4

Size reduction

Size reduction or ‘comminution’ is the unit operation in which the average size of solid pieces of food is reduced by the application of grinding, compression or impact forces. When applied to the reduction in size of globules of immiscible liquids (for example oil globules in water) size reduction is more frequently referred to as homogenisation or emulsification. The size reduction of liquids to droplets (by atomisation) is described in Chapter 15. Size enlargement is achieved by extrusion (Chapter 14), agglomeration (Chapter 15) or forming (Chapter 5).

Size reduction has the following benefits in food processing:

- There is an increase in the surface-area-to-volume ratio of the food which increases the rate of drying, heating or cooling and improves the efficiency and rate of extraction of liquid components (for example fruit juice or cooking oil extraction (Chapter 6)).
- When combined with screening (Chapter 3), a predetermined range of particle sizes is produced which is important for the correct functional or processing properties of some products (for example icing sugar, spices and cornstarch).
- A similar range of particle sizes allows more complete mixing of ingredients (Chapter 5) (for example dried soup and cake mixes).

Size reduction and emulsification have little or no preservative effect. They are used to improve the eating quality or suitability of foods for further processing and to increase the range of products available. In some foods they may promote degradation by the release of naturally occurring enzymes from damaged tissues, or by microbial activity and oxidation at the increased area of exposed surfaces, unless other preservative treatments are employed.

Different methods of size reduction are classified according to the size range of particles produced:

1. *Chopping, cutting, slicing and dicing*:
   (a) large to medium (stewing steak, cheese and sliced fruit for canning)
   (b) medium to small (bacon, sliced green beans and diced carrot)

(c) small to granular (minced or shredded meat, flaked fish or nuts and shredded vegetables).
2. *Milling* to powders or pastes of increasing fineness (grated products > spices > flours > fruit nectars > powdered sugar > starches > smooth pastes)
3. *Emulsification* and *homogenisation* (mayonnaise, milk, essential oils, butter, ice cream and margarine).

4.1 Size reduction of solid foods

4.1.1 Theory

In all types of size reduction there are three types of force used to reduce the size of foods:

1. compression forces
2. impact forces
3. shearing (or attrition) forces.

In most size reduction equipment, all three forces are present, but often one is more important than the others. When stress (force) is applied to a food the resulting internal strains are first absorbed, to cause deformation of the tissues. If the strain does not exceed a certain critical level named the *elastic stress limit* (*E*), the tissues return to their original shape when the stress is removed, and the stored energy is released as heat (elastic region (O–E) in Fig. 4.1).

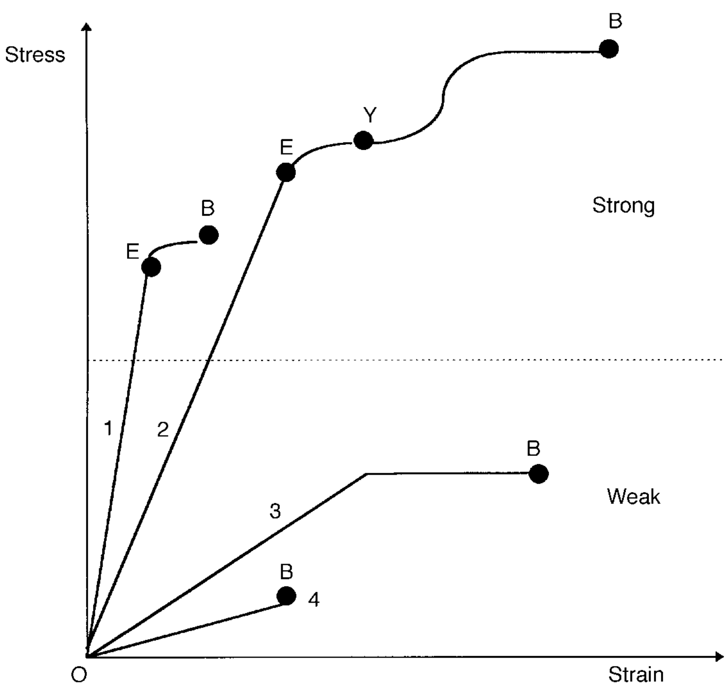

Fig. 4.1 Stress-strain diagram for various foods.
(E = elastic limit; Y = yield point; B = breaking point; O–E = elastic region; E–Y = inelastic deformation; Y–B = region of ductility; (1) = hard, strong, brittle material; (2) = hard, strong, ductile material; (3) = soft, weak, ductile material and (4) = soft, weak brittle material.) (After Loncin and Merson (1979).)

However, when the strain within a localised area exceeds the elastic stress limit, the food is permanently deformed. If the stress is continued, the strain reaches a *yield point* (*Y*). Above the yield point the food begins to flow (known as the 'region of ductility' (Y–B) in Fig. 4.1). Finally, the *breaking stress* is exceeded at the breaking point (B) and the food fractures along a line of weakness. Part of the stored energy is then released as sound and heat. As little as 1% of applied energy may actually be used for size reduction. As the size of the piece is reduced, there are fewer lines of weakness available, and the breaking stress that must be exceeded increases. When no lines of weakness remain, new fissures must be created to reduce the particle size further, and this requires an additional input of energy. There is therefore a substantial increase in energy requirement as the size of the particles is reduced (see Sample problem 4.1). It is important to specify the required size distribution in the product to avoid unnecessary expenditure of time and energy in creating smaller particles than are required for a particular application.

The amount of energy that is needed to fracture a food is determined by its hardness and tendency to crack (its *friability*) which in turn depends on the structure of the food. The fewer the lines of weakness in a food, the higher is the energy input needed to cause fracturing. Harder foods absorb more energy and consequently require a greater energy input to create fractures.

Compression forces are used to fracture friable or crystalline foods; combined impact and shearing forces are necessary for fibrous foods, and shearing forces are used for fine grinding of softer foods. It is thought that foods fracture at lower stress levels if force is applied for longer times. The extent of size reduction, the energy expended and the amount of heat generated in the food therefore depend on both the size of the forces that are applied and the time that food is subjected to the forces.

Other factors which influence the energy input are the moisture content and heat sensitivity of the food. The moisture content significantly affects both the degree of size reduction and the mechanism of breakdown in some foods. For example, before milling wheat is 'conditioned' to optimum moisture content and maize is thoroughly soaked and wet milled in order to obtain complete disintegration of the starchy material. Further details are given by Kent (1983). However, excessive moisture in a 'dry' food can lead to agglomeration of particles which then block the mill and very dry foods create excessive dust which causes a health hazard, and is extremely inflammable and potentially explosive.

Substantial amounts of heat are generated in high-speed mills. The heat sensitivity of the food determines the permissible temperature rise and the necessity to cool the mill. In *cryogenic grinding*, liquid nitrogen or solid carbon dioxide are mixed with foods (for example spices) before milling, to cool the product and to retain volatiles or other heat sensitive components. Solid carbon dioxide is also used to cool meat during size reduction in the manufacture of sausagemeat.

The energy required to reduce the size of solid foods is calculated using one of three equations, as follows:

1. Kick's law states that the energy required to reduce the size of particles is proportional to the ratio of the initial size of a typical dimension (for example the diameter of the pieces) to the final size of that dimension:

$$E = K_K \ln\left(\frac{d_1}{d_2}\right) \qquad \boxed{4.1}$$

where E (J) = the energy required per mass of feed, K_K = Kick's constant, d_1 (m) = the average initial size of pieces, and d_2 (m) = the average size of ground particles.

d_1/d_2 is known as the *size reduction ratio* (*RR*) and is used to evaluate the relative performance of different types of equipment. Coarse grinding has *RR*s below 8:1, whereas in fine grinding, ratios can exceed 100:1 (Brennan *et al.*, 1990).

2. Rittinger's law states that the energy required for size reduction is proportional to the change in surface area of the pieces of food (instead of a change in dimension described in Kick's law):

$$E = K_R \left(\frac{1}{d_2} - \frac{1}{d_1} \right) \tag{4.2}$$

where K_R = Rittinger's constant.

3. Bond's law is used to calculate the energy required for size reduction from:

$$\frac{E}{W} = \sqrt{\left(\frac{100}{d_2}\right)} - \sqrt{\left(\frac{100}{d_1}\right)} \tag{4.3}$$

where W (J kg^{-1}) = the Bond Work Index (40 000–80 000 J kg^{-1} for hard foods such as sugar or grain (Loncin and Merson, 1979)), d_1 (m) = diameter of sieve aperture that allows 80% of the mass of the feed to pass and d_2 (m) = diameter of sieve aperture that allows 80% of the mass of the ground material to pass.

In practice it has been found that Kick's law gives reasonably good results for coarse grinding in which there is a relatively small increase in surface area per unit mass. Rittinger's law gives better results with fine grinding where there is a much larger increase in surface area and Bond's law is intermediate between these two. However, equations (4.2) and (4.3) were developed from studies of hard materials (coal and limestone) and deviation from predicted results is likely with many foods.

Sample problem 4.1

Food is milled from 6 mm to 0.0012 mm using a 10 hp motor. Would this motor be adequate to reduce the size of the particles to 0.0008 mm? Assume Rittinger's equation and that 1 hp = 745.7 W.

Solution to Sample problem 4.1

From Equation (4.2),

$$7457 = K_R \left(\frac{1}{0.0012 \times 10^{-3}} \right) - \left(\frac{1}{6 \times 10^{-3}} \right)$$

Therefore,

$$K_R = \frac{7457}{1/1.2 \times 10^{-6} - 1/6 \times 10^{-3}} = 0.0089$$

To produce particles of 0.0008 mm

$$E = 0.0089 \frac{1}{0.0008 \times 10^{-3}} - \frac{1}{6 \times 10^{-3}} = 11123 \text{ W}$$
$$= 15 \text{ hp}$$

Therefore the motor is unsuitable and an increase in power of 50% is required.

4.1.2 Equipment

This section describes selected equipment used to reduce the size of both fibrous foods to smaller pieces or pulps, and dry particulate foods to powders. Summaries of the main applications are shown in Tables 4.1 and 4.2. Further details of the properties of powders are given by Lewis (1996) and in Chapter 15.

Most meats, fruits and vegetables fall into the general category of 'fibrous' foods. Meats are frozen or 'tempered' to just below their freezing point (Chapters 19 and 21) to improve the efficiency of cutting. Fruits and vegetables have an inherently firmer texture and are cut at ambient or chill temperatures. All types of cutters require the blade to be forced through the food with as little resistance as possible. Knife blades must be kept sharp, to both minimise the force needed to cut the food and to reduce cell rupture and consequent product damage and reduced yield. In moist foods, water acts as a lubricant, but in some sticky products, such as dates or candied fruits, food grade lubricants may be needed to cut them successfully. In general blades are not coated with non-slip materials, such as 'Teflon' or poly-tetra-fluoro-ethylene (PTFE) as these may wear off and contaminate the product, and are instead mirror-polished during manufacture.

During the 1990s improved cutting has been achieved with the introduction of *ultrasonic cutters*. These use knife blades or 'horns' (probes) which vibrate longitudinally (as a piston) at 20 kHz, with a cutting stroke of 50–100 μm. Details of the component parts and method of cutting are described by Rawson (1998). They are readily automated and have the following benefits:

- quality of the cut face is visually excellent
- the product is virtually undisturbed
- the required cutting force is significantly reduced
- multi-layered products or hard particles contained in a soft matrix can be cut
- the blade is self-cleaning
- crumbs and debris are significantly reduced
- it is cost effective, having low running costs
- less sharp blades are needed and longer intervals between sharpening, compared to conventional blades (Rawson, 1998).

Table 4.1 Applications of size reduction equipment

Equipment	Type of product[a]					Fineness[b]			
	1	2	3	4	5	a	b	c	d
Slicers			*	*	*	*			
Dicers			*	*	*	*			
Shredders				*	*	*	*		
Bowl choppers			*	*	*		*	*	
Pre-crushers	*			*	*		*		
Hammer mills	*	*		*	*		*	*	
Fine impact mills	*			*	*		*	*	*
Classifier mills	*				*				*
Air jets mills	*	*			*				*
Ball mills		*							*
Disc mills	*							*	*
Roller mills	*			*	*			*	*
Pulpers				*				*	*

[a] 1 = soft brittle crystalline; 2 = hard abrasive; 3 = elastic tough cuttable; 4 = fibrous; 5 = heat sensitive greasy.
[b] a = coarse lumps; b = coarse grits; c = medium to fine; d = fine to ultra-fine.
Adapted from Anon. (1986)

Table 4.2 Properties and applications of selected size reduction equipment

Type of equipment	Type(s) of force	Peripheral velocity ($m\,s^{-1}$)	Typical products
Pin-and-disc mill	Impact	80–160	Sugar, starch, cocoa powder, nutmeg, pepper, roasted nuts, cloves
Wing-beater mill	Impact and shear	50–70	Alginates, pepper, pectin, paprika, dried vegetables
Disc-beater mill	Impact and shear	70–90	Milk powder, lactose, cereals, dried whey
Vertical toothed disc mill	Shear	4–8 17	Frozen coffee extract, plastic materials Coarse grinding of rye, maize, wheat, fennel, pepper, juniper berry
Cutting granulator	Impact (and shear)	5–18	Fish meal, pectin, dry fruit and vegetables
Hammer mill	Impact	40–50	Sugar, tapioca, dry vegetables, extracted bones, dried milk, spices, pepper
Ball mill	Impact and shear	–	Food colours
Roller mills	Compression and shear	–	Sugar cane, wheat (fluted rollers) Chocolate refining (smooth rollers)

After Loncin and Merson (1979).

The technique is particularly suitable for products that are difficult to cut using other methods (for example, sticky confectionery, hot bread and soft cake) and is increasingly used for bakery products of all types, frozen pies, ice cream, and fresh meats, fish and vegetables.

Size reduction of fibrous foods

There are four main types of size reduction equipment, classified in order of decreasing particle size as follows:

1. slicing and flaking equipment
2. dicing equipment
3. shredding equipment
4. pulping equipment.

Slicing and flaking equipment

The growth of the chilled sandwich market (also Chapter 19) has stimulated development of high speed slicers for both cutting bread precisely from corner to corner and for slicing fillings. In some designs (Fig. 4.2(a)) food is held against the slicer blades by centrifugal force and each slice falls away freely. This eliminates the problems found in earlier cutters, where multiple knife blades caused compression of the food and damage as it passed between the blades. High speed cutters are used to slice bacon and 'wafer thin' cooked meats at up to 2000 slices per minute and vegetables at up to 6 tonnes per hour. Newer designs are computer controlled and can be programmed easily by operators to bulk slice and stack a range of products including cheeses, pizza toppings, cooked meats, cucumber and tomato, and then apply them onto sandwich bread. Meats are also cut using circular rotary knives with a blade at right angles to the path of the meat. An 'intelligent' cheese cutter weighs and measures each block to determine the maximum number of portions that can be cut to the required weight with the minimum amount of waste (Sharp, 1998).

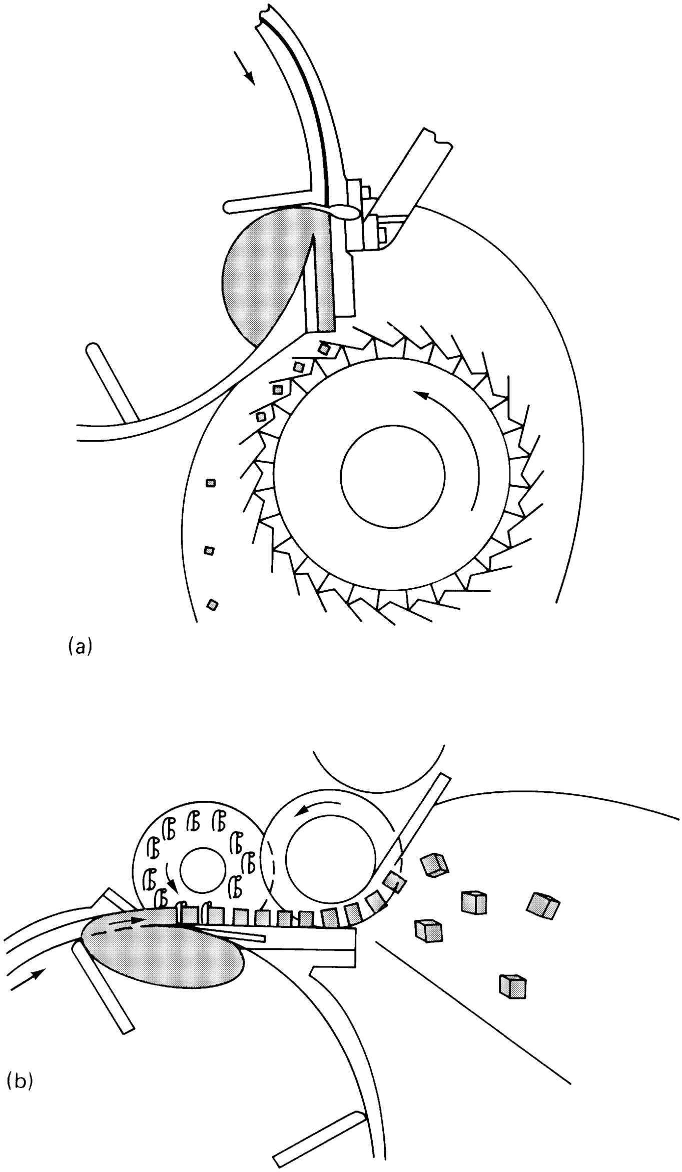

Fig. 4.2 (a) Slicing equipment; (b) dicing equipment.
(Courtesy of Urschel Ltd.)

Harder fruits such as apples are simultaneously sliced and de-cored as they are forced over stationary knives fitted inside a tube. In a similar design (the *hydrocutter*) foods are conveyed by water at high speed over fixed blades. More sophisticated slicers are able to cut vegetables into tagliatelle or garland shapes. Intermittent guillotine cutters are used to cut confectionery products, such as liquorice. The blade advances with the product on the conveyor to ensure a square cut edge regardless of the conveyor speed or cut length. The size of the cut can be adjusted from the control panel, without mechanical adjustment or downtime (Sharp, 1998). Flaking equipment for flaked fish, nuts or meat is similar to slicing equipment. Adjustment of the blade type and spacing is used to produce the flakes.

Dicing equipment
For dicing, vegetables, fruits and meats are first sliced and then cut into strips by rotating blades. The strips are fed to a second set of rotating knives which operate at right angles to the first set and cut the strips into cubes (Fig. 4.2(b)).

Shredding equipment
Typical equipment is a modified hammer mill (see Fig. 4.4(b)) in which knives are used instead of hammers to produce a cutting action. A second type of shredder, known as the *squirrel cage disintegrator*, has two concentric cylindrical cages inside a casing. They are fitted with knife blades along their length and the two cages rotate in opposite directions. Food is subjected to powerful shearing and cutting forces as it passes between them.

Pulping equipment
This uses a combination of compression and shearing forces for juice extraction from fruits or vegetables, for cooking oil production and for producing puréed and pulped meats. For example a rotary fruit crusher consists of a cylindrical metal screen fitted internally with high-speed rotating brushes or paddles (Nelson and Tressler, 1980). Grapes, tomatoes or other soft fruits are heated if necessary to soften the tissues, and pulp is forced through the perforations of the screen by the brushes. The size of the perforations determines the fineness of the pulp. Skins, stalks and seeds are discarded from the end of the screen. Other types of pulper, including roller presses and screw presses, are used for juice expression or cold extraction of cooking oils (Chapter 6). A *bowl chopper* (Fig. 4.3) is used to chop meat and harder fruits and vegetables into a pulp (for example for sausagemeat or mincemeat preserve). A horizontal, slowly rotating bowl moves the ingredients beneath a set of high-speed rotating blades. Food may be passed several times beneath the knives until the required degree of size reduction and mixing has been achieved.

Size reduction of dry foods
There are a large number of mills available for specific types of food. In this section a selection of common types is described and a summary of their properties and applications is shown in Table 4.2. Other types of equipment are described by Loncin and Merson (1979) and Leniger and Beverloo (1975). More recently, nibblers which use a grating rather than grinding action, have been used to replace mills, and are claimed to reduce problems of noise, increased temperatures and dust (Sharp, 1998). In an alternative design, sharp knives are arranged in a 152 mm diameter cylinder and an impeller operating at 2000–12 000 rpm pushes the product over the knives to give a controlled comminution to micro-fine powder. At this speed, products such as rice pass the blades at speeds in excess of 90 m s^{-1} (320 kph or 200 mph) and are rapidly reduced to a flour (Urschel, 1988).

Ball mills
These have a slowly rotating, horizontal steel cylinder which is half filled with steel balls 2.5–15 cm in diameter. At low speeds or when small balls are used, shearing forces predominate. With larger balls or at higher speeds, impact forces become more important. They are used to produce fine powders, such as food colourants. A modification of the ball mill named a *rod mill* has rods instead of balls to overcome problems associated with the balls sticking in adhesive foods.

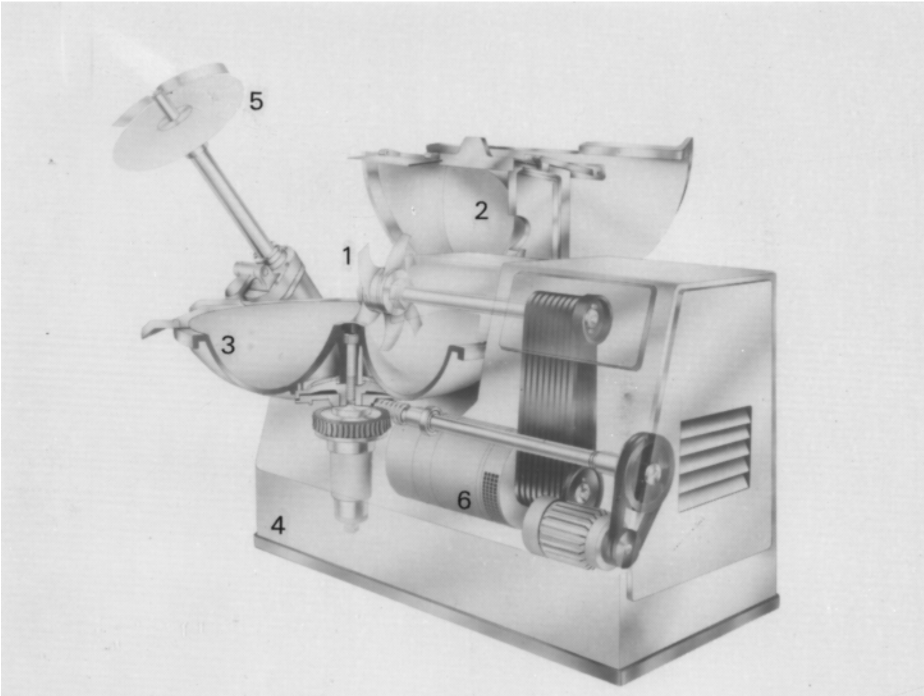

Fig. 4.3 Bowl chopper: 1, cutting blades; 2, cover; 3, rotating cutter bowl; 4, casing; 5, rotating unloader disc; 6, main motor.
(Courtesy of Hoegger Alpina Ltd.)

Disc mills

There are a large number of designs of *disc mill*, each employing shearing forces for fine grinding or shearing and impact forces for coarser grinding. For example:

- single-disc mills in which food passes through an adjustable gap between a stationary casing and a grooved disc, which rotates at high speed
- double-disc mills which have two discs that rotate in opposite directions to produce greater shearing forces
- pin-and-disc mills which have intermeshing pins fixed either to the single disc and casing or to double discs (Fig. 4.4(a)). These improve the effectiveness of milling by creating additional impact and shearing forces (see also Section 4.2.2, colloid mills).

Hammer mills

These have a horizontal cylindrical chamber, lined with a toughened steel breaker plate. A high-speed rotor inside the chamber is fitted with swinging hammers along its length (Fig. 4.4(b)). Food is disintegrated mainly by impact forces as the hammers drive it against the breaker plate. Hammer mills are widely used for crystalline and fibrous materials including spices and sugar.

The above mills can be operated in three modes:

1. free flow of materials through the mill in a single pass
2. the exit from the mill is restricted by a screen and food remains in the mill until the particles are sufficiently small to pass through the screen apertures (under these 'choke' conditions, shearing forces play a larger part in the size reduction)

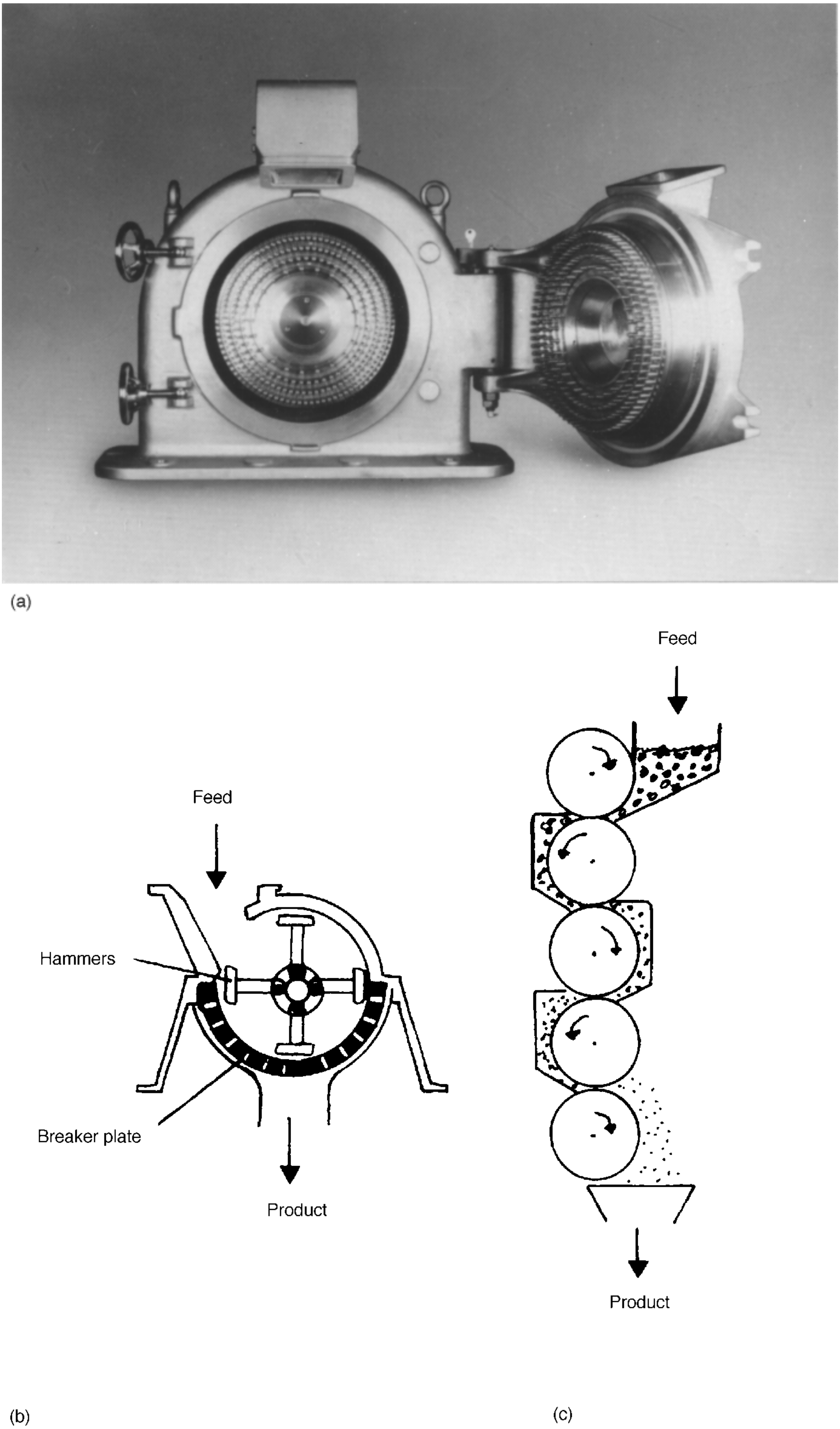

Fig. 4.4 Mills: (a) pin and disc mill (Courtesy of Alpine Process Technology); (b) hammer mill; (c) roller mill. (After Leniger and Beverloo (1975).)

3. recirculation through the mill of all material or larger pieces until sufficient size reduction has been achieved.

Roller mills

Roller mills are widely used to mill wheat. Two or more steel rollers revolve towards each other and pull particles of food through the 'nip' (the space between the rollers) (Fig. 4.4(c)). The main force is compression but, if the rollers are rotated at different speeds, or if the rollers are fluted,[1] additional shearing forces are exerted on the food. The size of the nip is adjustable for different foods and overload springs protect against accidental damage from metal or stones.

4.1.3 Effect on foods

Size reduction is used in processing to control the textural or rheological properties of foods and to improve the efficiency of mixing and heat transfer. The texture of many foods (for example bread, hamburgers and juices) is controlled by the conditions used during size reduction of the ingredients. There is also an indirect effect on the aroma and flavour of some foods. The disruption of cells and resulting increase in surface area promotes oxidative deterioration and higher rates of microbiological and enzymic activity. Size reduction therefore has little or no preservative effect. Dry foods (for example grains or nuts) have a sufficiently low a_w (Chapter 1) to permit storage for several months after milling without substantial changes in nutritional value or eating quality. However, moist foods deteriorate rapidly if other preservative measures (for example chilling, freezing and heat processing) are not taken.

Sensory characteristics

There are small but largely unreported changes in the colour, flavour and aroma of dry foods during size reduction. Oxidation of carotenes bleaches flour and reduces the nutritional value. There is a loss of volatile constituents from spices and some nuts, which is accelerated if the temperature is allowed to rise during milling. In moist foods the disruption of cells allows enzymes and substrates to become more intimately mixed, which causes accelerated deterioration of flavour, aroma and colour. Additionally the release of cellular materials provides a suitable substrate for microbiological growth and this can also result in the development of off-flavours and aromas.

The texture of foods is substantially altered by size reduction, both by the physical reduction in the size of tissues and also by the release of hydrolytic enzymes. The type and duration of size reduction and the delay before subsequent preservation operations are closely controlled to achieve the desired texture. The relationship between the size of food particles and perceived texture is discussed by Stanley and Tung (1976) and Sherman (1976).

Nutritional value

The increase in surface area of foods during size reduction causes loss of nutritional value due to oxidation of fatty acids and carotenes. Losses of vitamin C and thiamin in chopped or sliced fruits and vegetables are substantial (for example 78% reduction in vitamin C during slicing of cucumber) (Erdman and Erdman, 1982). Losses during storage depend on the temperature and moisture content of the food and on the concentration of oxygen

1. Shallow ridges along the length of the roller.

Table 4.3 Effect of milling on vitamin content of selected grains

Product	Content per 100 g									
	Viatamin A (IU)	a-Tocopherol (mg)	Thiamin (mg)	Riboflavin (mg)	Niacin (mg)	Vitamin C (mg)	Pantothenic acid (mg)	Vitamin B_6 (mg)	Folic acid (μg)	Biotin (μg)
Maize										
Kernel	400	1.43	0.15	0.12	1.7	12	0.54	0.16	26.8	11.0
Flour	340	–	0.20	0.06	1.4	0	–	–	–	–
Rice										
Grain	0	0.68	0.34	0.05	4.7	0	1.10	0.55	20.2	12.0
White grain	0	0.10	0.07	0.03	1.6	0	0.55	0.17	14.1	5.0
Bran	0	–	2.26	0.25	29.8	0	2.8	2.5	150	60
Wheat										
Grain (hard)	0	1.35	0.57	0.12	4.3	0	1.5	0.4	14.4	12
80% extraction[a]	–	–	0.25	0.08	1.6	–	0.9	0.11	13	1.4
70% extraction[a]	–	–	0.08	0.05	1.1	–	0.7	0.06	10	1.1
Bran	0	1.71	0.72	0.35	21.0	0	2.9	0.82	155	49

[a] Percentage extraction = weight of flour per 100 parts of flour milled.

Adapted from Houston and Kohler (1970), Bauernfeind (1977), Toepfer *et al*. (1951) and Frigg (1976).

in the storage atmosphere. In dry foods the main loss in nutritional value results from separation of the product components after size reduction (for example the separation of bran from rice, wheat or maize in Table 4.3).

4.2 Size reduction in liquid foods (emulsification and homogenisation)

The terms *emulsifiers* and *homogenisers* are often used interchangeably for equipment used to produce emulsions: emulsification is the formation of a stable emulsion by the intimate mixing of two or more immiscible liquids, so that one (the dispersed phase) is formed into very small droplets within the second (the continuous phase). Homogenisation is the reduction in size (to 0.5–30 μm), and hence the increase in number, of solid or liquid particles in the dispersed phase by the application of intense shearing forces. Homogenisation is therefore a more severe operation than emulsification. Both operations are used to change the functional properties or eating quality of foods and have little or no effect on nutritional value or shelf life. Examples of emulsified products include margarine and low-fat spreads, salad cream and mayonnaise, sausagemeat, ice cream and cakes.

4.2.1 Theory

The two types of liquid–liquid emulsion are:

1. oil in water (o/w) (for example milk)
2. water in oil (w/o) (for example margarine).

These are relatively simple systems and more complex emulsions are found in such products as ice cream, sausagemeat and cakes (Section 4.2.3).

The stability of emulsions is determined by:

- the type and quantity of emulsifying agent (Appendix C)
- the size of the globules in the dispersed phase
- the interfacial forces acting at the surfaces of the globules
- the viscosity of the continuous phase
- the difference between the densities of the dispersed and continuous phases (see Chapter 1, Section 1.1.3).

The action of homogenisers reduces the size of droplets in the dispersed phase and emulsifying agents that are present in, or added to, a food form micelles around each droplet. This reduces the interfacial tension between the phases and prevents the droplets from coalescing (the higher the interfacial tension between the continuous and dispersed phases, the more difficult it is to form and maintain a stable emulsion). Emulsifying agents therefore lower the energy input needed to form an emulsion.

Naturally occurring proteins and phospholipids act as emulsifying agents, but in food processing synthetic agents (including esters of glycerol or sorbitan esters of fatty acids) are more effective and these are normally used. Synthetic emulsifying agents are classified into polar and non-polar types. Those that contain mostly polar groups bind to water and therefore produce o/w emulsions. Non-polar agents are adsorbed to oils to produce w/o emulsions. They are characterised by their hydrophile–lipophile balance (HLB) value (Table 4.4). Agents with low HLB values (below 9) are lipophilic and used for w/o emulsions; those with HLB values between 8 and 11 are intermediate and used as

Table 4.4 Selected emulsifying agents used in food processing

Emulsifier	HLB value	Function and typical application
Ionic		
Phospholipids (e.g. lecithin)	18–20	Crumb softening (baked goods)
Potassium or sodium salts of oleic acid		Aid to extrusion and reduction in stickiness (pasta, snackfoods, chewing gum)
Protein (e.g. gelatin, egg albumin)		Improved whipping and aeration (instant potato, frozen cream and toppings)
Sodium stearyl-2-lactylates		Dispersion (coffee whiteners)
Non-ionic		
Glycerol monostearate	2.8	Anti-staling, crumb softening (most baked
Polyglycerol esters		products)
Polyoxyethylene sorbitol fatty acids	14.9	Fat crystal modification (peanut butter,
Propylene glycol fatty acid esters	3.4	coatings – see Chapter 23)
Sorbitol esters of fatty acids	4.7	Bloom retardation (chocolate, coatings)
		Overrun control (ice cream)
Hydrocolloids		
Alginates		
Carboxymethyl cellulose		
Carrageenan		
Guar		
Gum arabic		
Locust bean		
Methyl cellulose	10.5	
Pectin		
Tragacanth	11.9	
Xanthan		

Adapted from Lewis (1990) and Lissant (1974).

wetting agents; and those with high values (11 to 20) are hydrophilic and are used for o/w emulsions, detergents and solubilisers (Lewis, 1990). Polar emulsifying agents are also classified into ionic and non-ionic types. Ionic types have different surface activities over the pH range, owing to differences in their dissociation behaviour. The activity of non-ionic emulsifiers is independent of pH. Careful selection of the type of emulsifying agent is therefore needed to create the required emulsion in a given food system. Details are given in Lissant (1984).

Stabilisers (Appendix C) are polysaccharide hydrocolloids which dissolve in water to form viscous solutions or gels. In o/w emulsions, they increase the viscosity and form a three-dimensional network that stabilises the emulsion and prevents coalescence. Microcrystalline cellulose and related cellulose powders are able to stabilise w/o emulsions.

The factors that influence the stability of an emulsion are related by *Stoke's Law*:

$$v = \frac{d^2 g(\rho_p - \rho_s)}{18\mu} \tag{4.4}$$

where v (m s^{-1}) = terminal velocity (i.e. velocity of separation of the phases), d (m) = diameter of droplets in the dispersed phase, g = acceleration due to gravity = 9.81 m s^{-2}, ρ_p (kg m^{-3}) = density of dispersed phase, ρ_s (kg m^{-3}) = density of continuous phase, and μ (N s m^{-2}) = viscosity of continuous phase.

The equation indicates that stable emulsions are formed when droplet sizes are small (in practice between 1 μm and 10 μm), the densities of the two phases are reasonably close and the viscosity of the continuous phase is high. Physical changes to droplets, and equations which relate droplet distortion to shear rate, are described by Loncin and Merson (1979).

4.2.2 Equipment

The five main types of homogeniser are:

1. high-speed mixers
2. pressure homogenisers
3. colloid mills
4. ultrasonic homogenisers
5. hydroshear homogenisers and microfluidisers.

They are described in more detail by Rees (1967) and Brennan *et al*. (1990).

High-speed mixers

High-speed mixers use turbines or propellers (see Chapter 5, Fig. 5.6), to pre-mix emulsions of low-viscosity liquids. They operate by a shearing action on the food at the edges and tips of the blades.

Pressure homogenisers

Pressure homogenisers consist of a high-pressure pump, operating at 10 000–70 000 $\times$ 10^3 Pa, which is fitted with a homogenising valve on the discharge side (Fig. 4.5). When liquid is pumped through the small adjustable gap (up to 300 μm) between the valve and the valve seat, the high pressure produces a high liquid velocity (80–150 $m\,s^{-1}$). There is then an almost instantaneous drop in velocity as the liquid emerges from the valve. These extreme conditions of turbulence produce powerful shearing forces and the droplets in the dispersed phase become disrupted. The collapse of air bubbles (termed cavitation) and impact forces created in some valves by placing a hard surface (a breaker ring) in the path of the liquid, further reduce the globule size. In some foods, for example milk products,

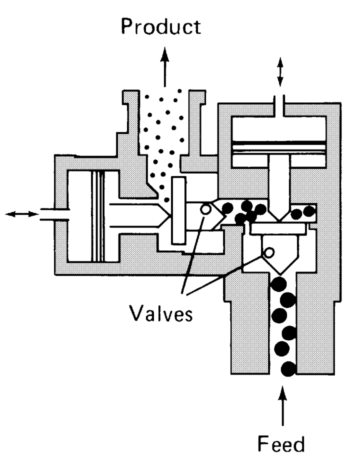

Fig. 4.5 Hydraulic two-stage pressure homogenising valve. (Courtesy of APV Crepaco Inc.)

there may be inadequate distribution of the emulsifying agent over the newly formed surfaces, which causes fat globules to clump together. A second similar valve is then used to break up the clusters of globules. Pressure homogenisers are widely used before pasteurisation (Chapter 11) and ultra high-temperature sterilisation (Chapter 12) of milk, and in the production of salad creams, ice cream and some soups and sauces.

Colloid mills

Colloid mills are essentially disc mills with a small clearance (0.05–1.3 mm) between a stationary disc and a vertical disc rotating at 3000–15 000 rpm. They create high shearing forces and are more effective than pressure homogenisers for high-viscosity liquids. With intermediate-viscosity liquids they tend to produce larger droplet sizes than pressure homogenisers do. Numerous designs of disc, including flat, corrugated and conical shapes, are available for different applications. Modifications of this design include the use of two counter-rotating discs or intermeshing pins on the surface of the discs to increase the shearing action. For highly viscous foods (for example peanut butter, meat or fish pastes) the discs may be mounted horizontally as in the *paste mill*. The greater friction created in viscous foods may require these mills to be cooled by recirculating water.

Ultrasonic homogenisers

Ultrasonic homogenisers use high-frequency sound waves (18–30 kHz) to cause alternate cycles of compression and tension in low-viscosity liquids and cavitation of air bubbles, to form emulsions with droplet sizes of 1–2 μm. The two phases of an emulsion are pumped through the homogeniser at pressures of 340–1400 $\times$ 10^3 Pa. The ultrasonic energy is produced by a vibrating metal blade (Fig. 4.6). The frequency of vibration is controlled by adjusting the clamping position of the blade. This type of homogeniser is used for the production of salad creams, ice cream, synthetic creams, baby foods and essential oil emulsions. It is also used for dispersing powders in liquids (Chapter 5).

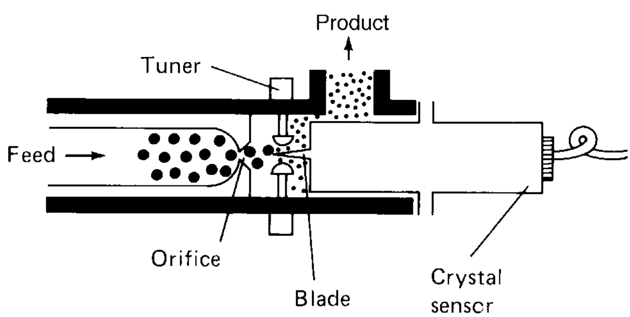

Fig. 4.6 Ultrasonic homogeniser.
(After Loncin and Merson (1979).)

Hydroshear homogenisers and microfluidisers

The *hydroshear homogeniser* is a double-cone shaped chamber which has a tangential feed pipe at the centre and outlet pipes at the end of each cone. The feed liquid enters the chamber at high velocity and is made to spin in increasingly smaller circles and increasing velocity until it reaches the centre and is discharged. The differences in velocity between adjacent layers of liquid causes high shearing forces, which together with cavitation and ultra-high frequency vibration, break droplets in the dispersed phase to within a range of 2–8 μm. A similar type of equipment, termed a *microfluidiser* operates by pumping fluids into a chamber and causing shear and turbulence when they interact and producing droplets of less than 1 μm in diameter, within a narrow size range (Brennan *et al*., 1990).

4.2.3 Effect on foods

Viscosity or texture

In many liquid and semi-liquid foods, the desired mouthfeel is achieved by careful selection of the type of emulsifying agent and stabiliser and by control over homogenisation conditions. In milk, homogenisation reduces the average size of fat globules from 4 μm to less than 1 μm, thereby giving the milk a creamier texture. The increase in viscosity is due to the higher number of globules and adsorption of casein onto the globule surface. These changes are discussed in detail by Harper (1979).

In solid food emulsions the texture is determined by the composition of the food, the homogenisation conditions and post-processing operations such as heating or freezing. Meat emulsions (for example sausage and paté) are o/w emulsions in which the continuous phase is a complex colloidal system of gelatin, proteins, minerals and vitamins, and the dispersed phase is fat globules. The stability of the continuous phase is determined in part by the water-holding capacity (WHC) and fat-holding capacity (FHC) of the meat proteins. The factors which affect WHC and FHC are described by Laurie (1985). The quality of the emulsion is influenced by:

- the ratios of meat:ice:water:fat
- use of polyphosphates to bind water
- the time, temperature and speed of homogenisation.

The emulsion is set by heat during subsequent cooking.

Cream is an o/w emulsion that is mechanically agitated (churned) to cause a partial breakdown of the emulsion when it is made into butter. During this stage, air is incorporated to produce a foam. Liquid fat is released from globules at the surfaces of air bubbles, and this binds together clumps of solid fat to form butter 'grains'. These are then mixed at low speed (worked) to disperse water as fine droplets throughout the mass and to rupture any fat globules remaining from the cream. Although butter is thought of as a w/o emulsion, the complete inversion of the o/w emulsion of cream does not take place. The final product has a continuous phase of 85% fat which contains globules and crystals of solid fat and air bubbles. The dispersed phase (15%) consists of water droplets and buttermilk. The stability of butter is mostly due to its semi-solid nature which prevents migration of bacteria trapped in water droplets, and not due to the action of an emulsifying agent. Details of butter production are given by Lane (1992).

Margarine and low-fat spreads are w/o emulsions. They are produced from a blend of oils, which is heated with a solution of skim milk, salt, added vitamins and emulsifying agents. The warm mixture is emulsified and then chilled and worked to the desired consistency in a continuous operation, using a high pressure tubular chiller. The fats crystallise as they cool, to form a three-dimensional network of long thin needles, which produce the desired smooth texture. Fats are polymorphic and it is the β'-form that is required; the β-form is larger and causes a grainy texture and the α-form rapidly undergoes transition to the β'-form (see also a discussion of fats in chocolate in Chapter 23). The fat content of margarine is similar to butter, whereas low-fat spreads have approximately 40% fat. The oils are chosen to have low melting points and these products are therefore spreadable at refrigeration temperatures. Details are given by Lane (1992).

In ice cream and cake batters, the emulsion is formed as a liquid, and the texture of the final product is partly determined by subsequent unit operations of freezing and baking respectively. Ice cream is a thick o/w emulsion which has a complex continuous phase of ice crystals, colloidal milk solids, dissolved sugar, flavouring, colouring and stabilisers, and a solid–air foam. The dispersed phase is milk fat. Air is incorporated into the emulsion during freezing to create the foam having air cells $<100\mu$ in diameter. This increases the softness and lightness of the product and allows it to be easily scooped. The amount of air is measured as the overrun (see Chapter 1, Section 1.1.1). Commercial ice creams have overruns of 60–100%.

Freezing partially destabilises the emulsion to produce a degree of clumping of fat globules, which improves the texture. Commercial ice creams usually have a softer texture than home-made products due to faster freezing, which produces smaller (40–50μ) ice crystals (Chapter 21), the overrun, and emulsifiers (e.g. esters of mono- and di-glycerides) and stabilisers (e.g. alginates, carrageenan, gums or gelatin) (Appendix C), which cause a larger proportion of the aqueous phase to remain unfrozen. This prevents lactose crystallisation and reduces graininess. As a result, less heat is needed to melt the ice cream and it does not therefore feel excessively cold when eaten. Details of ice cream production are given by Jaspersen (1989) and Andreasen and Nielsen (1992).

Cake batters are similarly o/w emulsions, in which the continuous phase is colloidal starch, a solution of sugar and flavours, and a foam produced during mixing. The dispersed phase is added fats or oils. Details of the changes to cake batters during mixing and baking, and the effects of variations in their formulation are described by Mizukoshi (1990).

Colour, aroma, nutritional value and shelf life

Homogenisation has an effect on the colour of some foods (for example milk) because the larger number of globules causes greater reflectance and scattering of light. Flavour and aroma are improved in many emulsified foods because volatile components are dispersed throughout the food and hence have greater contact with taste buds when eaten. The nutritional value of emulsified foods (Table 4.5) is changed if components are separated (for example in butter making), and there is improved digestibility of fats and proteins owing to the reduction in particle size. The nutritional value of other foods is determined by the formulation used and is not directly affected by emulsification or homogenisation. However, the additional unit operations (for example chilling, freezing and baking), which are necessary to extend the shelf life, may cause changes to nutritional value. In all food emulsions, degradative changes such as hydrolysis or oxidation of pigments, aroma compounds and vitamins, and microbial growth on the finely dispersed material, are minimised by careful control over the processing, packaging and storage conditions. In many countries, special regulations are in force to control hygienic standards during preparation of food emulsions (particularly meat and dairy emulsions) owing to the risk of dispersing pathogenic bacteria throughout the food.

Table 4.5 Effect of emulsification on nutritional value

Nutrient (per 100 g food)	Amount in the following	
	Cream (double)	Butter (salted)
Water (g)	48	15.4
Protein (g)	1.5	0.4
Fat (g)	48	82
Carbohydrate (g)	2.0	0
Energy (kJ)	1850	3040
Vitamin A (μg)	430	730
Vitamin D (μg)	0.28	0.50
Thiamin (μg)	20	0
Riboflavin (μg)	80	0

Adapted from Rolls (1982).

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