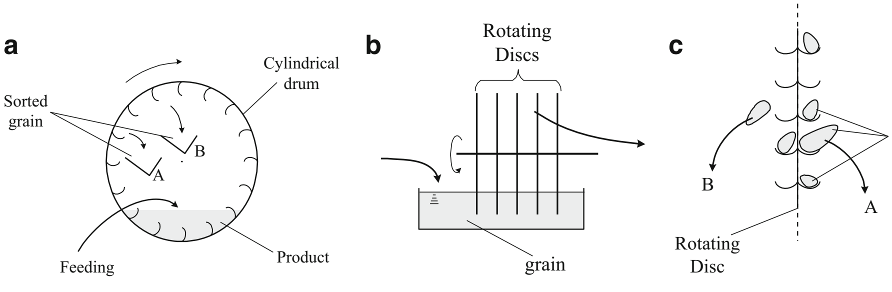


Fig. 5.2 Dry sorting of grains. (**a**) Cylindrical separator; (**b**, **c**) rotating disks

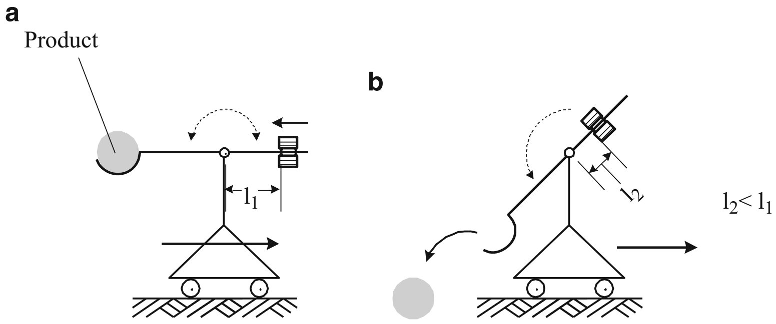


Fig. 5.3 Weight sorter

Separators based on different surface textures can be used to separate, e.g., weed seeds from wheat grain. They consist of a rotating drum of rough outside surface, which picks up the rough weed seeds and transfers them out of smoother grains, through an attachment/bouncing mechanism (Henderson and Perry 1955).

Weight sorters are used for valuable foods, like eggs, cut meats, and sensitive fruits, where accuracy in size separation and caution in handling are needed. Eggs can be sorted at the rate of 12,000/h. They are first inspected visually over tungsten lights (candling) to remove unfit eggs (Fellows 1990).

The weight sorter consists of a slanted conveyor which transports intermittently the eggs above a series of counterbalanced arms (Fig. 5.3). While the conveyor is stationary, the arms are raised and the eggs weighed. Heavy eggs are discharged into a padded chute, and light eggs are replaced in the conveyor belt to travel to the next weighing stop. Weight sorters, equipped with PLC sensors, can be operated in a computerized weighing packaging system (see Appendix C—Food Process Control).

The application of color sorting is widely used in the food processing industry. The operation of the color sorters is based on the reflection of incident light on a food piece/particle, which is measured by a photodetector. The reflected light is compared with preset color standards, and the rejected particle is removed from the product mixture by a short blast of compressed air (Grandison and Lewis 1996; Low and Maughan 1993) (Fig. 5.4). Color sorters can separate particles of sizes 2–10 mm (rice, coffee beans, frozen peas) at the rates of 100–1000 kg/h and some large units up to more than 10 tons/h. A large color sorting machine requires about 2–5 kW and 20–30 L/s air at 6–8 bar. It weighs about 700 kg and it has the basic dimensions (1.5–2.0) × (1.5–2.0) × (2.0–3.0) m. The capacity of a large tea sorting unit can be up to 20 tons/h.

Image processing can be used as a color sorting system (Fellows 1990). The food pieces/particles are fed on a roller conveyor, beneath a video camera. A composite image of each food piece is constructed by the computer, which is compared to preset color specifications, and the rejected particle is removed by an automatic mechanism. In bakery operations, the image analyzer can control the color of the product by controlling the gas/electricity supply to the oven.

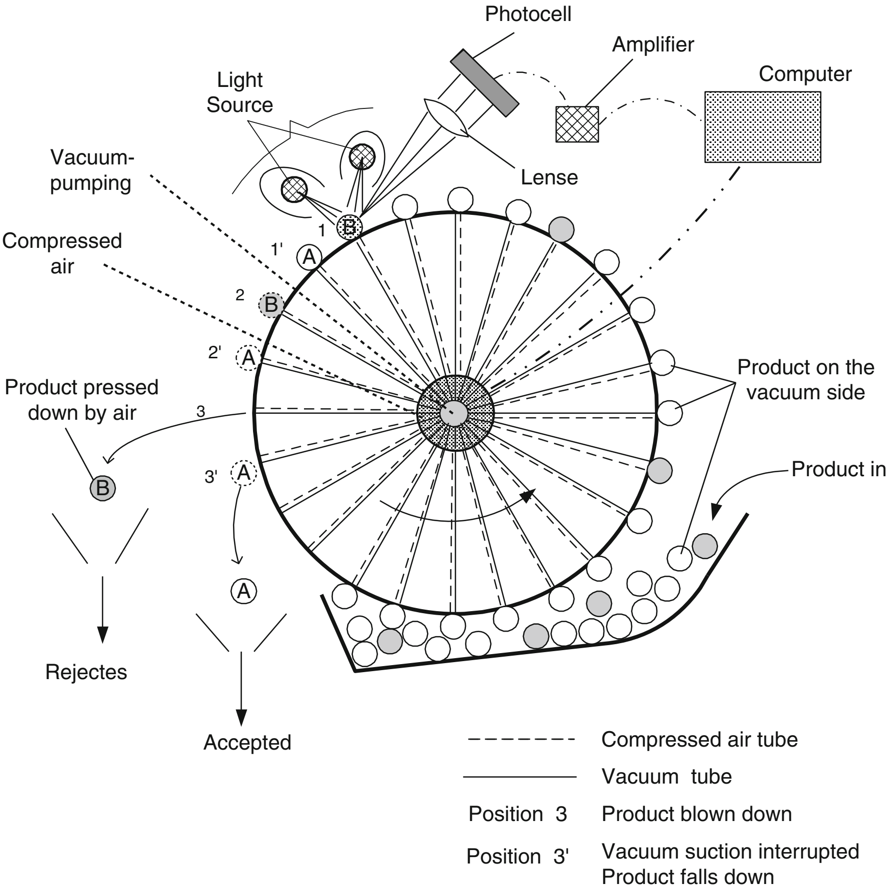


Fig. 5.4 Color sorting

Other food properties, on which a quick sorting can be established, are the constitution and, in the case of liquids, the viscosity of the products. Automated refractometers indicate the sugar content (°Brix), while microwaves can be used for nondestructive water and fat content measurements.

5.3 Solid/Solid Separations

5.3.1 Screening

Screening (sieving) is the simplest mechanical operation for separating solid particles in a series of sieves with openings of standard size. The screening surface may consist of parallel bars, perforated or punched plates, and woven wire, silk, or

Table 5.4 Typical sizes of standard sieves

USA, μm	Tyler, mesh	British, mm or μm	German, mm or μm
125 mm			
100″			
75″			
50″			
25″			2.5 mm
19″	0.742 in.		20.0″
9.5″	0.371″		10.0″
6.7″	3 mesh		6.3″
4.0″	5″		4.0″
1.7″	10″	1.68 mm	1.6″
1.0″	16″	1.0″	1.0″
850 μm	20″	850 μm	800 μm
500″	32″	500″	500″
250″	60″	250″	250″
150″	100″	150″	160″
90″	170″	90″	90″
75″	200″	75″	75″
63″	270″	63″	50″
45″	325″	45″	45″
38″	400″	38″	40″

plastic cloth. The screens may be flat or cylindrical. In all cases, a relative motion between product and screen is applied. Depending on the type of screen, this is achieved by vibration, shaking, or rotation of the screens.

5.3.1.1 Sieve Sizes

The openings of the sieves are usually squares, the dimension of which determines the size of the particles that can pass through (undersize) or remain on the screen (oversize).The industrial sieves are characterized by standard dimensions, which may be different in the various countries. Typical sizes of the standard sieve series, used in the USA, Britain, and Germany, are given in Table 5.4 (Walas 1988; Perry and Green 1984). See also Table 4.5 in Chap. 4.

The Tyler series is based on the concept of mesh, which is defined as the number of openings per linear inch (25,400 μm). The mesh number of a screening surface with square openings of dimension (a, μm) and wire diameter (d, μm) is given by the equation

$$N = 25,400/(a + d) \tag{5.1}$$

The Tyler series is based on the 200-mesh sieve with dimensions $a = 75$ μm and $d = 53$ μm. The ratio of the openings of two successive sieves is $2^{0.5} = 1.41$ or $2^{0.25} = 1.19$.

The US standard series of Table 5.4 is the ASTM specification E-11-70. The Canadian standard series (8-GP-1d) is similar to the US standard. The British standard (BS-410-62) is very close to the US series. The German sieve series is the standard DIN 4188 specification. The ratio of two successive openings in this series is $10^{0.1} = 1.25$. The French standard sieve series (CAFNPR X-11-501) is identical with the German series, but the openings are given in mm instead of μm.

5.3.1.2 Sieving Equipment

The screens used in food processing are normally made of stainless steel, according to the general rules of hygienic design and easy cleaning (Chap. 2). Depending on the thickness and the application of sieves, their cleaning can be made by tapping, spraying, scraping, or brushing.

The screening process is facilitated by some kind of movement of the screening surface (vibration or shaking), which prevents the blocking of the screen openings with particles (blinding) and decreases the product flow rate and the separation efficiency of the screen.

Screens can be classified in the following categories (Fig. 5.4): (1) grizzlies/belt screens, (2) trammels, (3) flat/vibrating screens, and (4) rotating sifters.

Efficient operation of screens is obtained when the particle bed is stratified, i.e., when the particles form layers of different sizes. Stratification is facilitated by vibration or shaking of the screens, which moves the small particles down to the screen surface so that they can pass easily though the screen (undersize). At the same time, the larger particles concentrate on the surface of the bed, being removed as the oversize product. The overall separation efficiency of industrial screens is the product of the separation efficiencies of the undersize and oversize products, varying from 85 to 95 %.

The design and specifications of screening equipment require physical and engineering data on the material to be separated, such as sieve size analysis, particle shape, density, hardness, flowability, moisture content, and temperature. The product flow rate, the separation required, and the type of screening (dry or wet) should be specified. In general, the efficiency of separation is reduced, when the product capacity (flow rate) is increased.

Moisture can cause agglomeration of the fine particles, which will not pass through the screen.

The following screening equipment is used for separating solid pieces and particles:

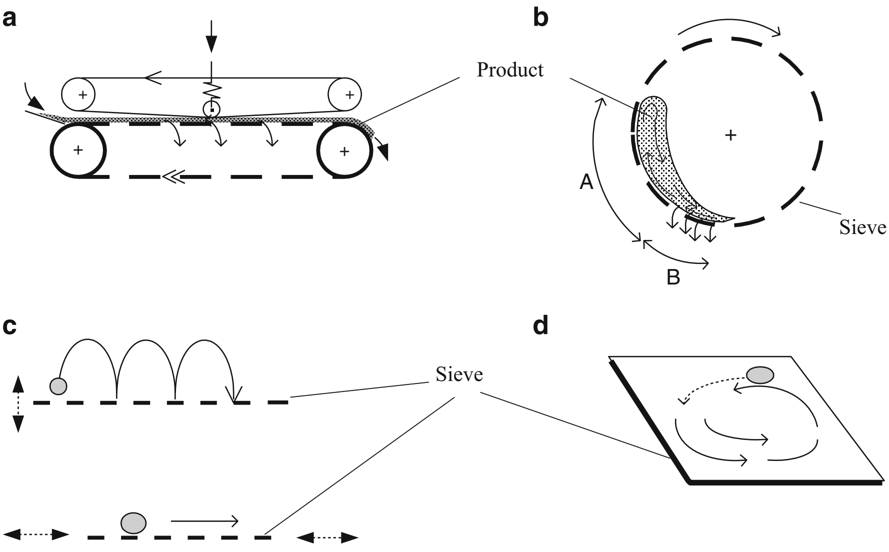


Fig. 5.5 Screening systems: (**a**) belt, (**b**) rotating trommel, (**c**) vibrating flat, (**d**) rotating sifter

Grizzlies/Belt Screens

Grizzlies or bar screens consist of horizontal or inclined (30–50°) parallel bars (or rods), which can separate relatively large pieces and lumps of particles (larger than 25 mm) from smaller particles. Grizzlies are used for scalping, i.e., removal of a small proportion (about 5 %) of large particles from a bed of otherwise medium- to small-sized particles. Blocking of the grizzlies by solid pieces/particles is prevented by using bars of trapezoid or wedge cross section. In some cases, the grizzlies or bars are part of an endless belt. A second belt, moving at a different speed, can be also used to improve separation (Fig. 5.5a).

Trommels

Trommels or revolving screens consist of perforated cylinders (1–3 m diameter, 3 m long), rotating at about 15–20 rpm below the critical velocity (Fig. 5.4b). They are usually inclined at 10–20°, and they are used to separate particles in the size range of 10–60 mm (Walas 1988).

The critical velocity (N_{cr}, rpm) of trommels, at which the particles will not fall down because of the centrifugal force, is estimated from the equation

$$N_{cr} = 42.3/d^{0.5} \tag{5.2}$$

This simple relation is derived by equating the centrifugal and gravity forces ($2\,m\,u^2/d = m\,g$), where (d) is the diameter of the cylinder (m), $u = (3.14\,N\,d/60)$

is the peripheral velocity (m/s), m is the mass of the particle (kg), and $g = 9.81$ m/s^2. As indicated in Fig. 5.5b, the actual sieving takes place only in a small part of the trommel (zone B), which is about 15–20 % of its circumference (Feustel et al. 1987).

Drum (trommel) screens are often used in various combinations (consecutive, parallel, or concentric) in the separation of grains and seeds.

Flat Screens

Flat screens consist of flat screening surfaces of several sieve sizes, arranged vertically or in line and usually inclined, which can separate and classify various solid particles. Flat screens are usually vibrated at 600–7000 strokes/min and they can separate particles of sizes down to 400 mesh (38 μm).

Vibration can be vertical or horizontal (shaking or reciprocating screens), as shown in Fig. 5.5c. In the vertical vibration, the best sieving is achieved when there is resonance vibration and no contact between moving grain and screen (Feustel et al. 1987). Shaking and reciprocating screens are inclined slightly and vibrate at 30–1000 strokes/min, separating particles in the size range of 0.25–25 mm.

The width of the screens relates to the capacity (kg/h) of the system, while the length affects strongly the screening (separating) efficiency.

Typical operating characteristics of flat screens are capacities, 10–80 tons/h; screen dimensions, 75 × 150 to 200 × 365 cm; and motor power, 2–10 kW (Walas 1988). The overall dimensions of screening equipment, consisting of 30 screens, is about 3 × 4 × 2.5 m, and the weight is about 5–6 tons. Ultrasonic screening enables this process even to smaller particles (20 μm). It also reduces plugging in screens. In whey separation of cheese dairies, the productivity of such systems may be about 80 m^3/h.

Rotating Sifters

Rotating sifters consist of a series of square or round sieves (0.6–1.0 m), stratified on springs and placed atop of one another, which rotate in a gyratory motion. Such sieve systems may consist of more than 24 rotating sieves, which are grouped so that flour is classified in 4–8 categories (grades). A rotating shifter of a 30-m^2 filtering surface requires 2.2 kW. Its main dimensions can be 2.5 × 2.5 × 2.5 m and its weight 2.5 tons. Some gyratory sifters use bouncing balls on the sifting surface for auxiliary vibration and efficient separation (Fig. 5.5d).

Screening Cloths

Most of the wire cloths are square mesh, but in some cases, an oblong weave may be used, which provides greater open area and higher capacity. Screens with relatively large length-to-width ratio are preferred when moist and sticky materials tend to blind the square of short rectangular openings (Perry and Green 1984).

Synthetic woven materials, made from monofilaments (e.g., nylon) and Swiss silk, are used in light, standard, and heavy weights. The finer the wire of the cloth, the higher the screening capacity, although the operating life of the screen will be shorter. Worn or damaged screens should be replaced, because they will let oversize particles pass through and reduce separation efficiency.

Magnetic Separators

Pieces and particles of iron and other ferrous metals (nickel and cobalt) are easily removed from food materials by magnetic separators. Electromagnets are preferred over permanent magnets, because they can be cleaned more easily (Fellows 1990). The principles of magnetic separations of solid particles are discussed by Perry and Green (1984).

Two simple magnetic separators which can be used in food in food processing are the magnetic drum and the magnetic pulley systems. A belt magnetic detector ($1.2 \times 0.8 \times 1.0$ m) can detect iron balls of a diameter as small as 0.5 mm, by a belt conveying grain products at a speed of 6–60 m/min.

Electrostatic Separators

Electrostatic (or high-tension) separation is based on the differential attraction or repulsion of charged particles in an electrical field. Electrical charging is accomplished by contact, induction, and ion bombardment. Some particles in a mixture are charged and they can be removed electrically, while the rest are separated by gravity. Particle sizes up to 1.5 mm (granular) or 25 mm (thin/long) can be separated. An application to food materials is the electrostatic separation of nuts from the shells (Perry and Green 1984).

5.3.1.3 Sieving of Flour

One of the major applications of sieving in food processing is the separation of the various fractions of flour during the milling of wheat and other cereal grains. Scalping is the removal of the large particles from the flour, while dedusting is the removal of the very fine powder.

Grading of the flour is the classification of the flour into fractions of restricted particle size, like semolina and middlings. Narrow size distribution within a fraction can be obtained by closed cycle milling, in which the oversize stream from a sieve is returned to the mill for further size reduction. Size reduction equipment (mills) is discussed in Chap. 4.

5.3.2 Fluid Classification

Separation and classification of solid particles by fluids (air or liquids) is based on differences of density, shape, hydrodynamic surface, and electrical and magnetic properties of the materials in the mixture. Air classification is used to separate various fractions of food components, while wet sieving and hydrocyclones are used in some separations of fractions of food materials. Subsieve-size particles in the range of 2–40 μm can be separated effectively using various fluid classifiers.

5.3.2.1 Air Classifiers

Air classification of solid particles is a dry separation process, used in various food processing operations, like cleaning of raw food materials and fractionation of particulate food components.

Equipment used in air classification of chemical and mineral products has been adapted to food products, taking into consideration the hygienic and quality requirements of food products.

Simple air classifiers are based on drag forces acting on particles by the airstream, which counteract the gravity forces. Aspiration classifiers are used to separate chaff (skins) from peas and grain in harvesting machines.

Figure 5.6 shows schematically two types of simple air classifiers. In the vertical classifier, the airstream will carry away the fine particles, leaving behind the larger (coarse) particles. In the horizontal classifier, the mixture of particles, carried by a horizontal air stream, is separated into various fractions according to the size and the density of the particles. The separation of particles is facilitated by passing the particle-containing airstream through a zigzag arrangement. Horizontal air classifiers of cleaning capacity 100 tons/h need 20 kW (90 % of it for the ventilators). The main dimensions and weight of such equipment are about 2.5 × 2.0 × 2.5 m and 3 tons, respectively.

Most of the modern air classifiers are used to separate the protein fraction from the starch granules of ground cereals and legumes (Grandison and Lewis 1996), based on differences of size, shape, and density. Air classification is characterized by the cut size, defined as the size where the weight of particles below the cut size in the coarse fraction is the same with the weight of the particles above the cut size in the fine stream.

The basic elements of an air classifier are a rotating plate and air circulation fan, installed in a special separation chamber (Walas 1988; Perry and Green 1984). The basic forces acting on the particles in the air classifier are the centrifugal force (F_c), the gravity force (F_g), and the drag force, measured by the Stokes settling velocity of the particle (u_p). Figure 5.7 shows the diagram of a rotating plate (disk), on which the particles are subjected to a centrifugal force, while air, sucked by a fan, removes the fine particles from the plate and separates them from the coarse particles.

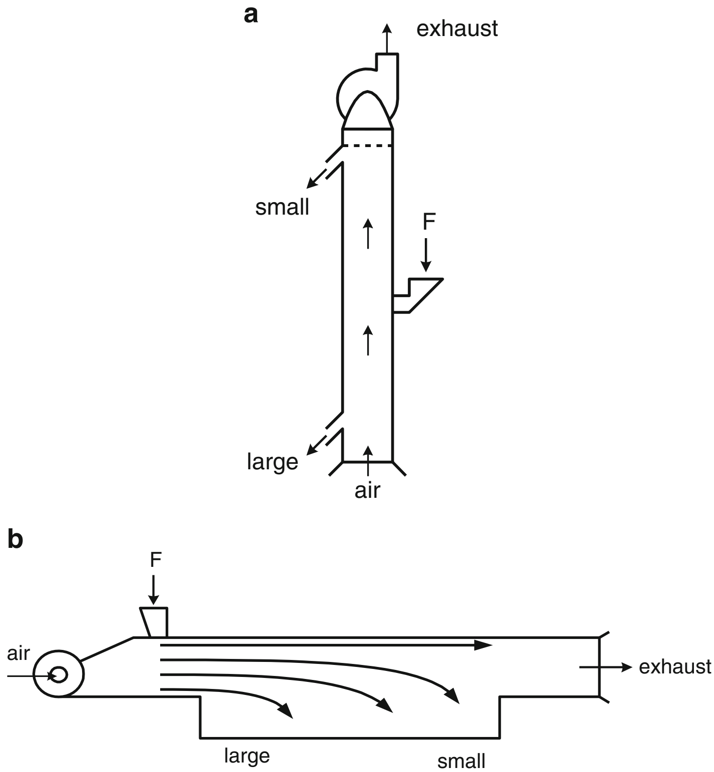
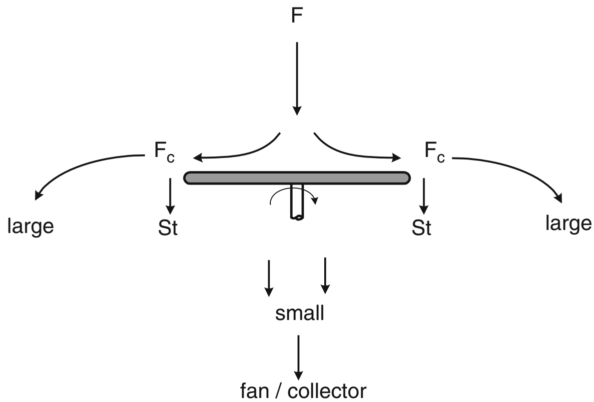


Fig. 5.6 Diagrams of simple air classifiers: (**a**) vertical, (**b**) horizontal. *F* feed

Fig. 5.7 Diagram of rotating plate (disk) air classifier. *F* feed, F_c centrifugal force, *St* Stokes (gravity) force



Fine (undersize) and coarse (oversize) particles are discharged separately from the air classifier.

The centrifugal force F_c (N), acting on a solid particle of mass (m) at a peripheral velocity u_p (m/s) of the rotating plate of radius R (m), is given by the equation

$$F_c = m\, u_p^2/R \tag{5.3}$$

where m (kg) is the mass of the particle.

Air is blown on the surface of rotating plate at a radial velocity u_a (m/s), moving the small particles toward the periphery (edge). The velocity of settling by gravity in the air of a particle of equivalent diameter (d, m) is given by the Stokes equation

$$u_{St} = \left(d^2 \rho g\right)/18\eta \tag{5.4}$$

where ρ is the particle density (kg/m^3), η is the viscosity of the air (Pa s), and $g = 9.81$ m/s^2.

The cut size (d_c) in an air classifier is defined as the size of the particles which begin to settle in the air at the edge of the rotating plate, i.e., $u_{St} = u_a$. Under these conditions, the centrifugal force is equal to the weight of the particle, i.e., $F_c = m\, g$, and according to Eq. (5.3),

$$u_p^2/R = g \tag{5.5}$$

Combining Eqs. (5.4) and (5.5), we obtain the relation for the cut size (d_c):

$$d_c^2 = (18\eta R u_a)/\left(\rho u_p^2\right) \tag{5.6}$$

Equation (5.6) indicates that the cut size increases by increasing the radial air velocity (u_a) or by reducing the rotational velocity (u_p) of the particles.

The cut size separates the particles into two equal parts, i.e., the undersize and the oversize. The sharpness of separation is expressed by the ratio (k), defined by the equation,

$$k = x_{0.75}/x_{0.25} \tag{5.7}$$

where ($x_{0.25}$, $x_{0.75}$) are the particle sizes corresponding to 75 and 25 % cumulative distributions (% R). The theoretical sharpness ratio is ($k = 1$), but in industrial separations, it may vary from 0.3 to 0.6 (Schubert 1987a, b).

Industrial air classifiers are described by Walas (1988) and Perry and Green (1984). Air classifiers used in food processing, particularly in separations of protein from starch, are discussed by Grandison and Lewis (1996). The rotating (separation) disk can be mounted either horizontally or vertically in the classifier. More than one rotating plates (or turbines) may be installed in one large air classifier.

In the milling of wheat flour, the protein fractions concentrate in the small particles (1–10 μm), while the starch granules are larger (15–40 μm), making possible the separation of the two components in air classifiers. Hard wheat contains about 13 % protein, while soft wheat contains only 7 %. Roller mills are more effective in milling soft rather than hard wheat. More effective milling of the wheat is achieved using impact mills, like pin disk and attrition disk mills (see Chap. 4).

In simple pin mills, only one set of pins rotates. Finer particles of wheat and fibrous materials can be obtained by rotating both sets of pins in opposite directions at different speeds, e.g., 6000–18,000 rpm. The optimum impact velocity for disintegrating most endosperm is about 200 m/s, which will not damage seriously the starch granules (Grandison and Lewis 1996).

Starch granules in legumes have sizes 16–21 μm × 2–28 μm, and pin milling can separate effectively the small protein particles from the coarser starch granules.

5.3.2.2 Wet Classifiers

Wet classification is used extensively in the minerals industry, where particles of different density are suspended in water and separated in various types of solid/liquid classifiers. This method finds some applications in food processing, with examples of wet sieving, hydrocyclones, and separation of tomatoes in water tanks (see cleaning operations in this chapter).

Wet Sieving

Wet sieving is used to separate small-size particles which are difficult to go through the standard sieves, because they are sticky or they form agglomerates, when the humidity in the screening area is high. Typical example is the wet sieving of starch products, suspended in water. The suspending medium should be a liquid other than water (e.g., ethanol), when the particles are water soluble, e.g., sugar crystals.

Hydrocyclones

Hydrocyclones are similar to the normal solid/air cyclone separators. They are small inexpensive units, which can separate particles in the range of 5–300 μm, which are suspended usually in water, e.g., protein/starch particles. The separation is based on differences in density of the particles, and it is also affected by the viscosity of the fluid suspension.

The characteristic diameter of the particles (d_{50}) separates the mixture into 50 % undersize and 50 % oversize. The water suspension is fed to the hydrocyclone tangentially, forming a central vortex, which moves to the exit at the top of the cyclone, carrying the smaller particles (undersize). The coarse particles are thrown by the self-generated centrifugal force to the walls of the cyclone, and they are removed from the bottom.

The high shear rates, developed within the cyclone, reduce significantly the apparent viscosity of the non-Newtonian (pseudoplastic) suspension, improving the efficiency of separation.

5.4 Solid/Liquid Separators

Solid/liquid separators are used in food processing: (a) for cleaning food liquid from undesirable particles and (b) for recovering useful food particles from water suspensions. They are also applied in the expression (expulsion) of juices and oils from fruits/vegetables and oilseeds.

The mechanical separation methods of solids are based on the particle size, shape, density, and concentration in the water suspension. The principle, scale-up, and applications of solid/liquid separations in the general field of process engineering are discussed by Cheremisinoff (1995) and Purchas and Wakeman (1986).

Four separation methods are used mainly in food processing, i.e., screening, sedimentation, filtration, and centrifugation. Screening is used for particles larger than 200 μm and concentration 5–30 %. Sedimentation is applied to particles in the range 1–300 μm and concentrations up to 25 %. Filtration and centrifugation are applied over a wider range of particle size and concentration.

5.4.1 Screens

Large pieces of food and waste materials are removed easily from water by grate screens, consisting of curved parallel bars. Smaller pieces and particles are separated by screens of various sizes and shapes (rectangular or circular). Vibration of the screens is required in most cases to facilitate filtration and remove the solids. The construction and operation of the screens are discussed in connection with the solid/solid separations earlier in this section.

5.4.2 Sedimentation Equipment

Gravity sedimentation equipment is applied to the clarification of food liquids from suspended particles (clarifiers) or to the concentration of solid particles (thickeners). Gravity settling of suspended particles in water solutions/suspensions can take place in three mechanisms:

1. Particulate settling, following the Stokes equation (5.4). The settling velocity is a function of the particle diameter and density, the viscosity of the liquid, and the gravitational force.
2. Zone or hindered settling. The particles fall together as a zone, creating a distinct clear water layer.
3. Compression regime. The particles are compressed by gravity to form a compressed bed.

Gravity sedimentation is used widely in the treatment of drinking water, industrial water, and wastewater. Due to the large volumes of water involved, large sedimentation tanks are required, which are designed on the basis of laboratory tests and practical experience (Perry and Green 1984).

The sedimentation tanks are fed with the water suspension at the center, while the clear water overflows from the sides and the concentrated particles (sludge) are removed from the bottom.

The settling velocity of water suspensions is estimated from laboratory tests in long or short tubes. The depth of the sedimentation tank should be sufficient for settling the smallest solid particles, while the diameter should be such that the upward velocity of the clear water should be lower than the settling (Stokes) velocity of the particles.

Depending on the particle concentration, the tank charge (load) of the settling tanks varies in the range 0.3–3.0 m^3/m^2 h with residence times of about 10 h. From the total feed rate (kg/h) and the assumed load, the tank cross-sectional area (A) and diameter (D) are calculated. Diameters of 10–50 m are used, while the length of rectangular tanks may be as high as 80 m and the width 5–10 m. The depth of the sedimentation tanks varies from 3 to 5 m. Long agitating arms with scraping rakes, installed on a bridge and rotating slowly, are used to move and collect the settled particles (sludge) to the center of the tank, from where they are removed with special pumps.

Small metallic settling tanks, designed on the same principles of large installations, are used in the clarification or thickening of water or other liquid suspensions in the food processing plants. They consist of a cylindrical tank with a cone bottom, which are fed with liquid suspension in the center, while the clear liquid (water) overflows from the top and the sludge is removed from the bottom.

Sedimentation of colloidal and other difficult to settle particles in water is facilitated by the use of various flocculating agents, like alum (aluminum sulfate) and some polymeric materials, which form large agglomerates that settle faster into more compact sludges.

5.4.3 Industrial Filters

Two main types of solid/liquid filtration are used in food processing, i.e., cake filtration and depth (bed) filtration. In addition, microfiltration and ultrafiltration (membrane separations) are used to separate very small particles of molecular size and microorganisms from water suspensions/solutions (Chap. 12).

In cake filtration, the particles form a layer of particles on the surface of the filter medium, which acts a screen of the particles during operation. In depth filtration, the particles are removed from the suspension within the bed, filling the pores of the filter medium. In both types of filtration, pressure drop and filtration rate are the basic quantities considered.

5.4.3.1 Cake Filtration

In cake filtration, the total pressure drop (Δp) is given by the equation

$$\Delta p = \Delta p_{\mathrm{m}} + \Delta p_{\mathrm{c}} \tag{5.8}$$

where Δp_{m} and Δp_{c} are the pressure drops through the filter medium and filter cake, respectively, given by the following empirical equations:

$$\Delta p_{\mathrm{m}} = (\eta R_{\mathrm{m}})(\mathrm{d}V/A\,\mathrm{d}t) \tag{5.9}$$

$$\Delta p_{\mathrm{c}} = (\eta R\,C\,V/A)(\mathrm{d}V/A\,\mathrm{d}t) \tag{5.10}$$

where (R_{m}) and (R) are the resistances to flow of the filter medium and filter cake, respectively, (V) is the volume of filtrate (m^3), (C) is the mass of particles deposited as cake per unit volume of filtrate ($\mathrm{kg/m}^3$), (A) is the surface area of filtration (m^2), and (η) is the viscosity of the liquid (Pa s). The units of R_{m} are (1/m) and of R_{c} (m/kg).

It should be noted that, at constant filtration rate, $(\mathrm{d}V/A\,\mathrm{d}t) = u$, where ($u$) is the superficial filtration velocity (m/s) for the given pressure drop. Also, in dilute suspensions, (C) is approximately equal to the concentration of solid particles ($\mathrm{kg/m}^3$).

In most industrial filters, the resistance of the filter medium (R_{m}) is negligible, compared to the resistance of the filter cake (R), and, therefore, the pressure drop (Δp_{m}) can be neglected.

For constant pressure drop (Δp), the filtration time (t) to obtain a filtration volume of (V) is found by integrating Eq. (5.10), neglecting the pressure drop through the filter medium:

$$t = (\eta R\,C/2\,\Delta p)(V/A)^2 \tag{5.11}$$

The total mass of cake deposited after volume (V) of filtrate is calculated from the relation $m = V\,C$.

The specific cake resistance (R) is approximately constant for incompressible cakes. For compressible cakes of colloid and gelatinous particles, the resistance (R) increases significantly with the pressure drop (Δp) according to the equation

$$R = R_o(\Delta p)^s \tag{5.12}$$

where (R_o) is a constant and (s) is the compressibility of the cake. The compressibility of hard solid particles, like salt or sugar crystals, is ($s = 0$). For compressible colloid particles, ($s = 0.8$–1.0).

The filter media used in industrial filtration should have good strength and wear resistance and low cost, e.g., woven fabrics of cotton, wool, nylon, and other synthetic materials.

Plate-and-Frame Filters

Plate-and-frame filters, or filter presses, are batch-operated units, in which the suspension is filtered through the surface of plates, forming a cake within the supporting frames. The filtrate is collected through special piping and the cake is discharged, when the operation is stopped for cleaning. Figure 5.8 shows diagrammatically the principle of operation of a plate-and-frame filter.

The square filtering plates are made of stainless steel and they have dimensions of 15–150 cm and thickness of 1–5 cm. The filtering surface is made of a strong metallic screen, covered with a filter medium (woven fabric) during filtration. Depending on the type of filtered suspension, the operating pressure can vary from 2 to 20 bar. The total surface of a filter depends on the dimensions and on the number of plates used. Large units may have more than 100 plates with operating pressure up to 6 bar. The filtration area in such units may be up to 70 m^2 and the total length of the equipment may be 5–7 m. Its weight is about

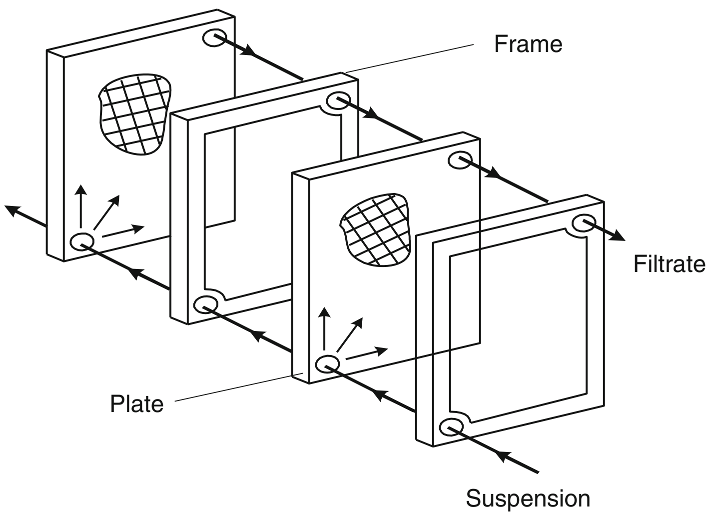


Fig. 5.8 Diagram of a plate-and-frame filter

1 ton and, in the case of, e.g., wine clarification, its filtering capacity may be about 1 ton/h.

When the filter cake is a useful product, it may be washed with water on the filter at the end of the operating cycle. The removal of the cake from the plates is facilitated with the flow of compressed air.

Filtration of colloidal and gelatinous particles is facilitated by using filter aids, i.e., inert powders which increase the porosity and the permeability of the cakes. Typical filter aids are diatomaceous earth, perlite, and cellulose paper. The filter aid is mixed with the water suspension before the filtration at proportions (filter aid/solid particles) of 1:1 to 1:5, for crystalline to slimy solids, respectively (Bhatia and Cheremisinoff 1979).

Vacuum Rotary Filters

The vacuum rotary filters are used widely in the process industries, because of their advantages over the plate-and-frame filters. They are continuous and faster, and they require less labor, but they are more expensive than the batch filter presses. Figure 5.8 shows diagrammatically the principle of operation of a vacuum rotary filter.

The filter consists of a horizontal drum 0.3–3 m diameter and 0.3–4 m long, partially submerged in a trough containing the suspension and rotating slowly at 0.1–2 rpm. The surface of the cylinder is made of a metallic screen; it is covered with a filter medium, and it acts as the filtration surface. Vacuum is applied to the interior of the drum and filtration takes place under a constant pressure drop, which is equal to the atmospheric pressure minus the pressure in the filter. A cake of particles is formed on the filter surface, while the filtrate is collected inside the filter, from where it is removed by a special pump. The cake is removed continuously from the filtering surface by scraping with a doctor knife, before the filtration cycle is repeated.

Based on the integrated filtration in Eq. (5.11), the mean filtration rate in a vacuum filter is given by the following equation:

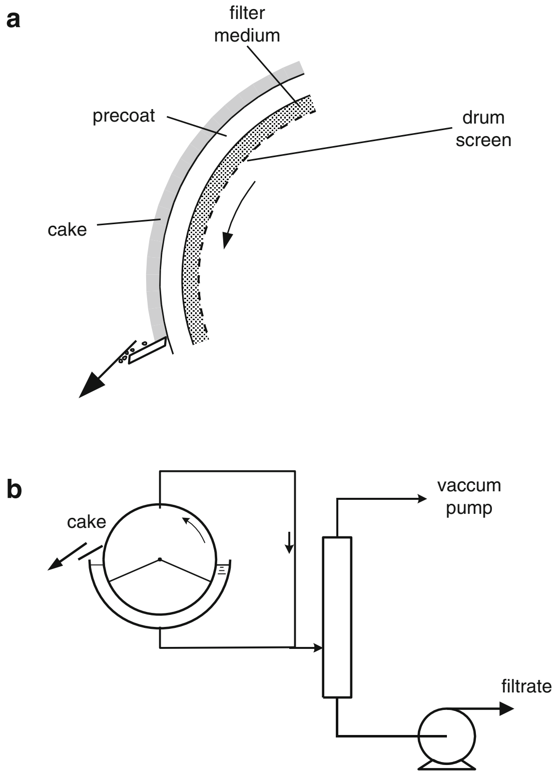
$$(V/At) = [(2\Delta p f)/(\eta C R t)]^{1/2} \tag{5.13}$$

where (f) is the fraction of the submerged filtering area $(0 < f < 0.5)$.

The filter cake on the drum surface is usually washed with water before it is removed by scraping. Applying a stream of compressed air at the last stage of filtration facilitates removal of the washed cake. For this reason, the filter drum is divided into a number of sectors, which are connected successively to vacuum, atmospheric pressure, and air pressure, while the filter is rotated slowly.

Filtration of colloidal and compressible particles (e.g., juices, wine) is facilitated by precoating the filtering area with a filter aid, e.g., diatomaceous earth, before starting the filtration process. A layer of 5–15 cm thickness is formed on the

Fig. 5.9 Diagram of a rotary vacuum filter with precoat operation



filtration surface by filtering a water slurry of the 7–10 % filter aid for 1–1.5 h, before starting the actual filtration. During filtration, the particles form a cake layer on the precoat, which is removed continuously by a slowly advancing "doctor" knife. Since part of the precoat is removed continuously together with the product cake, it becomes necessary to precoat again the filter, after some time of operation.

Vacuum rotary disk filters are similar in principle with the vacuum rotary filters (Fig. 5.9). They consist of a number of vertical disks connected through a manifold to the vacuum system. The perforated or screen disks are covered with a filter cloth, and they are divided into sectors for vacuum filtration, washing, and air pressure removal (Perry and Green 1984).

Pressure Filters

The pressure coat filters are used when pressure drops higher than those obtained in rotary vacuum filters are required. They include pressure leaf filters and cartridge filters (Bhatia and Cheremisinoff 1979).

The pressure leaf filters consist of a horizontal pressure vessel, containing a series of parallel leaf filters, made of perforated metal or metallic screens, which act as coated filters. The liquid suspension is forced by air pressure through the leaves and the clean product is collected in a manifold. Cartridge filters are small and inexpensive units that are used for the clarification of relatively small volumes of industrial liquids, containing low concentrations of solid particles. Filter cartridges consist of tubes 6–8 cm in diameter and 10–120 cm long, with a cylindrical filtration surface. The cartridges are placed in pressure housings, and the liquid to be filtered is forced though the cartridge by air pressure (Bhatia and Cheremisinoff 1979).

Two types of cartridges are used: (a) throwaway (expendable) filters, made of woven fibers, like cotton and synthetic materials, and (b) cleanable (reusable) cartridges, made of porous ceramics or stainless steel. Liquids cleaned with cartridges include boiler and cooling water, mineral oils, and alcohols.

Filtration of Juices

Filtration of clarified fruit juices (e.g., apple and grape), wine, and beer is applied widely to remove various small particles and colloids, which may precipitate during storage and affect product quality. Normal cake filtration is difficult because the filter cake formed is compressible, resulting in reduced filtration rate and increased pressure drop. This problem is overcome by precoating the filter surface with a filter aid, which forms a porous layer and reduces the flow resistance.

A precoat layer of about 0.5–1.0 kg/m^2 is formed on the filtration surfaces of plate, leaf, or disk filters, by filtering a water slurry of 0.3–1.0 % of filter aid (diatomaceous earth, perlite, or cellulose paper) at a rate of about 20 L/m^2 for about 30 min. Filtration is improved by adding continuously a small amount of filter aid to the juice during filtration, using a dosimetric pump (McLellan 1993). Filtration is stopped when the pressure drop and the filtration rate reach preset limits. The cake, containing the filter aid, is backwashed and removed by scraping and vibration.

5.4.3.2 Depth Filtration

Sand Filters

The depth or bed filters are used in cleaning potable and industrial water from small concentrations of small-sized solid particles. The particles are collected within the mass of the bed, which should be cleaned after some time of operation. Larger particles are removed previously by some less expensive separation process, like sedimentation.

Filter beds made of cleaned sand particles of size 0.6–1.2 mm are normally used as filter media. The close size distribution of the particles is necessary, since the pores are more uniform and they can collect the suspended particles more efficiently. By contrast, a bed of particles of wide particle size distribution would be blocked early in the filtration process, increasing sharply the pressure drop and reducing the filtration rate.

Gravity bed filtration is commonly used in water filtration with sand beds 70–80 cm deep on a layer of gravel 15–25 cm deep. Filtration takes place usually at a constant pressure drop, and the filtration rate decreases gradually with time. Operation at a constant filtration rate is possible by increasing the pressure drop with time, e.g., by raising the water level above the bed surface (controlling the opening of the valve of clean water discharge).

The filtration rate in sand filters is in the range of 4–10 m^3/m^2h, and the maximum operating pressure drop is 2 m of water (0.2 bar).When the maximum pressure drop is reached, the filtration is stopped and the sand filter is cleaned by backwashing with water. Clean water is forced from the bottom through the bed at a high flow rate (20–50 m^3/m^2h), dislodging the collected particles and carrying them out of the system. Bed washing is facilitated by simultaneous blowing of compressed air at 20–40 m^3/m^2h.

Dual Media Filters

Dual media filters, consisting of a coal bed on top of a sand bed, are used for the filtration of quality potable and industrial water. The filters are enclosed in pressure vessels, and they are operated in a similar manner with the gravity sand filters. The carbon filter removes the undesirable odors and dissolved chlorine by adsorption.

The filter bed consists of a carbon layer of 0.25–0.50 m on a sand layer of 0.15–0.30 m, supported on a layer of gravel and an underdrain plate. High filtration rates are obtained (10–40 m^3/m^2h) with maximum pressure drops in the range of 0.8–1.7 bar (Bhatia and Cheremisinoff 1979).

Sterile Filters

Sterile filters are used in the laboratory and the plant for the removal of microorganisms from various liquids, which are too sensitive for thermal sterilization. Microorganisms of sizes 0.5–10 μm (bacteria to fungi) can be removed with membrane filters of known openings and porosity. Typical sterile filters (Millipore) are made of cellulose membranes, 130 μm thick, with opening of 0.22 μm and porosity of 0.75. They are operated at pressure drops of 1–4 bar and temperatures up to 120 °C. For viruses (<0.1 μm) or for effective sterilization, fine filters or two-stage sterile filtration may be required (see Chap. 12).

5.4.4 Centrifuges

Centrifuges are compact but expensive equipment for efficient mechanical separations, used in both sedimentation (separation) and filtration applications of solid/liquids and liquid/liquids.

5.4.4.1 Centrifugal Separators

Centrifugal sedimentation is based on the application of the centrifugal force to separate particles and liquids of different size and density.

The Stokes equation (5.4) for settling velocity (u, m/s) of particles of size (d, m) in a centrifugal field of rotational speed (ω, 1/s) at a distance (r, m) from the center of rotation is written as follows:

$$u = \left[\omega^2 r(\rho_s - \rho)d^2\right]/(18\eta) \tag{5.14}$$

where ρ_s and ρ are the densities of the particles and the liquid (kg/m^3), respectively.

The liquid flow though a centrifuge is considered as a plug flow with a residence time $t = V/Q$, where (V) is the holdup volume (m^3) and (Q) is the flow rate (m^3/s). The time required to remove 50 % of the particles (of "cut diameter" d_c) will be $t_c = z/(2\,u)$, where (z, m) is the thickness of the liquid in the centrifuge. The flow rate to remove 50 % of the particles will be $Q_c = 2\,u\;V/z$. Substituting the settling velocity (u) from Eq. (5.14), the last relation becomes

$$Q_c = \left[\omega^2 r(\rho_s - \rho)d_c^2/(9\eta)\right]\left(V^2/z\right) \tag{5.15}$$

Equation (5.15) is equivalent to the following:

$$Q_c = 2\,u_g \Sigma \tag{5.16}$$

where (u_g, m/s) is the gravity settling velocity of the particles (diameter d_c) and (Σ, m^2) is a characteristic parameter of the system, equivalent to the cross-sectional area of a gravity settling tank, which has the same settling capacity with the specific centrifuge (Perry and Green 1984).

By combining Eq. (5.16) with the Stokes (gravity) equation (5.4), the "sigma" parameter (Σ) is given by the relation

$$\Sigma = V\omega^2 r/gz \tag{5.17}$$

Equation (5.17) for cylindrical centrifuges becomes

$$\Sigma = \pi b\omega^2\left(3r_2^2 + r_1^2\right)/2g \tag{5.18}$$

where (r_1, r_1) are the distances (m) of the internal and external surfaces of the liquid for the center of rotation and (b) is the length (m) of the active cylinder.

For disk centrifuges, the following equation is used:

$$\Sigma = \left[2\pi\omega^2(N-1)\left(r_2^3 - r_1^3\right)\right]/(3g\ \tan\theta) \tag{5.19}$$

where (N) is the number of disks, (r_1, r_2) are the internal and external radii and (2θ) is the cone angle of the disks.

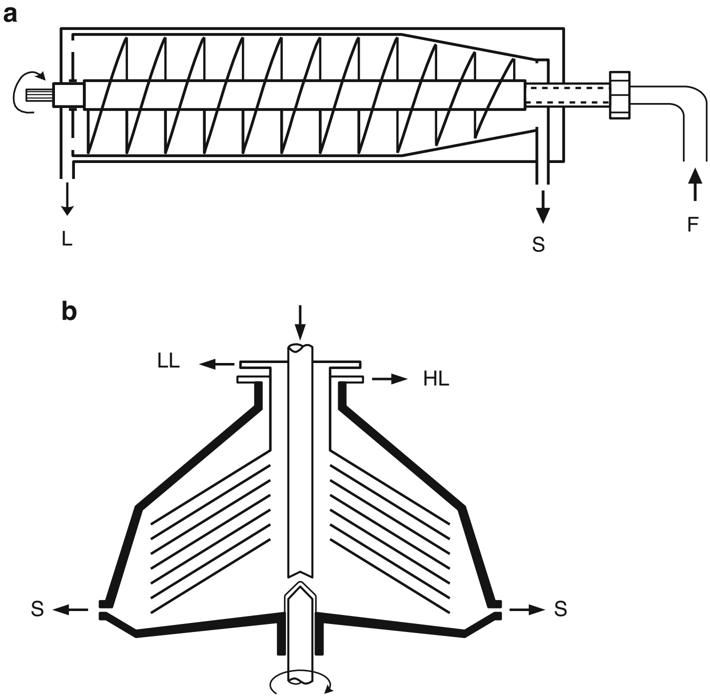


Fig. 5.10 Diagrams of centrifugal separators: (**a**) horizontal screw filter, (**b**) disk separator. *F* feed, *L* liquid, *S* solids, *LL* light liquid, *HL* heavy liquid

Estimated values of the (Σ) parameter of industrial centrifuges vary from 300 to 10,000 m^2. It is evident that the separating capacity of industrial centrifuges is quite high, e.g., equivalent to a gravity settling tank of a cross section of 1000 m^2 (equivalent tank diameter of about 35 m).

Cylindrical, cone, and disk centrifuges are used for separation of particles and liquids of different densities. The cylindrical units give clear liquids and wet sludges, while the cone systems give dry sludges and cloudy liquids. Cylindrical and cone systems are combined in efficient continuous centrifuges, like the screw settler in Fig. 5.10a (decanters). Cylindrical or tubular (bowl) centrifuges are used in edible oil processing and in clarification of fruit and vegetable juices and sugar syrups.

Disk centrifuges (Fig. 5.10b) are mainly used in clarification of various liquids, like fruit juices and citrus oils. They consist of a centrifugal bowl 20–50 cm in diameter, with a series of cone disks. Perforated disks are used to facilitate the centrifugal separation of liquids of different density (e.g., cream/milk). The liquid feed mixture enters at the center of the bowl and it is separated by the centrifugal force into a light and a heavy stream, which are removed separately with special piping. Nozzle-discharge centrifuges are used when significant amounts of solid particles settle in the centrifugal field. They have small openings at the bottom sides of the bowl, through which the settled particles are removed continuously.

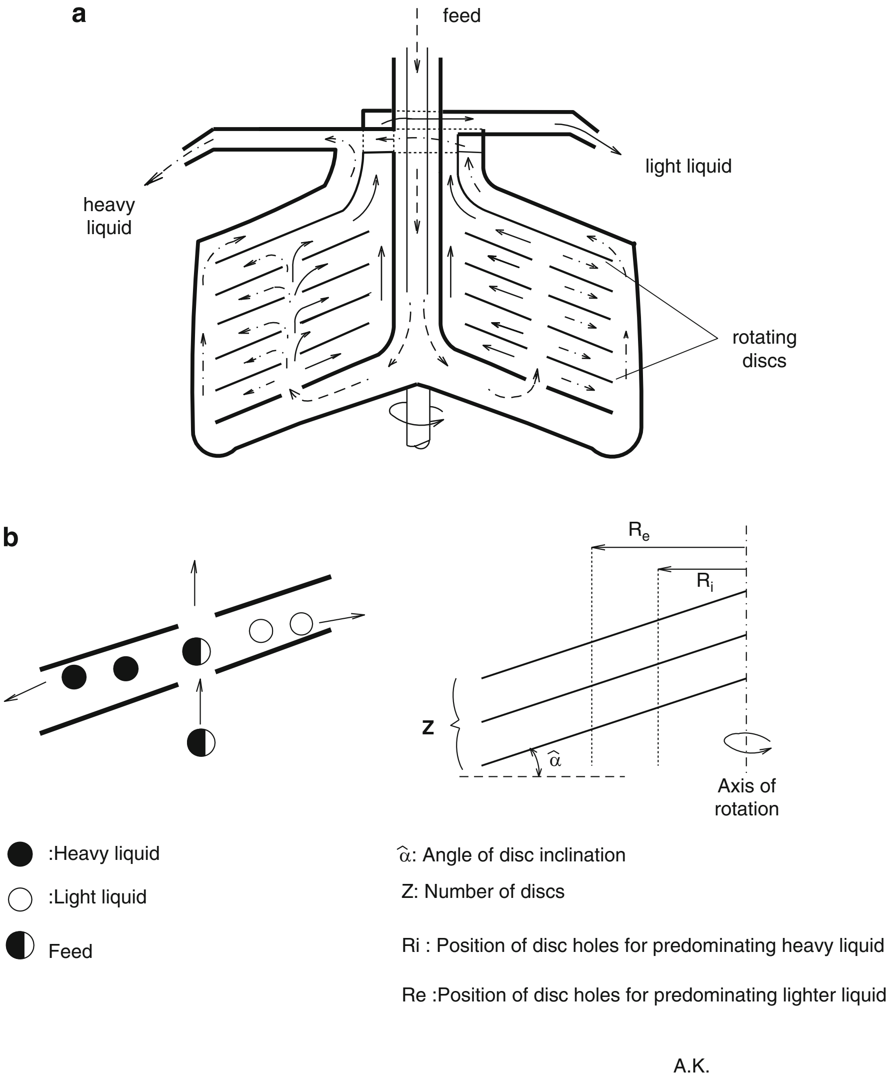


Fig. 5.11 Diagrams of a milk separator

The separation of skim milk from an initial milk quantity producing whole milk as well is done in a centrifugal separator with conic disks (Fig. 5.11a). The disks have holes laying exactly one over the other when the disks assembled in the equipment. The heavier phase of milk, i.e., the more water-containing part of the initial quantity of milk, slides down toward the periphery of the equipment. The lighter (fatter) part of milk slides upward toward the central axis of the centrifugation equipment. Finally, the two phases of the centrifuged milk use different exits to leave the equipment. The efficiency of separation of the two phases of the milk depends on the speed of rotation, the inclination of the disks (α), and the number of disks (Fig. 5.11b). The position of the holes of the disks depends on the estimated concentration of fat in the initial milk.

5.4.4.2 Filtering Centrifuges

Filtering centrifuges are used in food processing to separate effectively solid particles from water suspensions, e.g., in recovering sugar crystals from a crystallizer. The filter consists of a horizontal or vertical basket with perforated or wire mesh wall, which is rotated at high speed. The suspension is fed in the center of the basket and the solid particles are forced to the walls, forming a cake, through which filtration takes place, like in the normal pressure or vacuum filters.

The pressure drop through the filter cake in a rotating basket is given by the equation

$$\Delta p = \rho\, \omega^2 \left(r_2^2 - r_1^2\right)/2 \tag{5.20}$$

where (ρ) is the density (kg/m^3) of the particles, (ω) is the rotation speed (1/s), and (r_1, r_2) are the distances (m) of the internal and external surface of the cake ring from the center of rotation.

Assuming that the main resistance to filtration is the filter cake and neglecting the resistance of the filter medium, the integrated filtration equation (5.11), combined with the centrifugal equation (5.20), yields the following relation for the filtration rate (V/t):

$$(V/t) = \left[\rho\omega^2 \left(r_2^2 - r_1^2\right)\right](A_a A_L)/(2\eta RC) \tag{5.21}$$

where, $A_a = 2\pi\, b\, (r_1 + r_2)$ and $A_L = [2\pi\, b\, (r_2 - r_1)]/[\ln (r_2/r_1)]$, and ($b$) is the length of the basket.

For given centrifugal filtration, the filtration rate will decrease as the mass of the particles in the filter cake (C) increases with the filtration time.

Various centrifugal filters are used in process engineering. The basket centrifuges consist of suspended vertical baskets 0.7–1.2 m in diameter and 0.5–0.8 m deep, rotating at speeds 600–1800 rpm. The filtration of the batch unit is stopped, when sufficient cake is formed, and the cake is washed with water. Subsequently, the basket is emptied and cleaned before the cycle is repeated. In the horizontal continuous centrifugal filters, the cake is washed and removed continuously, e.g., by a pusher-discharge system.

5.4.5 Mechanical Expression

5.4.5.1 General Aspects

Mechanical expression is used widely in the extraction of juices and oils from fruits, vegetables, and oilseeds. They are based on the application of pressure to disrupt the plant cells and release the contained juice or oil constituents. Mechanical pressure is also used in the expression of fish oils. The by-products of mechanical expression are solid residues like pomace or peels, which are either processed into animal feeds or are disposed in the land.

Mechanical expression does not include solvent extraction and water leaching of solutes from plant or animal materials, which are essentially mass transfer processes, and they are discussed in Chap. 11. Solvent extraction may be required to recover significant amounts of residual solutes from mechanically expressed materials, like oilseeds.

The mechanical expression of vegetables was reviewed by Cantarelli and Riva (1983). The expression process depends on the following factors (Brennan et al. 1990): (1) the applied mechanical pressure, (2) the yield stress of the food material, (3) the porosity of the cake formed, and (4) the viscosity of the expressed liquid.

Mechanical expression is a complex physical process with no satisfactory theory in the literature. The main engineering parameters of the process are the pressure drop (Δp) and the flow rate of the liquid, which depend on the material and the equipment.

The following empirical equation relates the equilibrium pressure (p) to the volume of the solid cake (V_c) (Perry and Green 1984):

$$\log(p) = k + k'/V_c \tag{5.20}$$

where (k, k') are empirical constants.

Mechanical expression of a liquid from a solid matrix is possible only if the solid is compressible, i.e., the compressibility factor (s) of Eq. (5.12) is above zero ($s > 0$). In incompressible solids ($s = 0$), mechanical pressure cannot express the liquid, and other separation methods must be used.

The mechanical expression equipment is divided into batch and continuous presses, which are described briefly first. Because of its industrial importance and the variety of equipment used, the mechanical expression of fruit juices is discussed in more detail.

5.4.5.2 Batch Presses

Box and Pot Presses

The material to be expressed is wrapped in a canvas (cotton) cloth and is placed and compressed in a series of steel boxes, fitting the fixed and moving heads of a vertical

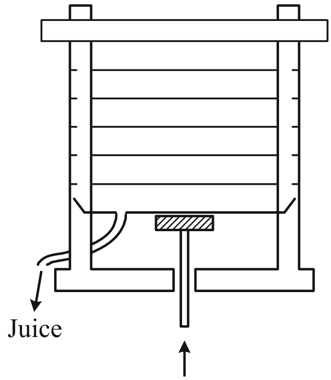


Fig. 5.12 Batch box press

hydraulic press. The boxes are perforated with vertical drainage channels. An installation of 15 box presses will handle about 7 tons of cottonseed per 24 h, reducing the oil content from 30 to 6 %. Expression time is 20–30 min/batch, and the final pressure on the residual cake may reach 100 bar.

The material is enclosed in a cylindrical pot, with fiber pads or screens in the bottom and on the top, and it is compressed with a hydraulic ram entering from above. The pot press can handle fluid materials. It is used, e.g., for oil expression from olives and separation of cocoa butter from chocolate. Pot load per cycle is about 250 kg, and the final expression pressure can reach 400 bar (Fig. 5.12).

Curb and Cage Presses

The curb and cage presses are used for the expression of solutes from fibrous materials, which do not require high pressures, like apple juice and olive or copra (coconut) oils. They consist of a cylindrical perforated vessel or a cage with fine longitudinal grooves on the walls, leading to larger drainage channels. The contained material is pressed slowly by a mechanical piston.

5.4.5.3 Continuous Presses

Continuous presses are used widely for the expression of fruit juices and oils from various oilseeds. They are preferred over the batch presses because they require less labor and they are more efficient in processing large volumes of material. The screw press is the most popular equipment, because of its many advantages.

Screw Presses

The screw press consists of a horizontal or vertical rotating screw, fitting closely inside a slotted or perforated curb (frame). Both screw and curb are tapered toward the discharge to increase the pressure on the material. The pressure can also be

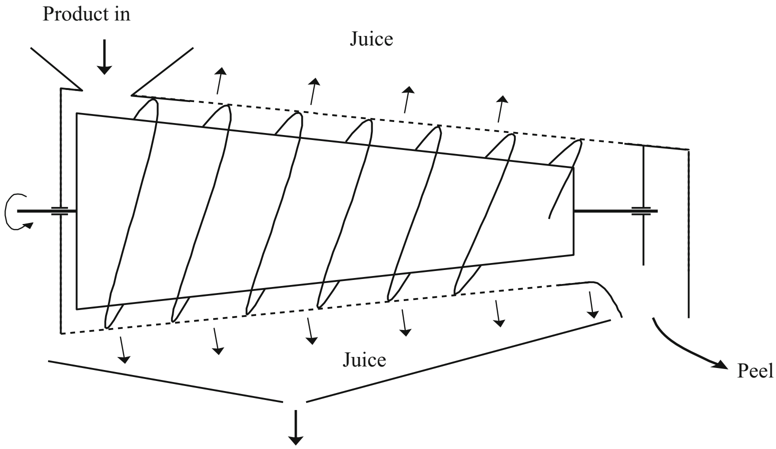
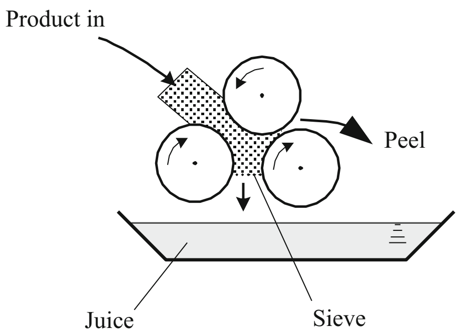


Fig. 5.13 Principle of screw press

Fig. 5.14 Roller press



increased by varying the pitch of the screw. As the material is pressed by the screw, the liquid escapes through the openings of the curb (Fig. 5.13).

Shaft speeds of 5–500 rpm are used with very high pressures, up to 2500 bar. The capacity of the screw presses can reach 200 tons/24 h, and the residual oil in the press cake can be as low as 2 %.

Screw presses or "expellers" are used widely in the vegetable oil industry.

Roller Presses

Continuous roller mills are used principally for expressing juice from fibrous food materials, such as sugarcane and some fruits. They consist normally of three rollers, which squeeze the material as it is forced to pass between them successively. The rolls are made of cast iron, and they are corrugated or grooved in various patterns (Fig. 5.14).

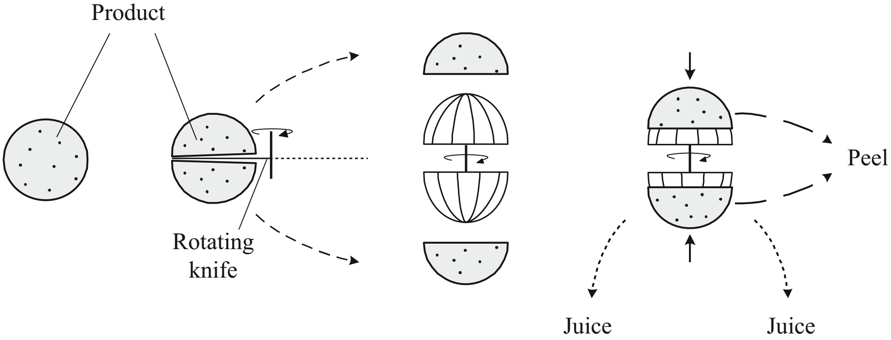


Fig. 5.15 Fruit juice reamer

The sugarcane is macerated dry, but water is added during pressing for recovering the sugar juice. The pressed cake is scraped off the last roller with a knife.

Belt Presses

The belt press combines the filtering and expression actions in one continuous operation. Initially, the belt press was used to dewater suspensions of wet materials like paper pulp, but recently, this system is applied in juice expression from various fruits (next section).

The slurry is enclosed between two serpentine belts and is pressed gradually by a series of rolls, forcing the liquid out. The pressures developed are relatively low, and expression is confined to easily remove solutes, like fruit juices. A belt press processing 3.5–5 tons of apples/h into juice (60-cm-wide belt) was described by Swientek (1985).

Juice Reamers

The simple home reamers are used industrially in expressing orange and other juices (Fig. 5.13). The fruit is sliced with a sharp knife and the rotating serrated reamers extract the juice and pulp. The reamers are the basic elements of the high-capacity Brown citrus extractor (Fig. 5.15).

5.4.5.4 Fruit Juice Expression Equipment

Pressing or expression is the most important operation in fruit juice processing, since it is related immediately to both economics (yield) and quality (composition) of the product. Expression equipment for two different types of juices, i.e., apple and citrus, is described briefly, because of the commercial importance and the variety of the employed equipment. Some of the expression equipment used for apple juice can be applied to grape and other juices.

Apple and Grape Juices

Extraction of juice from apple fruits can be accomplished if the following requirements are met (Cockram 1993): (a) pressing, which should be applied quickly, so that the juice is removed from the slower moving bulk material, (b) exit path to remove the expressed juice, (c) time to complete the process, and (d) bulk material to withstand the pressure, without appreciable movement.

The grapes are prepared for pressing in a stemmer/crusher, which is a rotating drum with perforations of 2.5 cm. The grapes are removed from the stems and are crushed by passing through the holes, while the stems are discharged from the center of the drum. Stems and seeds should be separated from the grapes before crushing and expression to prevent extraction of undesirable bitter components. The crushed grapes are pressed between two rotating cylinders to express the juice. Grape pigments, e.g., from Concord grapes, can be extracted into the juice by heating the crushed grapes at about 60 °C.

The pressing operation of the fruit mass is affected by the following factors:

(a) Fruit quality. Ripe fruits yield the best quality and quantity of juice. Juice expression is difficult from overripe fruit.
(b) Milling. The fruit pieces and particles should be of the proper size (not too small or too large). Special grinding mills with knives are required for apples.
(c) Enzymes. Pectolytic and cellulose- or starch-splitting enzymes, added to the fruit mash, will facilitate juice expression. Enzyme pretreatment should be done at the optimum pH, temperature, and time. Excessive enzymatic breakdown results in a viscous mash, from which the juice cannot be expressed.
(d) Press aids. They help juice expression by increasing the permeability of the fruit mash (cake). Common press aids are mixtures of wood fibers, paper fibers, and rice hulls. The proportion of each of these press aids added to the fruit mass is about 3–4 %.
(e) Leaching. Water is added to the press cake to dissolve the residual solids, and pressing is repeated, increasing the overall yield of juice.

The following expression equipment is used for the expression of apple and grape juices:

- Rack and Frame Press
  "Cheese" cloths are used, containing fruit mash 5–8 cm thick, which are stacked and pressed under a hydraulic ram, forcing the juice out. At the end of pressing the cake, about 1 cm thick is removed from the cloths and the operation is repeated. No filter aid is used and the yield is low.
- Willmes Press
  The Willmes (bladder) press is used mostly in grape juice and wine processing. It is a pneumatic system, consisting of a perforated, rotatable, horizontal

cylinder with an inflatable rubber tube in the center. The cylinder is filled with grape mass, and the air bag compresses the material, forcing the juice out. The bag is then collapsed and the cylinder retracted. The rotation and pneumatic compression of the mash is repeated many times with increasing pressure.

- Screw Press
  Screw presses are used in the expression of large quantities (9 up to 50 tons/h) of apple and grape juices with yields of about 80 %. Screw diameters range from 15 cm to 3 m. Press aids are normally used in screw presses. Screw presses made of stainless steel for fruit processing are expensive equipment, justified in large-scale continuous processing lines.
- Bucher Press
  The Bucher press is a large complex and expensive unit, processing 5–7 tons/h of fruit with yield of about 85 %, which can reach 92 % with the use of enzymes and leaching. The unit consists of a rotating cylinder (basket) 2 m in diameter and 2 m long with a hydraulic piston at one end. The basket contains 280 small filter elements, which are flexible, grooved openings, covered with filter cloth. Juice flows through the cloth, down the grooves to the end of the press, where it is collected.

  The fruit mash is added to the basket and the piston presses the mash and it is retracted. Then a new amount of mash is added and the pressing operation is repeated, until a high pressure is developed, reaching 190 bar, before the pressed mash is washed and dumped from the basket.

  In addition to the high capital cost, the system has high operating and maintenance costs.
- Belt Press
  The serpentine belt press is less expensive than the screw and Bucher presses, but it has lower efficiency (78–82 %). Capacities up to 30 tons/h can be achieved.

  The belt press consists of two belts moving through a series of rollers. The belts are fed with a layer of 3–8 cm of fruit mass, which is compressed gradually until a compressed cake of about 0.5 cm is formed at the end of the line. The belts are difficult to clean after each operating cycle.
- Screening Centrifuge
  Screening centrifuges (filtering centrifuges) can be used in the expression of juices from a fruit mass that has been treated with enzymes to release the juice from the cellular structure. Operating capacities can reach 10 tons/h, with juice yields of 85–90 %.

Citrus Juices

Citrus juices, mainly orange, lemon, and grapefruit, are produced in large quantities, using special juice expression equipment. Due to the unique structure and composition of citrus fruits, some equipment developed for other fruit juices is applied only in limited cases.

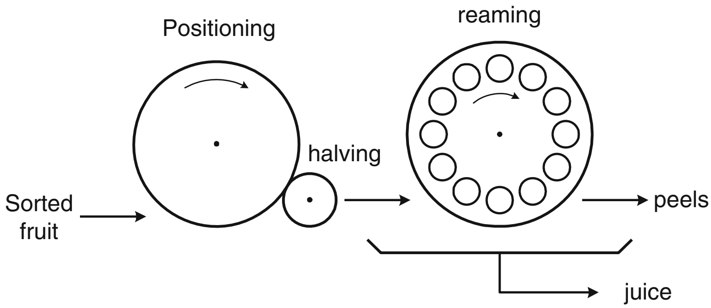


Fig. 5.16 Diagram of the Brown citrus juice extractor

Two different citrus juice expression systems, developed in the USA, are used worldwide, i.e., the Brown and the FMC extractors (Nagy et al. 1993; Kimball 1999). The citrus fruit is first washed and sorted into different sizes to accommodate the operation of the extractors, which are adjusted to handle specific sizes. The expressed juice is processed further mechanically to remove seeds, peel fragments, and vesicular membranes (rag), using screen finishers, similar to those of other juice processing systems.

The composition and quality of the citrus juices are affected strongly by the expression and finishing conditions, namely, mechanical pressure, shear, and residence time. If the finishing procedures are too rigorous or not rapid, bitter components (limonin and naringin) may be leached into the juice.

The Brown extractor is based on the same principle of the home reamer, i.e., the fruit is cut into halves and the juice is expressed by a mechanical reamer of appropriate size. Figure 5.16 shows a diagram of the commercial Brown extractor.

The sorted fruits are positioned in a vertical turntable for cutting into halves with a sharp knife. The fruit halves are oriented and picked up by rubber cups, mounted on tracks in a vertical turntable. Plastic serrated reamers on a vertical turntable express the juice from the approaching fruit halves. The reamers penetrate the fruit rapidly at first but slowly later as the point of maximum penetration is reached. The juice collects on a pan, while peels and rag (fruit membranes) are ejected separately. The citrus peels are used to express the peel oils and, finally, they are dehydrated to produce animal feed.

The FMC extractor operates on a completely different principle, i.e., the juice is extracted from the whole fruit, without halving and reaming, as shown diagrammatically in Fig. 5.17. The fruit is placed into the lower extraction cup of the appropriate size. The upper cup descends pressing the fruit, while a circular cutter below cuts a bore, which is removed from the bottom. The fruit is squeezed and the expressed juice is separated from the fruit residue (seeds, rag, and peel fragments) through the small-diameter strainer. The juice is collected in the cup below and the residue (pulp) inside the strainer is discharged from the bottom through the orifice tube (plunger).

The strainer of the FMC extractor acts as a prefinisher for the citrus juice. The squeezed peel of the fruit is discharged from the lower cup. The expressed oil is separated by centrifuges, and the peels are dried in air-dryers.

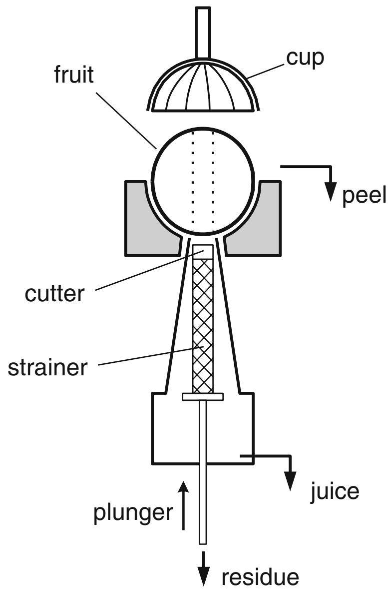


Fig. 5.17 Principle of operation of the FMC citrus juice extractor

5.5 Solid/Air Separators

Solid/air separators are used in the recovery of solid food particles from exhaust air in various food processing operations, such as spray drying and pneumatic transport, in reducing air pollution from industrial air effluents, and in cleaning the atmospheric air in food processing plants. The industrial air exhaust streams may contain high particle concentrations (up to 45 g/m^3), while the concentration of particles in the atmospheric air is less than 1 mg/m^3. The size of particles ranges from 1 to 1000 μm.

The design of solid/air separators is based on the same principles of the air classifiers (Sect. II1b), i.e., the hydrodynamic, centrifugal, and gravity forces. In addition, the electrostatic forces play a significant role in the separation of the small-sized particles. The most common separation equipments used in food processing are cyclones and bag filters. Wet scrubbers and electrical filters are mainly used in the chemical and mineral process industries and in power generation (Perry and Green 1984).

5.5.1 Cyclone Separators

Cyclones are simple and inexpensive units, which can remove effectively solid particles (and liquid droplets) larger than 10 μm from industrial gases and air. Figure 5.18 shows diagrammatically the flow pattern and the dimensions of a standard industrial cyclone.

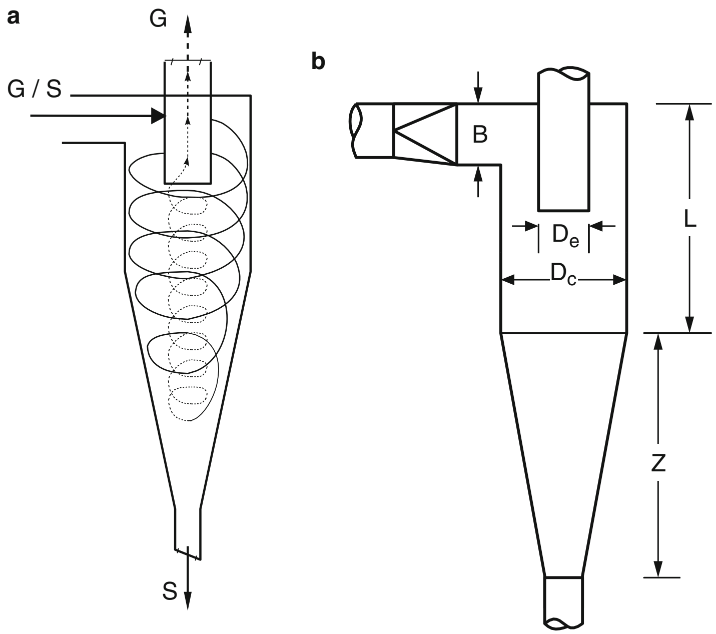


Fig. 5.18 Diagram of flow pattern in cyclone separator (**a**) and standard cyclone dimensions (**b**). *S* solids, *G* gas (air), D_c cyclone diameter, $L = Z = 2D_c$, $B = D_e = D_c/2$

The particle/air mixture enters the cyclone tangentially, following a spiral flow pattern from top to bottom and a vortex flow from bottom to top, and exits from the collector. The solid particles are subjected to self-generated centrifugal force, thrown to the cyclone walls, from which they fall and are collected at the bottom. The air exits from the top of the cyclone, and it may contain significant amounts of small-sized particles. In order to eliminate the very small particles, which escape the cyclone and cause particulate pollution in the environment, bag filters of wet scrubbers should be installed after the cyclone.

In general, small-diameter cyclones (about 25 cm in diameter) are used in practice, because they are more efficient in removing the relatively small-sized particles.

The self-generated (no mechanical means) centrifugal force, developed by the cyclone spiral flow, is very large, due to the small cyclone diameter, reaching up to 1000 times the gravitational force. The separation efficiency of the cyclone is characterized by the cut diameter (d_c) of the particles, which is defined by the analogous equation of air classification (5.6)

$$d_c^2 = (9\eta B)/(2\pi N \rho u) \tag{5.22}$$

where (B) is the entrance width (m) and N is the number of spiral “turns” of the cyclone, (ρ) is the particle density (kg/m^3), and (u) and (η) are the air velocity (m/s) and viscosity (Pa s), respectively. The value $N = 5$ is used for normal cyclone collectors. In cyclone design, the air (entrance) velocity is taken as $u = 15$ m/s. The cut diameter (or cut size) corresponds to a collection efficiency of 50 %.

The cut diameter is reduced and, therefore, the efficiency of the cyclone collector is increased by increasing the air velocity and/or the particle density or by reducing width of the cyclone entrance.

The efficiency of a cyclone collector is estimated from the Lapple diagram (Perry and Green 1984), as a function of the particle size ratio (d/d_c). The efficiency drops sharply for small particles, e.g., to lower than 10 % at $(d/d_c) = 0.3$ and exceeds 90 % at $(d/d_c) = 3$.

As an illustration, for milk powder of solids density $\rho = 1400$ kg/m^3 (low porosity) and a cyclone of 20 cm diameter and air velocity $u = 15$ m/s and viscosity $\eta = 0.02$ mPa s, the cut diameter will be $d_c{}^2 = (9 \times 0.00002 \times 0.05)/(2 \times 3.14 \times 5 \times 15 \times 1400) = 1.36 \times 10^{-10}$ m^2 and $d_c = 11.7$ μm. It should be noted that, for particles smaller than (11.7)/3 = 3.9 μm, the collector efficiency will be less than 10 %, i.e., more than 90 % of the particles will pass through the cyclone. Thus, it becomes necessary to install another, more efficient collector after the cyclone, e.g., a bag filter, in order to collect most of the escaping particles and discharge a clean air stream into the environment.

Since, for efficiency reasons, the diameter of the cyclones should be small, a number of collectors, operated in parallel, will be required in order to handle large volumes of industrial gas (air) streams. The collectors are usually installed in parallel in compact structures (multiclones).

Small cyclone units and high air flows result in significant pressure drops (Δp) and considerable power requirements (kW). The fan is installed either before (pressure) or after (suction) the collector. The suction installation is preferred because the exhaust air from the cyclone will be free of the large particles, which might damage the fan rotor.

The pressure drop through the cyclone is proportional to the square of the air (entrance) velocity (u^2), while the energy loss or "head" (in m of water) will be (Perry and Green 1984)

$$\Delta p/\rho = 4.7(u)^2 \tag{5.23}$$

where (Δp) is the pressure drop (Pa), (ρ) is the density of air (kg/m^3), and (u) is the air velocity (m/s). Thus, the "head" loss through the cyclone is about ten times higher than the velocity "head" ($u^2/2$).

5.5.2 *Bag Filters*

Bag filters are usually made of woven cloth or felt, which act as surface filters (Fig. 5.19).

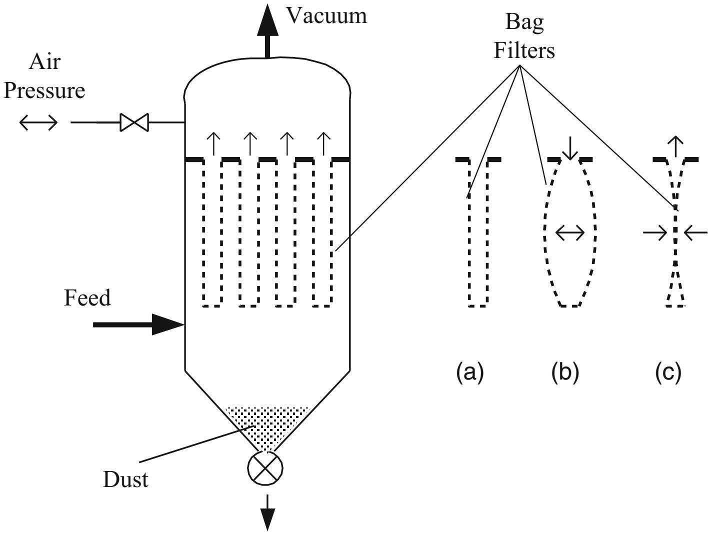


Fig. 5.19 Bag filter. (**a**) Normal position; (**b**, **c**) filter shaking for cleaning

Small solid particles, passing through cyclone collectors, can be separated from industrial airstreams (or gas) by bag filtration, which is similar in principle with the solid/liquid filtration, discussed in Sect. 5.4.

Depending on their size (d), the particles are collected mainly by inertia ($d > 1$ μm) or electrostatic forces ($d < 0.5$ μm). In bag filters, the particles form a mat on the surface, which acts as a filter medium, increasing the efficiency of filtration and the pressure drop. Filtration is interrupted when the pressure drop exceeds a preset limit and the filter is cleaned.

Bag filter design is based on the choice of a suitable fabric of felt which will give the optimum pressure drop (Δp)–superficial air velocity (u) relationship for the longest operating cycle.

The pressure drop through a bag filter is given by the empirical equation (Perry and Green 1984)

$$\Delta\pi = K_{\psi}\eta\theta + K_{\delta}\eta\varsigma\theta \tag{5.24}$$

where (K_c) is the fabric resistance coefficient (1/m), (K_d) is the particle layer resistance coefficient (m/kg), (u) is the superficial air velocity (m/s), (w) is the particle loading of the filter (kg/m^2), and (η) is the air viscosity (Pa s).

The particle layer resistance coefficient (K_d) is related to the particle diameter (d), the particle shape factor (φ), and the porosity (ε) of the fabric by the Carman–Kozeny equation:

$$K_d = 160(1-\varepsilon)/\left(\varphi^2 d^2 \varepsilon^3\right) \tag{5.25}$$

The fabric resistance coefficient (K_c) is related to the pressure drop through the fabric (Δp_c), according to Eq. (5.26):

$$K_c = \Delta p_c / \eta u \tag{5.26}$$

The pressure drop through the particle layer (Δp_d) is given from the following equation, which is derived from Eq. (5.24):

$$\Delta p_d = K_d \eta C u^2 t \tag{5.27}$$

where (C) is the concentration of the particles in the air (k/m^3) and (t) is the filtration time (s).

The fabrics used in bag filters are made of cotton, wool, nylon, Dacron, and Teflon. The bag filters have a diameter of 12–20 cm and length of 2.5–5.0 m, and they are often assembled in compartments, called "bag houses," of 100–200-m^2 cloth surface. The diameter of large cylindrical bag filter compartments of, e.g., 120-m^2 cloth surface area, can be 3 m and their height 6–7 m. Their weight is about 2 tons and the power consumption is 1 kW.

The bag filters are cleaned either by shaking or by reverse flow of air. Shaking may be periodic, or after a preset pressure is built up, using a differential pressure instrument. Cleaning may be necessary when the pressure drop reaches 50–150 mm water (500–1500 Pa).

Superficial air velocities (air filtration rates) for woven filters are 0.5–2 m/min and for felt filters 2–5 m/min (Fig. 5.17a–c).

The bag filters are operated at temperatures up to 120 °C, depending on the type of fabric. The operating temperature should be at least 30 °C higher than the wet bulb temperature of the air to prevent moisture condensation on the filters.

5.5.3 Air Filters

Air filters are used to clean atmospheric air from small particles ($d < 0.5$ μm) and produce very clean air for the pharmaceutical, biotechnological, semiconductor, and nuclear industries. They are also used in clean room technology (hospitals and some advanced food processing industries).

Concentration of particles in atmospheric air is normally lower than 12 mg/m^3, which is much lower than the particle concentration in industrial gas (air) streams.

Air filters are essentially deep-bed filters, made of porous cellulose materials. The mechanism of deep air filtration includes mechanical sieving and electrostatic forces.

Two types of fibrous filters are normally used: (1) viscous filters, in which the filter medium is coated with a viscous mineral oil, which retains the dust, and the used filters are cleaned periodically and returned to service, and (2) dry filters, which are cheaper; are made up of cellulose pulp, cotton, or felt; and are discarded after use.

Table 5.5 Technical characteristics of air filter materials

Material	Density (g/m^3)	Maximum operating temperature in dry environment (°C)
Glass	1.38	250
Polyacrylonitrile	1.17	125
Polyester	1.38	150
Polyphenylene sulfide	1.40	180
Polypropylene	0.91	90
PTFE (Teflon)	2.30	250

The pressure drop in a certain air filter depends on the volume of filtered air. As an example, the pressure drop in a glass-fiber fine filter of 7.3-m^2 surface area and an efficiency, according to ASHRAE, of 45 % at 3000 m^3/h is 65 Pa. The pressure drop becomes 110 Pa at 4250 m^3/h air flow (air velocity: 3.2 m/s).

Sizes of normal filters are 0.5 × 0.5 m, which can handle up to 4500 m^3/h at superficial air velocities of 1.5–3.5 m/s. They have a collection efficiency higher than 90 %, which can be increased at higher air velocities. The efficiency of air filters can be determined, e.g., according to ASHRAE standard 52–76 or DIN 24185. The operating cycles of air filters are about 1 week for the dry and 2 weeks for the viscous.

High-efficiency particulate air (HEPA) filters, developed in nuclear engineering, are used in some industrial applications. They are throwaway (disposable) filters of very high separation efficiency (99.97 % for particles 0.3 μm). Prefilters, removing larger particles, are used to protect these units.

Table 5.5 gives some technical characteristics of common types of filter materials.

5.5.4 Electrical Filters

Electrical filters are used to remove small particles from industrial gases and atmospheric air, based on electrical charging the particles, followed by collection on charged electrodes. Two types of filters are used: (1) electrical precipitators and (2) positively charged filters.

The electrical (or Cottrell) precipitators are large industrial installations used mainly in the chemical process industries and in power generating stations to remove various particles and fly ash from gaseous effluents, reducing air pollution. The particles, charged negatively from ionized gases, are collected in large positive plate electrodes, operated at about 50 kV, with efficiencies about 90 %. The gas velocity in the electrodes is about 2–3 m/s, and the precipitation (migration) velocity of the particles ranges from 5 to 15 cm/s. Electrical precipitators are complex installations and they have a high investment and maintenance cost (Perry and Green 1984).

Positively charged or two-stage precipitators are relatively small units, used mainly to clean atmospheric air from dust, smoke, and other particles, often as part of air-conditioning systems. The particles are charged positively by DC electrodes at about 13 kV and then collected on negative (grounded) electrodes operated at 6 kV. The collection efficiency is about 85–90 % and the filters should be cleaned, depending on particle loading, every 2–6 weeks.

5.5.5 Wet Scrubbers

Wet scrubbers, or wet particle collectors, are used to clean industrial gases and air from small solid particles that escape simpler separators, like cyclones. The main collection mechanism is inertial deposition of the particles on the liquid (water) droplets. Wet scrubbers are also used to absorb various gases from air streams in connection with air pollution control.

The absorption of gases and vapors in liquids is basically a mass transfer operation, like distillation and solvent extraction, which is analyzed in Chap. 11.

The particulate scrubbers consist of two parts: (a) the contactor stage and (b) the entrainment stage. The entrained sprays and deposited particles are removed from the cleaned gas (air) by cyclone or impingement separators.

The wet scrubbers are divided into two general classes: (a) low-energy equipment, which includes the spray towers, the packed towers, and the cyclone scrubbers, which can remove particles larger than 1 μm, and (b) the high-energy units, which include the venturi and the jet scrubbers, which can remove particles smaller than 1 μm.

Wet scrubbers are used extensively in the chemical process industry (Green and Perry 1984). They are used in some food processing plants in connection with antipollution systems for cleaning exhaust gases and air from undesirable gases, e.g., odorous compounds in the refining of edible oils.

A serious disadvantage of wet scrubbers is the production of a stream of polluted wastewater, which must be treated with some wet separation method before it is discharged into the environment.

5.6 Removal of Food-Related Parts

5.6.1 General Aspects

The separation operations may be classified also as solid and liquid processes (Table 5.1). In removing material or substances of solid food, two subcategories are the removal of product-own parts (e.g., cherry stems or cherry stones) and the removal of product-unrelated (foreign) parts (e.g., dust, insects, etc.). Furthermore,

Table 5.6 Methods of removal of product-own parts

Food parts	Undesired parts				Desired parts	
Location of food part	External parts			Internal parts	External	Internal
Method	Dry	Wet	Mixed	Dry	Dry	Dry
	Blistering	Peeling	Dragging	Brushing	Abrasion	Breaking
	Brushing	Steaming	Washing	Hand	Compression	Compression
	Breaking	Washing	Brushing	Screening	Cutting	Cutting
	De-hairing		Roasting	Suction	Hand	Hand
	Cutting		Brushing	Pitting		Milling
	Dehulling		Steaming	Coring		Suction
	Destemming		Brushing			
	Plucking		Washing			
	Hand		Soaking			
	Peeling		Brushing			
	Roasting					

the product-own parts can be internal (e.g., cherry stones, bones) or external (e.g., cherry stems, animal skin). The objective of a separation operation of product-own parts is to recover the separated materials or substances (e.g., juice from fruit, sugar from beets) or to remove undesired material or substances (e.g., fruit peels and filtrate residues).

In the removal of undesired external parts, dry, wet, or mixed methods are used. Table 5.6 gives some examples of methods used in removing external and internal food-own parts. Examples of dry methods are burning of chicken hair after plucking, knife peeling of onions and apples, brushing of oranges, and cutting and deboning of meat. Examples of wet methods are the washing of vegetables, the steaming of oysters, and the peeling of peaches in lye solutions. Mixed methods are the removal of potato peels and oyster shells by abrasion, just after steaming; the removal of chicken feathers by beating with rubber strap wheels, just after scalding; the suction of blood, just after slaughtering; and the removal of corn seeds, just after soaking. Mechanical wet and dry separations in foods include cleaning operations, which remove undesired product-unrelated (foreign) parts from foods.

5.6.2 Removal of Undesired Own Parts

5.6.2.1 Separations in Animal Products

Special mechanical equipment is used for the separation of external and internal parts of animal products (meat and seafood). They are designed to remove bones (deboning), meat strings, fish fins, hair from pigs and chicken, feathers from chicken, skins from animal and fish, shells from mussels, and blood from animals.

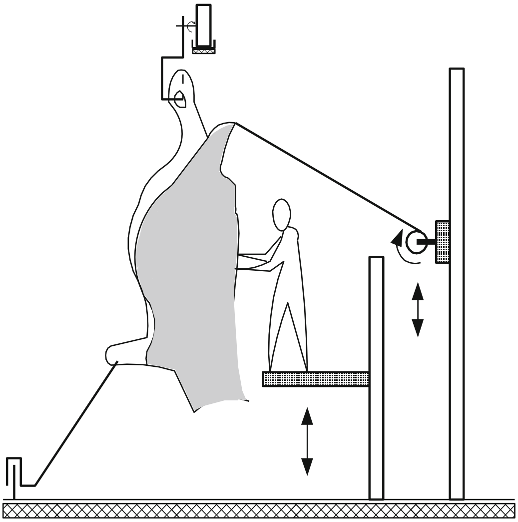


Fig. 5.20 Skinning of beef cattle

Skinning

Skinning of animals is usually done manually, i.e., using the cutting tools described in Chap. 4 and the auxiliary hoist mechanism shown in Fig. 5.20. The workers work on a vertically adjustable platform (elevator), while a vertically movable hoist pulls the skin. This work is quite elaborative as the skin makes about 7–11 % of the live weight of beef cattle (Lienhop 1981), and the skin must be removed carefully without damaging the meat.

De-hairing

De-hairing is applied to pigs and poultry. Two main methods of depilation are dragging and hair burning. Dragging is applied to pigs. Depilation is done after scalding at 60–80 °C, e.g., as the slaughtered pigs rotate on rubber cylinders, or it is done in the de-hairing tunnel. This equipment consists of several rows of scrapers (up to 22), which depilate the pigs, while they rotated and forwarded along the tunnel, due to the lattice supporting them and due to the spiral-shaped scraper. This way, all parts of the pig are de-haired. Water washes out hair and blood. This equipment has a capacity of more than 600 pigs/h. It requires 40 kW, 5 m^3 of water/h at 42 °C, and 0.85 m^3 of air/h at 6 bar. The machine weighs 15 tons. Burning is applied for de-feathering of poultry. The remaining hair is burned when poultry passes through a tunnel equipped with small gas burners.

Cutting

In cutting of hoofs and other animal parts, equipment described in Chap. 4 is used. In some cases, as, e.g., in removing the skin of fish, special cutting devices have

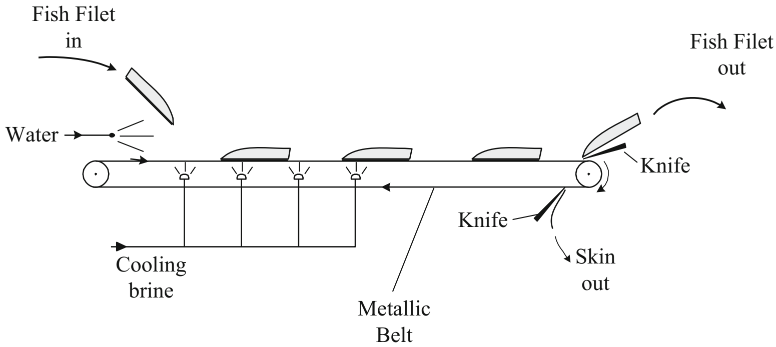


Fig. 5.21 Fish skin-removing machine

been developed. Figure 5.21 shows schematically a fish skin-removing machine. The skin of fish fillet, which is conveyed on a metallic belt, "sticks" on it, due to belt temperatures below 0 °C. The skin is separated from the rest of the fish by a knife at the end of the belt.

Screening

Screening is used for separating desired from non-desired parts, when it is difficult or noneconomic to do it manually. According to Neuhaeuser (1991), it is distinguished between separating meat from bones (hard separation) and meat from fibers (soft separation). In separating bones from meat, it is recommended to choose "flat bones," since the round bones contain also marrow. The bones with the residual meat are ground into 30–50-mm pieces and, subsequently, the mass is pressed at 350 bar in the hard-separator chamber, in which bones are retained, while the residual meat is filtered out. The capacity of such a machine is about 2 tons of input/h. It requires about 4 kW and weighs 600–700 kg with approximate dimensions of 1.2 × 1.2 × 1.2 m. For separating fibers from meat, the product is ground to about 18-mm particles. It is then pressed between a moving belt and a replaceable rotating perforated drum of 3-, 5-, and 8-mm apertures. The meat passes inside the drum, and the separated fibers are removed at the end of the belt (Fig. 5.22). This equipment can be also used in separating residual fish attached in other fish matter. In this case, the equipment may have the output of about 2 tons/h. It requires 4.5 kW, weighs approximately 1 ton, and has dimensions of about 1.5 × 1.5 × 2.0 m.

Removal of Mussel Shells

The mussel shells are steamed in a cooker, containing a wire-meshed conveyor, which is filled with mussels at a layer up to 250 mm. The working pressure is 4 bar. The mussels open and are discharged in the cylindrical de-clamping equipment, in

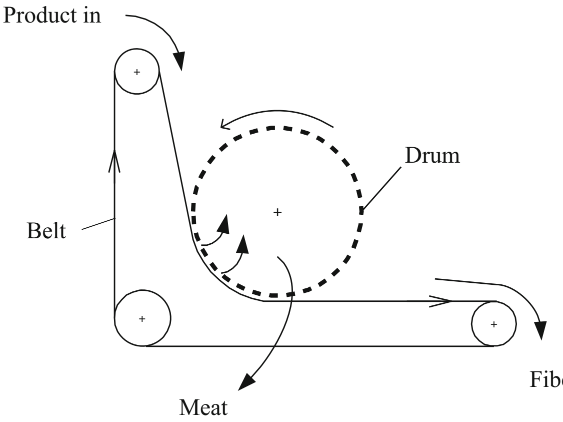


Fig. 5.22 Meat-fiber separator

which the shells are removed. This equipment consists of a rotating shaft with knives, working in a rotating perforated drum. After separation of the mussel meat from the shells, they are washed in a drum washing machine, in which small mussels and dirt are separated from the rest product. The capacity of a large cylindrical steaming unit can be about 10 tons/h. The steam consumption is 2 tons/h. The diameter is about 1 m and its length about 4–5 m. A large de-clamping unit may have the input capacity of about 30 m^3/h. The unit requires 6 kW of power and is about 5–6 m long.

Blood

Blood is removed immediately after stunning (electrical shock) of the animals in large slaughtering houses. It is aimed to pump out the blood as long as the heart is still in operation. For smaller animals, such as pigs and lambs, a carrousel-like unit can be used. The animals may lay or hang on the carrousel, while the blood is pumped out by a sticking knife (see Chap. 4), connected to a central pump through pipes.

5.6.2.2 Separations in Plant Products

The equipment for removing undesired own parts of plants is used to separate mainly food from shells, hulls, stems, and peels. They are also used for coring the seeds of fruits, such as apples or pears.

Breaking

The breaking processes are described in Chap. 4. Nuts are broken as they come between usually conical rolls that rotate in opposite direction to each other. The

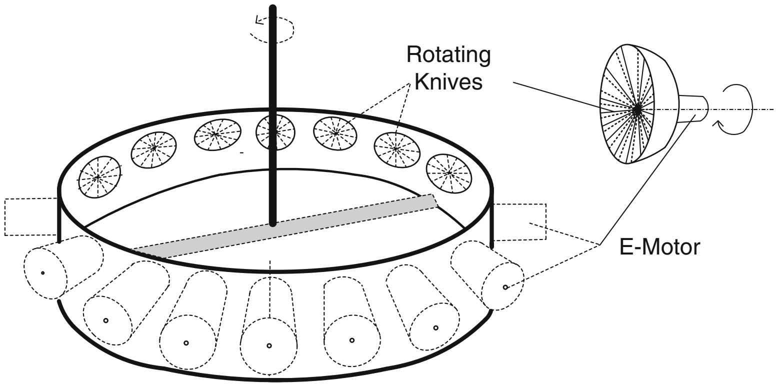


Fig. 5.23 Onion dehuller

clearance between the rolls is adjusted in such way that the shell, but not the kernel, breaks. In some cases, the rolls are grooved.

Dehulling

Dehulling of onions and seed coats from legumes is usually carried out with abrasion machines (attrition mills), which contain carborundum as an abrasive material. Onions may be also dehulled in a bin in which inside, around the surface of it, there are independently rotating disk knives. Figure 5.23 indicates such a machine. A rotating paddle moves/agitates the onions toward the disk knives. The capacity of such a batch process machine, equipped with 14 disk knives, is about 600 kg/h. Recently, this knife technique has been further developed to satisfy also continuous processing.

Dehulling of cereals, such as wheat, is part of the milling process. Part of the broken hull of ground wheat contains starch endosperm that is subsequently separated during screening (Chap. 4). In rice, since the grains are usually not milled, it is aimed to perform dehulling with minimal possible breaking of grains. It is accomplished as rice is rubbed between the surface of a conical cylinder and the jacket around it or between two parallel flat disks, as in the case of the colloid mill (Chap. 4). In both cases, the surfaces are coated with a hard material (e.g., corundum) for increasing friction. In the flat-disk equipment, the rice leaves the dehulling surface after 1/3 to 1/2 turn. In this case, about 67 % of rice is dehulled, 11 % is not dehulled, 4 % of grain is broken, 1.2 % is rice flour, and 16.8 % is hulls (Tscheuschner 1986). The clean dehulled rice is further polished as it is rubbed again between a fixed and a rotating disk or between two disks of different rotation. In the case that only one disk rotates, its peripheral speed is 18–20 m/s (Tscheuschner 1986). The energy required to dehull, clean, and polish rice is about 75 kWh/ton final product (Garloff 1991). Dehulling or removal of skins

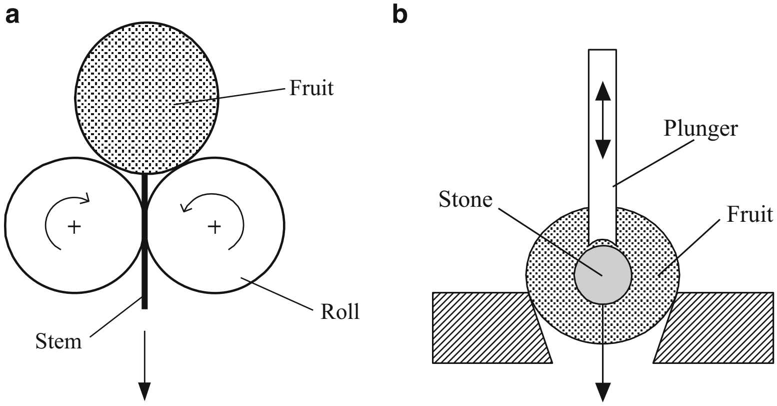


Fig. 5.24 Principles of destemming (**a**) and pitting (**b**)

from onions and seed coats from legumes (hulls) is usually carried out with abrasion machines (attrition mills), which contain carborundum as an abrasive material.

Brushing/Polishing

Brushing is done, e.g., for polishing fruits such as oranges and for removing a part of external contaminants (see also Fig. 5.1c). In products, like the oranges, brushing is combined with waxing. Usually, brushes placed on rotating rollers brush the product as it is conveyed. Waxing/brushing systems may have 8–30 rollers. Such a unit can be 2–3 m wide and 4–5 m long. Polishing of rice is carried out, e.g., in colloid mills (Chap. 4), removing the external layer (bran). The appearance and quality of breakfast cereals can be improved by polishing, e.g., removal of external insect or rodent injuries.

Destemming

Destemming of fruits, like cherries, is accomplished by parallel pairs of rolls rotating reversely. The stems coming between the rolls are dragged downward. The rolls are smooth and coated with rubber. Furthermore, they are as close as possible to each other, for avoiding crushing of the fruits (Fig. 5.24a). Equipment used for removing apple stems has a capacity of 400–500 pieces/min and require 3 kW of power. The weight of the equipment is 2 tons.

Pitting

Pits are removed from some stone fruits, mainly peaches and apricots, before further processing (canning and freezing). Pitting is also applied to cherries, olives, and some dried fruits, like prunes (Fig. 5.24b). The product is placed in specially designed dies automatically. A plunger with a suitably shaped end penetrates the product quickly, pushing out its stone, before coming back quickly to its initial position. A machine of this type may have dimensions of 1.7 × 1.7 × 1.7 m and capacity of 1.5–2.0 tons of cherries/h.

In peaches, the two mechanical pitting systems used in food processing are the Filper torque pitter and the FMC pitter (Woodroof and Luh 1986). In the Filper torque pitter, the fruit, e.g., peach, is placed in a cup and held with spring-loaded arms, while cutting blades cut it into two halves, and the pit is pushed out. The peach halves are moved onto a belt, cup down, where they are peeled with sprays of hot lye and washed with water. In the FMC pitter, the peaches come in parallel belt cups (e.g., 8 cups across the belt). Aligning wheels under each cup adjust the peaches so that each fruit can be cut by two stationary blades at the suture, around the longitudinal axis of the fruit. Subsequently, the pit is cut in half with a circular saw, and the two pit halves are cut from the fruit. The fruit and the pit halves are then discharged to a shaker-type separator. The FMC pitter can align and pit 300 clingstone peaches/min, which is approximately 3 tons/h. The equipment consumes 2.6 kW and 30 L of water /min. It weighs 2.5 tons and has dimensions of 4.5 × 2.0 × 2.0 m. A similar pitting machine (capacity: 4 tons/h) weighs 0.6 tons and requires 1.2 kW and 50–60 L air at 3–4 bar of pressure.

Coring/Scooping

Tube knives or rotating curved knives do coring and scooping (Fig. 5.25). By coring, the cut kernel comes inside the tube knife, which is subsequently removed by a piston, as indicated in Fig. 5.25b. A tube knife is used, when the kernel is concentrated along the vertical axis of a product. Rotating knives are applied to vegetables, such as peppers, and fruits, such as pineapples. They are also used in scooping and removing nests of kernels or seeds (Fig. 5.25c).

Equipments used for coring peppers, pineapples etc., have capacities of 16,000–24,000 pieces/h. They require 2–3 kW of power and 150–200 L air/min at 4–5 bar, and they weigh about 1.5 tons. Equipments used only for scooping of already cored products (e.g., pineapples) have double capacity and need less energy. There is equipment in which coring is a step of the overall processing, which may include mechanical peeling and slicing or cutting of fruits or vegetables. In case of apples, the diameter of coring tubes usually is 11 mm. In apples, the capacity of a coring machine is about 26,000 fruits/h. The seed celling knives are self-adjustable according to the size of individual apples, for minimizing product losses. Ultrasonic screening enables this process even to smaller particles (20 μm). It also reduces plugging in screens. In whey separation of cheese dairies, the productivity of such systems may be about 80 m^3/h (Fig. 5.26).

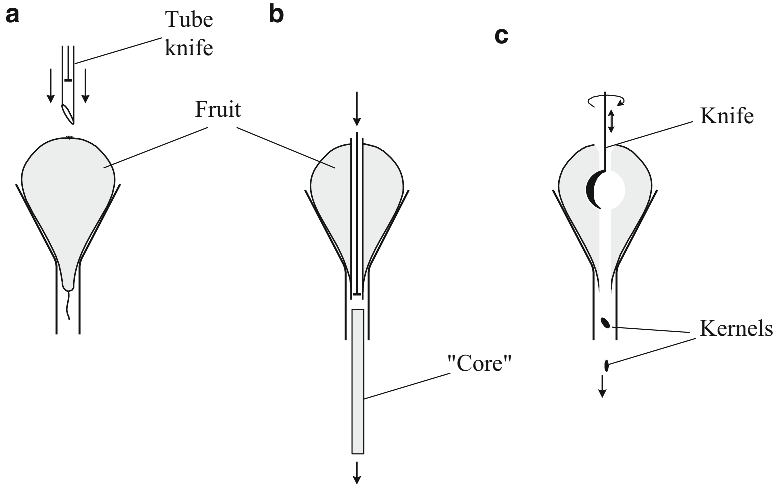
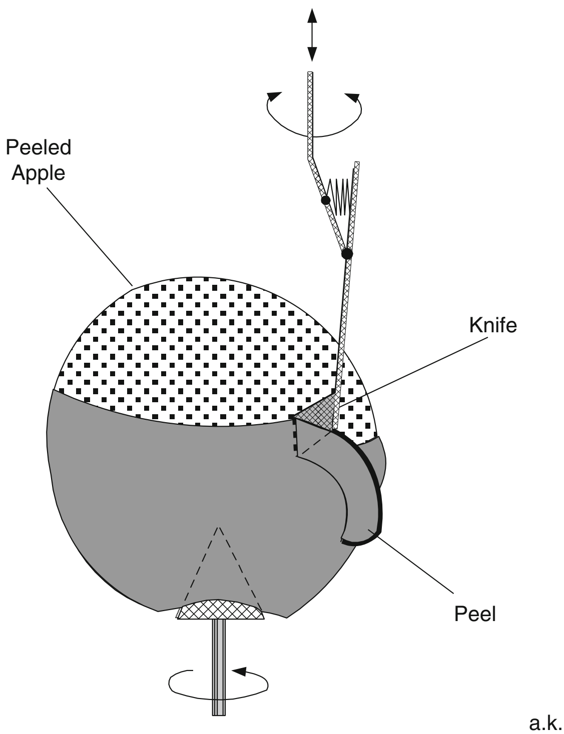


Fig. 5.25 Schematic pitting and coring of stone fruits. (**a**) Coring, (**b**) removal of cut core, (**c**) scooping

Fig. 5.26 Apple peeling



Cutting/Slicing

The capacity of a separate cutting equipment is about 50 apple pieces/h, requiring about 1.2 kW of power and 80 L of air/min and weighing about 0.5 ton. There is also cutting equipment used for peel shredding. Such equipment shreds and cuts, e.g., orange peels that are further utilized in processing of jam. In this case, the peel is the desired product. Typical equipment weighs about 0.5 ton, has dimensions of $1.0 \times 0.8 \times 1.0$ m, requires about 1 kW power, and has a capacity of about 0.5 ton of cut product/h.

Peeling

Peeling of raw food materials, such as fruits and vegetables, is necessary before further processing. The peels are removed mostly with wet peelers, using lye solutions or high-pressure steam. In some cases, dry peeling is used, e.g., onions and legumes. This includes flame peeling, abrasion, and peeling with knives. Flame peeling is used mainly for vegetables with thick and tough skins like peppers (pimientos) and eggplants, although sometimes flame peeling is also applied to remove thin skin, as that of onions. The food material is exposed to gas flames (temperatures up to 1000 °C) for a very short time, burning only the skin and not damaging the main product. The capacity of flame peelers is about 10 tons/h (Luh and Woodroof 1988).

Knives are used in the mechanical peeling of potatoes, onions, and some other tubers. A special onion peeling machine consists of a rotating pot with independent rotating knives located around its wall. The capacity of the unit depends on the volume of the pot and the number of knives. A pot of about 3.5 m in diameter and 2.0 m in height has the onion peeling capacity of 1.5 tons/h. The pot is filled to 50 kg during the operation that lasts up to 1.5 min/ batch. It has 4–30 rotating knives, requiring 0.2 kW each. The weight of the equipment is 2.5 tons.

Knife peeling is also used for some fruits, such as apples and citrus, which are difficult to be handled in wet peelers. In the mechanical peeler, stationary blades are pressed against the surface of the rotating fruit. Alternatively, the blades may rotate against the stationary fruit. Combination of knife and abrasion peeling is used for some food products. A knife apple-peeling equipment may have the capacity of 0.5–1 ton/h. It requires about 3 kW of power, 5–8 L of water/h, and 250 L of air/min (4–5 bar).

Lye peeling of fruits and vegetables, like peaches, apricots, and potatoes, is used as part of preprocessing of the product before canning, freezing, or dehydration. The main peeling equipment used in fruit and vegetable processing are the lye peelers and the flash steam peelers.

Lye peeling is carried out with a dilute solution of 1–2 % sodium hydroxide at a temperature of 100–120 °C for about 60 s (Woodroof and Luh 1986). Two types of lye peeling equipment are used, e.g., for peaches and potatoes: (1) the immersion (Draper) lye scalder, consisting of a long tank of dimensions of $1.2 \times 0.4 \times 30$ m

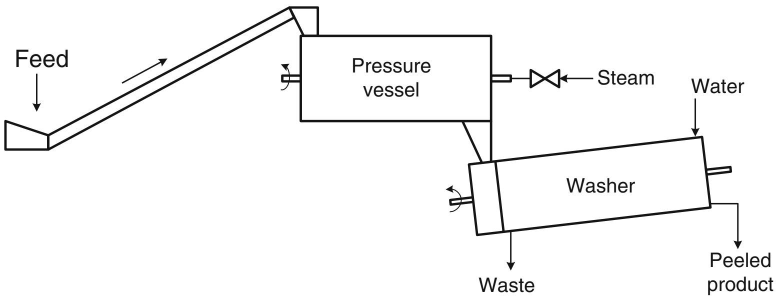


Fig. 5.27 Diagram of a pressure steam peeler

and capacity of about 20 tons/h, and (2) the lye-spray scalder, consisting of a conveyor belt moving slowly the fruit product (e.g., cup down peach halves), which are sprayed with the hot lye solution. The loosened skins are removed with sprays of wash water, and the residual alkali is normally neutralized by immersion in a 2 % solution of citric acid.

The "dry caustic peeling" uses concentrated sodium hydroxide (10–15 %) and infrared heating to peel the food material, e.g., potatoes, without the large amounts of water needed in the dilute-lye peeling process, cutting down considerably pollution of the environment.

The flash steam peeling method is used widely because of its important advantages over the lye methods. Less waste is produced, no chemicals are needed, the peels may be used as animal feed, and the pollution is minimal. The steam peeler consists basically of a pressure vessel, which is loaded with the food material and rotated slowly (5–6 rpm). Before processing products such as potatoes in retorting steam peelers, the products must be sorted out, so that they have almost similar shape and size. Figure 5.27 shows schematically a pressure (flash) steam peeler. It is important to flash the product quickly and cool it down immediately after steaming, so that the product is not overheated. Therefore, steam accumulators, which can supply quickly the required steam and large vapor condensing units, for assisting the quick vapor removal, are necessary. The capacity of such peeling units may be 16–30 tons /h. The volume of the pressure vessels can be 400–900 L. The overall dimensions of a large flash peeling unit may be $3 \times 7 \times 5$ m. The volume of large steam accumulators can be about 20 m^3. After steaming, the separation of the peels is done in rotating drum washers in which water is sprayed. For potato, rotating brush cylinders (6–12 pieces) may be also used. Steam peeling can also be accomplished in vacuum operation, in which the product is heated at atmospheric pressure and then flashed into a vacuum chamber (Hoch 1999). This is especially important in tomato peeling, since it occurs at reduced temperature that does not affect significantly the color and consistency of the product. In vacuum peeling, instead of heating the product up to 120–130 °C, temperatures of only 50–60 °C are applied. A double vacuum tomato peeling unit with 25 tons/h of processing capacity (2 pressure vessels of 350 kg/charge each) requires about 13 kW and 15 L of air/min (pressure 6 bar) and consumes about 8 tons of water/h. It also requires 900 kg of steam/h at maximum pressure of 15 bar. The unit (including conveyors, condenser, double pressure vessels, and washing equipment) requires a floor space of about 54 m^2.

High-pressure steam (15 bar) heats instantly the surface of the food material in a pressure vessel; the moisture of the product under the skin is vaporized and, when the vessel pressure is released, the skin is loosened so that it can be removed easily with water sprays afterward. Pressure vessel capacities of 100–1250 L, product capacity per charge of 34–666 kg, total product capacity of 1–20 tons/h, and power requirement of 6–10 kW are required (Greensmith 1998). Relative losses of product flesh in peeling operations are abrasion, up to 40 %; lye peeling, 18 %; and flash steam peeling, 10 %. Steam peeling is used normally in potato peeling. However, lye peeling is preferred for peaches, since a smoother surface is obtained in the peeled fruit.

Both lye and steam peelers are used in tomato peeling at capacities of about 30 tons/h. Lye peeling results in better quality and less product losses, but the peel waste must be either recovered (as tomato concentrate) or treated before disposal (Hoch 1999).

5.6.3 Removal of Desired Parts

The goal of separation is often the recovery of certain food parts. These parts can be external or internal food parts (Table 5.6). External parts that can be further utilized in food technology are, e.g., the solid matter of soya, the rice bran, and the peels of oranges. Internal product parts that are the main goal or that can be further utilized after separation are juices (fruit and vegetable), oil (seeds, olives), fat (animal, milk), starch (cereals), and nuts. Several animal by-products, such as collagen (jellies), bones (feedstuffs), and intestines (sausages), can be also utilized. However, the equipment used in the utilization of these products will not be discussed here, since most of it has been already described in connection with other processes (e.g., juice or oil extraction, solid/liquid separation, and production of starch or nuts, in the grinding, milling, and breaking processes).

5.6.4 Food Cleaning Operations

5.6.4.1 General Aspects

The cleaning processes refer to the separation and removal of external undesired material that either adheres on food or on food equipment. In cleaning of equipment, lye and acid solutions and several sophisticated chemicals are used. The trend is to automate cleaning as far as possible by installing a computerized CIP system (see Sect. 2.5). Furthermore, it is aimed to manufacture equipment that incorporates, in their construction materials, substances that make them resistant to microorganisms. In cleaning of equipment, rinsing, which follows washing with detergents, is also important. Details about washing and rinsing of food equipment and installations are discussed by Schornick and Thor (1976), Kopp and Gerhold (1977), Schluessel (1976), Loncin and Merson (1979), and Seiberling (1997).

For raw food, cleaning is an important preprocessing operation, which removes foreign materials and contaminants. Cleaning of raw food materials must remove completely the foreign materials and contaminants, resulting in an acceptable sound and nutritious product. The cleaning operation should not waste a large proportion of the product nor affect adversely the physical environment (pollution from the wastewater effluent). Cleaning from heavy foreign materials, such as stones and metal pieces, is necessary for protecting size reduction and milling equipment used downstream.

5.6.4.2 Wet Cleaning

Most of the cleaning methods use water as a cleaning medium, and a limited number of dry cleaning processes are applied in food processing.

Wet cleaning is effective in removing firmly adherent soils from raw fruits and vegetables, allowing the use of detergents and sanitizers (Brennan et al. 1990). Capacity of wet cleaners for vegetables is 8–15 tons/h. Water conservation methods should be used (e.g., recirculation) to reduce the large amounts of water needed in some processing operations, e.g., in the canning of fruits and vegetables, up to 15 m^3/ton of product may be used.

Besides soaking, in all wet cleaning equipment, a relative motion between the cleaning fluid and the product is applied. This can be achieved by the movement of the cleaning fluid, by the movement of the product, or by the movement of both. In soaking, the cleaning medium diffuses and separates the undesired dirt. The main categories of wet cleaning units are the soaking equipment, the spraying equipment, and the mixed systems in which two or more cleaning systems are involved.

Soaking of the raw materials in long tanks removes heavy contaminants, like stones and adhering soil. The efficiency of soaking is improved by relative movement of water against the product, e.g., using mechanical paddles or air currents at the bottom of the tank (Fig. 5.28b, c), or by moving the product by means of a rotating drum (Fig. 5.28a). Detergents may be used to remove the spray residues of agrochemicals from the surfaces of the fruits and vegetables, and chlorination of water may be required to prevent the growth of spoilage microorganisms.

Spray washers use less water and they are more efficient, due to mechanical action, than water soakers. It is important to use well-designed spraying nozzles and to maintain or replace them in time, since their efficiency falls as they are worn out by the fluid. Furthermore, the pressure exercised by water on the food must be also controlled, especially when delicate products are washed. In belt-type spray washers, the raw material is transported slowly on roller or vibratory conveyors under water sprays. Brushes and special rubber disks can remove the adhering dirt

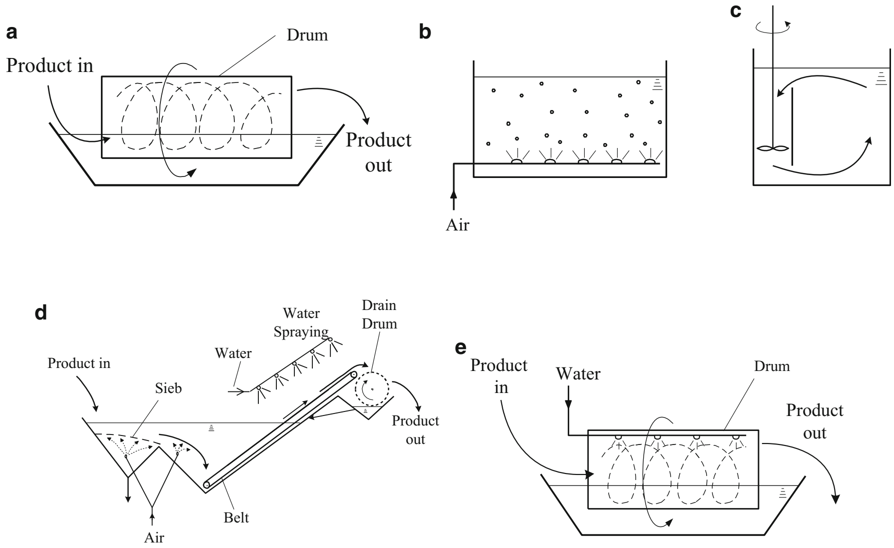


Fig. 5.28 Soak and spray washing equipment for fruits and vegetables: (**a**) soaking; (**b**, **c**) water circulation; (**d**, **e**) mixed washing systems

and contaminants from the sound product. The combination of soaking and spraying is sometimes used for more effective cleaning (Fig. 5.28c, d). The washer of Fig. 5.28c is quite common in washing of fruits and vegetables, due to its effective and gentle washing action. The equipment consists of two vessels and a conveying belt. In the first vessel, prewashing takes place, as the product is soaked. Air blown in the vessel improves the cleaning action. Stones or other heavy matter is collected on the bottom of the vessel. In the second vessel, soaking with the air-assisted water agitation is repeated. Subsequently, the product is sprayed with water as it is conveyed out of the second vessel. Finally, a perforated drum separates any remaining water from the washed product. Spray drum washers (Fig. 5.28d) consist of a rotating cylinder (reel), usually inclined slightly, made of longitudinal rods or wire mesh, which retain the fruit/vegetable product, while the debris is washed through. The rotating cylinder is partially immersed in water. A perforated long tube, installed in the center of the cylinder, supplies the water sprays. The washing capacity depends on the treated product. The capacity of a washing equipment as that of Fig. 5.28d, when used to wash spinach or other leafy vegetables, is only 25 % of what the same equipment that wash potatoes or other tubers has. An equipment that has dimensions of 6.5 × 1.8 × 1.8 m and weighs about 1 ton can wash 6 tons of potatoes/h and requires 6–7 kW power. A drum washer, like that of Fig. 5.28e, of the same capacity as the above washer, requires also 6–7 kW of power, but it has dimensions of 4.0 × 1.2 × 1.8 m, since due to the drum rotation, washing is more intensive.

The rotary brush washer consists of a trough-shaped frame with 6 or more brushes, rotating longitudinally, with economical use of water and capacities of 4–8 tons/h (Greensmith 1998).

Simple flotation in water may be used to separate bruised or rotten fruits or vegetables from sound products. Froth flotation can be used to separate foreign materials of the same size and density with the main product. The raw material is immersed in an emulsion of mineral oil/detergent, through which air is blown. The contaminants float at the surface and the product is separated from the bottom, e.g., clean peas.

5.6.4.3 Dry Cleaning

Dry cleaning by an air stream is based on the same aerodynamic principles discussed in Air Classifiers (Sect. 5.3). The most common operation of aspiration (winnowing) removes light materials (skins, leaves, etc.) from heavier food pieces, e.g., onions, peas, and beans (Fig. 5.6).

Screening, discussed under solid/solid separations, is used widely in dry cleaning of various food pieces and particles, like grains and seeds. In a 3-screen setup, the top screen (scalper) removes the largest pieces/particles, and the second screen collects the main product, while the bottom pan collects the undesirable product, the soil, and the debris. Depending on the shape of the grains, round, triangular, or slotted holes can be used (Henderson and Perry 1955).

Pneumatic separators or fanning mills consist of a set of screens and a fan for moving air though the grain, which removes chaff, dirt, and lightweight weed. A blowing or suction fan, i.e., an aspiration system, is used.

Combined cleaning methods are used for thorough separation of some raw materials, e.g., wheat, before milling: the wheat goes through a series of separations to remove various contaminants and separate the oversize and undersize fractions, like magnetic separation, screening, disk separation, washing, centrifugation, and drying (Brennan et al. 1990).

Brushing is applied in the dry cleaning of some fruits and vegetables. Electrostatic separation is discussed as a solid/solid separation method in Sect. 5.3.

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