3
Evaporation and Dehydration

James G. Brennan

3.1
Evaporation (Concentration, Condensing)

3.1.1
General Principles

Most food liquids have relatively low solids contents. For example, whole milk contains approximately 12.5% total solids, fruit juice 12%, sugar solution after extraction from sugar beet 15%, solution of coffee solutes after extraction from ground roasted beans 25%. For various reasons, some of which are discussed below in Section 3.1.5, it may be desirable to increase the solids content of such liquids. The most common method used to achieve this is to "boil off" or evaporate some of the water by the application of heat. Other methods used to concentrate food liquids are freeze concentration and membrane separation. If evaporation is carried out in open pans at atmospheric pressure, the initial temperature at which the solution boils will be some degrees above 100 °C, depending on the solids content of the liquid. As the solution becomes more concentrated, the evaporation temperature will rise. It could take from several minutes to a few hours to attain the solids content required. Exposure of the food liquid to these high temperatures for these lengths of time is likely to cause changes in the colour and flavour of the liquid. In some cases such changes may be acceptable, or even desirable, for example when concentrating sugar solutions for toffee manufacture or when reducing gravies. However, in the case of heat-sensitive liquids such as milk or fruit juice, such changes are undesirable. To reduce such heat damage, the pressure above the liquid in the evaporator may be reduced below atmospheric by means of condensers, vacuum pumps or steam ejectors (see Section 3.1.2.7). Since a liquid boils when the vapour pressure it exerts equals the external pressure above it, reducing the pressure in the evaporator lowers the temperature at which the liquid will evaporate. Typically, the pressure in the evaporator will be in the range 7.5–85.0 kPa absolute, corresponding to evaporation temperatures in the range 40–95 °C. The use of lower pressures is usually uneconomic. This is known as *vacuum*

evaporation. The relatively low evaporation temperatures which prevail in vacuum evaporation mean that reasonable temperature differences can be maintained between the heating medium, saturated steam, and the boiling liquid, while using relatively low steam pressures. This limits undesirable changes in the colour and flavour of the product. For aqueous liquids, the relationship between pressure and evaporation temperature may be obtained from thermodynamic tables and psychrometric charts. Relationships are available for estimating the evaporating temperatures of nonaqueous liquids at different pressures [1, 2].

Another factor which affects the evaporation temperature, is known as the boiling point rise (BPR) or boiling point elevation (BPE). The boiling point of a solution is higher than that of the pure solvent at the same pressure. The higher the soluble solids content of the solution, the higher its boiling point. Thus, the initial evaporation temperature will be some degrees above that corresponding to pressure in the evaporator, depending on the soluble solids content of the feed. However, as evaporation proceeds and the concentration of the soluble solids increases, the evaporation temperature rises. This is likely to result in an increase in changes in the colour and flavour of the product. If the temperature of the steam used to heat the liquid is kept constant, the temperature difference between it and the evaporating liquid decreases. This reduces the rate of heat transfer and hence the rate of evaporation. To maintain a constant rate of evaporation, the steam pressure may be increased. However, this is likely to result in a further decrease in the quality of the product. Data on the BPR in simple solutions and some more complex foods is available in the literature in the form of plots and tables. Relationships for estimating the BPR with increase in solids concentrations have also been proposed [1, 3]. BPR may range from <1 °C to 10 °C in food liquids. For example, the BPR of a sugar solution containing 50% solids is about 7 °C.

In some long tube evaporators (see Section 3.1.2.3), the evaporation temperature increases with increase in the depth of the liquid in the tubes in the evaporator, due to hydrostatic pressure. This can lead to overheating of the liquid and heat damage. This factor has to be taken into account in the design of evaporators and in selecting the operating conditions, in particular, the pressure of the steam in the heating jacket.

The viscosity of most liquids increases as the solids content increases during evaporation. This can lead to a reduction in the circulation rates and hence the rates of heat transfer in the heating section of the evaporator. This can influence the selection of the type of evaporator for a particular liquid food. Falling film evaporators (see Section 3.1.2.3) are often used for moderately viscous liquids. For very viscous liquids, agitated thin film evaporators are used (see Section 3.1.2.5). Thixotropic (or time-dependent) liquids, such as concentrated tomato juice, can pose special problems during evaporation. The increase in viscosity can also limit the maximum concentration attainable in a given liquid.

Fouling of the heat transfer surfaces may occur in evaporators. This can result in a decrease in the rate of heat transfer and hence the rate of evaporation. It can also necessitate expensive cleaning procedures. Fouling must be taken into account in the design of evaporators and in the selection of the type of eva-

porator for a given duty. Evaporators that feature forced circulation of the liquid or agitated thin films are used for liquids that are susceptible to fouling.

Some liquids are prone to foaming when vigorously boiling in an evaporator. Liquids which contain surface active foaming agents, such as the proteins in skimmed milk, are liable to foam. This can reduce rates of heat transfer and hence rates of evaporation. It may also result in excessive loss of product by entrainment in the vapour leaving the heating section. This in turn can cause contamination of the cooling water to spray condensers and lead to problems in the disposal of that effluent. In some cases, antifoaming agents may be added to the feed to reduce foaming. Care must be taken not to infringe any regulations by the addition of such aids.

Volatile aroma and flavour compounds may be lost during vacuum evaporation, resulting in a reduction in the organoleptic quality of products such as fruit juices or coffee extract. In the case of fruit juices, this loss may be partly offset by adding some of the original juice, known as "cut back juice", to the concentrate. Alternatively, the volatiles may be stripped from the vapour, concentrated and added to the concentrated liquid (see Section 3.1.4.3) [1, 5].

3.1.2
Equipment Used in Vacuum Evaporation

A single-effect vacuum evaporator has the following components.

A heat exchanger, known as a *calandria,* by means of which the necessary sensible and latent heat is supplied to the feed to bring about the evaporation of some of the liquid. Saturated steam is the usual heating medium but hot water and other thermal fluids are sometimes used. Tubular and plate exchangers of various designs are widely used. Other, more sophisticated designs are available, including agitated thin film models, expanding flow chambers and centrifugal exchangers.

A device to separate the vapour from the concentrated liquid phase. In vacuum evaporators, mechanical devices such as chambers fitted with baffles or meshes and cyclone separators are used to reduce entrainment losses.

A condenser to convert the vapour back to a liquid and a pump, steam ejector or barometric leg to remove the condensate, thus creating and maintaining the partial vacuum in the system.

Most evaporators are constructed in stainless steel except where there are extreme corrosion problems.

The following types of evaporators are used in the food industry.

3.1.2.1 Vacuum Pans
A hemispherical pan equipped with a steam jacket and sealed lid, connected to a vacuum system, is the simplest type of vacuum evaporator in use in industry. The heat transfer area per unit volume is small and so the time required to reach the desired solids content can run into hours. Heating occurs by natural

convection. However, an impeller stirrer may be introduced to increase circulation and reduce fouling. Small pans have a more favourable heat transfer area to volume ratio. They are useful for frequent changes of product and for low or variable throughputs. They are used in jam manufacture, the preparation of sauces, soups and gravies and in tomato pulp concentration.

3.1.2.2 Short Tube Vacuum Evaporators

This type of evaporator consists of a calandria made up of a bundle of short vertical tubes surrounded by a steam jacket, located near the bottom of a large vessel (see Fig. 3.1). The tubes are typically 25–75 mm in diameter and 0.5–2.0 m long. The liquid being concentrated normally covers the calandria. Steam condensing on the outside of the tubes heats the liquid causing it to rise by natural convection. Some of the water evaporates and flows to the condenser. The liquid circulates down through the larger, cooler tube in the centre of the bundle, known as the *downcomer*. This type of evaporator is suitable for low to moderate viscosity liquids, which are not very heat-sensitive. With viscous liquids heat transfer rates are low, hence residence times are relatively long and there is a high risk of fouling. Sugar solutions, glucose and malt extract are examples of products concentrated in this type of evaporator. It can also be used for crystallisation operations. For this application an impeller may be located in the downcomer to keep the crystals in suspension.
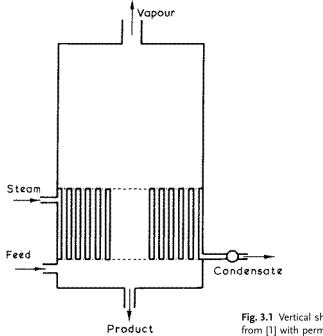

Fig. 3.1 Vertical short tube evaporator; from [1] with permission of the authors.
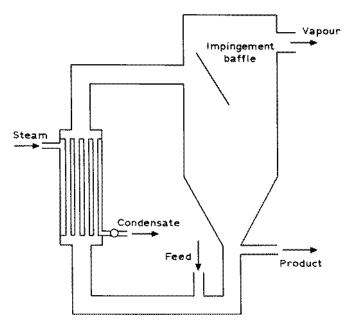
Fig. 3.2 Natural circulation evaporator; from [1] with permission of the authors.

In another design of a short tube evaporator the calandria is external to separator chamber and may be at an angle to the vertical (see Fig. 3.2). The liquid circulates by natural convection within the heat exchanger and also through the separation chamber. The liquid enters the separation chamber tangentially. A swirling flow pattern develops in the chamber, generating centrifugal force, which assists in separating the vapour from the liquid. The vigorous circulation of the liquid results in relatively high rates of heat transfer. It also helps to break up any foam which forms. The tubes are easily accessible for cleaning. Such evaporators are also used for concentrating sugar solutions, glucose and malt and more heat-sensitive liquids such as milk, fruit juices and meat extracts.

A pump may be introduced to assist in circulating more viscous liquids. This is known as forced circulation. The choice of pump will depend on the viscosity of the liquid. Centrifugal pumps are used for moderately viscous materials, while positive displacement pumps are used for very viscous liquids.

3.1.2.3 Long Tube Evaporators

These consist of bundles of long tubes, 3–15 m long and 25–50 mm in diameter, contained within a vertical shell into which steam is introduced. The steam condensing on the outside of the tubes provides the heat of evaporation. There are three patterns of flow of the liquid through such evaporators.

In the *climbing film evaporator* the preheated feed is introduced into the bottom of the tubes. Evaporation commences near the base of the tubes. As the vapour expands, ideally, it causes a thin film of liquid to rise rapidly up the inner walls of the tubes around a central core of vapour. In practice, slugs of liquid and vapour bubbles also rise up the tubes. The liquid becomes more concentrated as it rises. At the top, the liquid-vapour mixture enters a cyclone separator. The vapour is drawn off to a condenser and pump, or into the heating jacket of another calandria, in a multiple-effect system (see Section 3.1.3). The concentrated liquid may be removed as product, recycled through the calandria or fed to another calandria, in a multiple-effect system. The residence time of the liquid in the tubes is relatively short. High rates of heat transfer are attainable in this type of evaporator, provided there are relatively large temperature differences between the heating medium and the liquid being concentrated. However, when these temperature differences are low, the heat transfer rates are also low. This type of evaporator is suitable for low viscosity, heat-sensitive liquids such as milk and fruit juices.

In the *falling film evaporator* the preheated feed is introduced at the top of the tube bundle and distributed to the tubes so that a thin film of the liquid flows down the inner surface of each tube, evaporating as it descends. Uniform distribution of the liquid so that the inner surfaces of the tubes are uniformly wetted is vital to the successful operation of this type of evaporator [6]. From the bottom of the tubes, the liquid-vapour mixture passes into a centrifugal separator and from there the liquid and vapour streams are directed in the same manner as in the climbing film evaporator. High rates of liquid flow down the tubes are attained by a combination of gravity and the expansion of the vapour, resulting in short residence times. These evaporators are capable of operating with small temperature differences between the heating medium and the liquid and can cope with viscous materials. Consequently, they are suitable for concentrating heat-sensitive foods and are very widely used in the dairy and fruit juice processing sections of the food industry today.

A *climbing-falling film evaporator* is also available. The feed is first partially concentrated in a climbing film section and then finished off in a falling film section. High rates of evaporation are attainable in this type of plant.

3.1.2.4 Plate Evaporators

In these evaporators the calandria is a plate heat exchanger, similar to that used in pasteurising and sterilising liquids (see Chapter 2). The liquid is pumped through the heat exchanger, passing on one side of an assembly of plates, while steam passes on the other side. The spacing between plates is greater than that in pasteurisers to accommodate the vapour produced during evaporation. The liquid usually follows a climbing-falling film flow pattern. However, designs featuring only a falling film flow pattern are also available. The mixture of liquid and vapour leaving the calandria passes into a cyclone separator. The vapour from the separator goes to a condenser or into the heating jacket of the next

stage, in a multiple-effect system. The concentrate is collected as product or goes to another stage. The advantages of plate evaporators include: high liquid velocities leading to high rates of heat transfer, short residence times and resistance to fouling. They are compact and easily dismantled for inspection and maintenance. However, they have relatively high capital costs and low throughputs. They can be used for moderately viscous, heat-sensitive liquids such as milk, fruit juices, yeast and meat extracts.

3.1.2.5 Agitated Thin Film Evaporators

For very viscous materials and/or materials which tend to foul, heat transfer may be increased by continually wiping the boundary layer at the heat transfer surface. An agitated thin film evaporator consists of a steam jacketed shell equipped with a centrally located, rotating shaft carrying blades which wipe the inner surface of the shell. The shell may be cylindrical and mounted either vertically or horizontally. Horizontal shells may be cone-shaped, narrowing in the direction of flow of the liquid. There may be a fixed clearance of 0.5–2.0 mm between the edge of the blades and the inner surface of the shell. Alternatively, the blades may float and swing out towards the heat transfer surface as the shaft rotates, creating a film of liquid with a thickness as little as 0.25 mm. Most of the evaporation takes place in the film that forms behind the rotating blades. Relatively high rates of heat transfer are attained and fouling and foaming are inhibited. However, these evaporators have relatively high capital costs and low throughputs. They are used as single-effect units, with relatively large temperature differences between the steam and the liquid being evaporated. They are often used as "finishers" when high solids concentrations are required. Applications include tomato paste, gelatin solutions, milk products, coffee extract and sugar products.

3.1.2.6 Centrifugal Evaporators

In this type of evaporator a rotating stack of cones is housed in a stationary shell. The cones have steam on alternate sides to supply the heat. The liquid is fed to the undersides of the cones. It forms a thin film, which moves quickly across the surface of the cones, under the influence of centrifugal force, and rapid evaporation occurs. Very high rates of heat transfer, and so very short residence times, are attained. The vapour and concentrate are separated in the shell surrounding the cones. This type of evaporator is suitable for heat-sensitive and viscous materials. High capital costs and low throughputs are the main limitations of conical evaporators. Applications include fruit and vegetable juices and purees and extracts of coffee and tea.

3.1.2.7 **Ancillary Equipment**

Vapour-Concentrate Separators   The mixture of vapour and liquid concentrate leaving the calandria needs to be separated and entrainment of droplets of the liquid in the vapour minimised. Entrained droplets represent a loss of product. They can also reduce the energy value of the vapour which would make it less effective in multiple-effect systems or when vapour recompression is being used (see Sections 3.1.3., 3.1.4). Separation may be brought about by gravity. If sufficient headspace is provided above the calandria, as in Fig. 3.1, the droplets may fall back into the liquid. Alternatively, this may occur in a second vessel, known as a flash chamber. Baffles or wire meshes may be located near the vapour outlet. Droplets of liquid impinge on these, coalesce into larger droplets and drain back into the liquid under gravity. The mixture of vapour and liquid may be directed tangentially, at high velocity, either by natural or forced circulation, into a cyclone separator. Centrifugal force is developed and the more dense liquid droplets impinge on the inner wall of the chamber, lose their kinetic energy and drain down into the liquid. This type of separator is used in most long tube, plate and agitated thin film evaporators.

Condensers and Pumps   The water vapour leaving the calandria contains some noncondensable gases, which were in the feed or leaked into the system. The water vapour is converted back to a liquid in a condenser. Condensers may be of the indirect type, in which the cooling water does not mix with the water vapour. These are usually tubular heat exchangers. They are relatively expensive. Indirect condensers are used when volatiles are being recovered from the vapour or to facilitate effluent disposal. Direct condensers, known as jet or spray condensers, are more widely used. In these a spray of water is mixed with the water vapour, to condense it. A condensate pump or barometric leg is used to remove the condensed vapour. The noncondensable gases are removed by positive displacement vacuum pumps or steam jet ejectors [1, 3].

3.1.3
Multiple-Effect Evaporation (MEE)

In a single-effect evaporator it takes 1.1–1.3 kg of steam to evaporate 1.0 kg of water. This is known as the *specific steam consumption* of an evaporator. The specific steam consumption of driers used for liquid foods is much higher than this. A spray drier has a specific steam consumption of 3.0–3.5 kg of steam to evaporate 1.0 kg of water. That of a drum drier is slightly lower. Thus, it is common practice to concentrate liquid foods by vacuum evaporation before drying them in such equipment. It is also common practice to preheat the liquid to its evaporation temperature before feeding it to the evaporator. This improves the specific steam consumption. The vapour leaving a single-effect evaporator contains useful heat. This vapour may be put to other uses, for example, to heat water for cleaning. However, the most widely used method of recovering heat
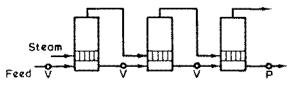
Fig. 3.3 The principle of multiple-effect evaporation, with forward feeding; adapted from [1] with permission of the authors.

from the vapour leaving an evaporator is multiple-effect evaporation, the principle of which is shown in Fig. 3.3.

The vapour leaving the separator of the first evaporator, effect 1, enters the steam jacket of effect 2, where it heats the liquid in that effect, causing further evaporation. The vapour from effect 2 is used to heat the liquid in effect 3 and so on. The vapour from the last effect goes to a condenser. The liquid also travels from one effect to the next, becoming more concentrated as it does so. This arrangement is only possible if the evaporation temperature of the liquid in effect 2 is lower than the temperature of the vapour leaving effect 1. This is achieved by operating effect 2 at a lower pressure than effect 1. This principle can be extended to a number of effects. The pressure in effect 1 may be atmospheric or slightly below. The pressure in the following effects decreases with the number of effects. The specific steam consumption in a double effect evaporator is in the range 0.55–0.70 kg of steam per 1.0 kg of water evaporated, while in a triple effect it is 0.37–0.45 kg. However, the capital cost of a multiple-effect system increases with the number of effects. The size of each effect is normally equivalent to that of a single-effect evaporator with the same capacity, working under similar operating conditions. Thus a three-effect unit will cost approximately three times that of a single effect. It must be noted that MEE does not increase the throughput above that of a single effect. Its purpose is to reduce the steam consumption. Three to five effects are most commonly used. Up to seven effects are in use in some large milk and fruit juice processing plants.

The flow pattern in Fig. 3.3 is known as forward feeding and is the most commonly used arrangement. Other flow patterns, including backward and mixed feeding, are also used. Each has its own advantages and limitations [1, 5].

3.1.4
Vapour Recompression

This procedure involves compressing some or all of the vapour from the separator of an evaporator to a pressure that enables it to be used as a heating medium. The compressed vapour is returned to the jacket of the calandria. This reduces the amount of fresh steam required and improves the specific steam consumption of the evaporator. The vapour may be compressed thermally or mechanically.

In *thermal vapour recompression* (TVR) the vapour from the separator is divided into two streams. One stream goes to the condenser or to the next stage

of a multiple-effect system. The other enters a steam jet compressor fed with fresh high pressure steam. As it passes through the jet of the compressor the pressure of the fresh steam falls and it mixes with the vapour from the evaporator. The vapour mix then passes through a second converging-diverging nozzle where the pressure increases. This high pressure mixture then enters the jacket of the calandria.

In *mechanical vapour recompression* (MVR) all the vapour from the separator is compressed in a mechanical compressor which can be driven by electricity, a gas turbine or a steam turbine. The compressed vapour is then returned to the jacket of the calandria. Both methods are used in industry. MVR is best suited to large capacity duties. Both TVR and MVR are used in conjunction multiple-effect evaporators. Vapour recompression may be applied to one or more of the effects. A specific steam consumption of less than 0.10 kg steam per 1.0 kg of water evaporated is possible. A seven-effect falling film system, with TVR applied to the second effect, the compressed vapour being returned to the first effect, was reported by Pisecky [7]. See also [1, 3–10].

3.1.5
Applications for Evaporation

The purposes for which evaporation is used in the food industry include: to produce concentrated liquid products (for sale to the consumer or as ingredients to be used in the manufacture of other consumer products), to preconcentrate liquids for further processing and to reduce the cost of transport, storage and in some cases packaging, by reducing the mass and volume of the liquid.

3.1.5.1 Concentrated Liquid Products

Evaporated (Unsweetened Condensed) Milk
The raw material for this product is whole milk which should of good microbiological quality. The first step is standardisation of the composition of the raw milk so as to produce a finished product with the correct composition. The composition of evaporated milk is normally 8% fat and 18% solids not fat (snf) but this may vary from country to country. Skim milk and/or cream is added to the whole milk to achieve the correct fat:snf ratio. To prevent coagulation during heat processing and to minimise age thickening during storage, the milk is stabilised by the addition of salts, including phosphates, citrates and bicarbonates, to maintain pH 6.6–6.7. The milk is then heat treated. This is done to reduce the microbiological load and to improve its resistance to coagulation during subsequent sterilisation. The protein is denatured and some calcium salts are precipitated during this heat treatment. This results in stabilisation of the milk. The usual heat treatment is at 120–122 °C for several minutes, in tubular or plate heat exchangers. This heat treatment also influences the viscosity of the final product, which is an important quality attribute. The milk is then con-

centrated by vacuum evaporation. The evaporation temperature is in the range 50–60 °C and is usually carried out in multiple-effect, falling film, evaporator systems. Plate and centrifugal evaporators may also be used. Two or three effects are common, but up to seven effects have been used. The density of the milk is monitored until it reaches a value that corresponds to the desired final composition of the evaporated milk. The concentrated milk is then homogenised in two stages in a pressure homogeniser, operating at 12.5–25.0 MPa. It is then cooled to 14 °C. The concentrated milk is then tested for stability by heating samples to sterilisation temperature. If necessary, more stabilising salts, such as disodium or trisodium phosphates, are added to improve stability. The concentrated milk is then filled into containers, usually tinplate cans, and sealed by double seaming. The filled cans are then sterilised in a retort at 110–120 °C for 15–20 min. If a batch retort is used, it should have a facility for continually agitating the cans during heating, to ensure that any protein precipitate formed is uniformly distributed throughout the cans. The cans are then cooled and stored at not more than 15 °C.

As and alternative to in-package heat processing, the concentrated milk may be UHT treated at 140 °C for about 3 s (see Chapter 2) and aseptically filled into cans, cartons or 'bag in box' containers.

Evaporated milk has been used as a substitute for breast milk, with the addition of vitamin D, in cooking and as a coffee whitener. A lowfat product may be manufactured using skimmed or semiskimmed milk as the raw material. Skimmed milk concentrates are used in the manufacture of ice cream and yoghurt. Concentrated whey and buttermilk are used in the manufacture of margarine and spreads.

Sweetened Condensed Milk

This product consists of evaporated milk to which sugar has been added. It normally contains about 8% fat, 20% snf and 45% sugar. Because of the addition of the sugar, the water activity of this sweetened concentrate is low enough to inhibit the growth of spoilage and pathogenic microorganisms. Consequently, it is shelf stable, without the need for sterilisation. In the manufacture of sweetened condensed milk, whole milk is standardised and heat treated in a similar manner to evaporated milk. At this point granulated sugar may be added, or sugar syrup may be added at some stage during evaporation. Usually, evaporation is carried out in a two- or three-stage, multiple-effect, falling film, evaporator at 50–60 °C. Plate and centrifugal evaporators may also be used. If sugar syrup is used, it is usually drawn into the second effect evaporator. The density of the concentrate is monitored during the evaporation. Alternatively, the soluble solids content is monitored, using a refractometer, until the desired composition of the product is attained. The concentrate is cooled to about 30 °C. Finely ground lactose crystals are added, while it is vigorously mixed. After about 60 min of mixing, the concentrate is quickly cooled to about 15 °C. The purpose of this seeding procedure is to ensure that, when the supersaturated solution of lactose crystallises out, the crystals formed will be small and not cause grittiness in the

product. The cooled product is then filled into cans, cartons or tubes and sealed in an appropriate manner.

Sweetened condensed milk is used in the manufacture of other products such as ice cream and chocolate. If it is to be used for these purposes, it is packaged in larger containers such as 'bag in box' systems, drums or barrels [10, 11].

Concentrated fruit and vegetable juices are also produced for sale to the consumer (see Section 3.1.5.3).

3.1.5.2 Evaporation as a Preparatory Step to Further Processing

One important application for evaporation is to preconcentrate liquids which are to be dehydrated by spray drying, drum drying or freeze drying. As stated in Section 3.1.3 above, the specific steam consumption of such dryers is greater than single-effect evaporators and much greater than multiple-effect systems, particularly, if MVR or TVR is incorporated into one or more of the effects. Whole milk, skimmed milk and whey are examples of liquids which are preconcentrated prior to drying. Equipment similar to that used to produce evaporated milk (see Section 3.1.5.1) is used and the solids content of the concentrate is in the range 40–55%.

Instant Coffee Beverages, such as coffee and tea, are also available in powder form, so called instant drinks. In the production of instant coffee, green coffee beans are cleaned, blended and roasted. During roasting, the colour and flavour develop. Roasting is usually carried out continuously. Different types of roasted beans, light, medium and dark, are produced by varying the roasting time. The roasted beans are then ground in a mill to a particle size to suit the extraction equipment, usually in the range 1000–2000 μm. The coffee solubles are extracted from the particles, using hot water as the solvent. Countercurrent, static bed or continuous extractors are used (see Chapter 15). The solution leaving the extractor usually contains 15–28% solids. After extraction, the solution is cooled and filtered. This extract may be directly dried by spray drying or freeze drying. However, it is more usual to concentrate the solution to about 60% solids by vacuum evaporation. Multiple-effect falling film systems are commonly used. The volatile flavour compounds are stripped from the solution, before or during the evaporation, in a similar manner to that used when concentrating fruit juice (see Section 3.1.5.3) and added back to the concentrate before drying. Coffee powder is produced using a combination of spray drying and fluidised bed drying (see Section 3.2.12.1). Alternatively, the concentrated extract may be frozen in slabs, the slabs broken up and freeze dried in a batch or continuous freeze drier (see Section 3.2.6) [12–14].

Granulated Sugar Vacuum evaporation is used in the production of granulated sugar from sugar cane and sugar beet. Sugar juice is expressed from sugar cane in roller mills. In the case of sugar beet, the sugar is extracted from sliced beet, using heated water at 55–85 °C, in a multistage, countercurrent, static bed or

moving bed extractor (see Chapter 15). The crude sugar juice, from either source, goes through a series of purification operations. These include screening and carbonation. Lime is added and carbon dioxide gas is bubbled through the juice. Calcium carbonate crystals are formed. As they settle, they carry with them a lot of the insoluble impurities in the juice. The supernatant is taken off and filtered. Carbonation may be applied in two or more stages during the purification of the juice. The juice may be treated with sulphur dioxide to limit nonenzymic browning. This process is known as sulphitation. The treated juice is again filtered. Various type of filters are used in processing sugar juice including plate and frame, shell and tube and rotary drum filters (see Chapter 15). The purified juice is concentrated up to 50–65% solids by vacuum evaporation. Multiple-effect systems are employed, usually with five effects. Vertical short tube, long tube and plate evaporators are used. The product from the evaporators is concentrated further in vacuum pans or single-effect short tube evaporators, sometimes fitted with an impeller in the downcomer. This is known as *sugar boiling*. Boiling continues until the solution becomes supersaturated. It is then *shocked* by the addition of a small amount of seeding material, finely ground sugar crystals, to initiate crystallisation. Alternatively, a slurry of finely ground sugar crystals in isopropyl alcohol may be added at a lower degree of supersaturation. The crystals are allowed to grow, under carefully controlled conditions, until they reach the desired size and number. The slurry of sugar syrup and crystals is discharged from the evaporator into a temperature-controlled tank, fitted with a slow-moving mixing element. From there it is fed to filtering centrifugals, or basket centrifuges (see Chapter 15) where the crystals are separated from the syrup and washed. The crystals are dried in heated air in rotary driers (see Section 3.2.3.7) and cooled. The dry crystals are conveyed to silos or packing rooms. The sugar syrup from the centrifuges is subjected to further concentration, seeding and separation processes, known as second and third boilings, to recover more sugar in crystal form [1, 15–18].

3.1.5.3 The Use of Evaporation to Reduce Transport, Storage and Packaging Costs

Concentrated Fruit and Vegetable Juices   Many fruit juices are extracted, concentrated by vacuum evaporation, and the concentrate frozen on one site, near the growing area. The frozen concentrate is then shipped to several other sites where it is diluted, packaged and sold as chilled fruit juice. Orange juice is the main fruit juice processed in this way [20]. The fruit is graded, washed and the juice extracted using specialist equipment described in [21, 22]. The juice contains about 12.0% solids at this stage. The extracted juice is then *finished*. This involves removing bits of peel, pips, pulp and rag from the juice by screening and/or centrifugation. The juice is then concentrated by vacuum evaporation. Many types of evaporator have been used, including high vacuum, low temperature systems. These had relatively long residence times, up to 1 h in some cases. To inactivate enzymes, the juice was pasteurised in plate heat exchangers

before being fed to the evaporator. One type of evaporator, in which evaporation took place at temperatures as low as 20 °C, found use for juice concentration. This operated on a heat pump principle. A refrigerant gas condensed in the heating jacket of the calandria, releasing heat, which caused the liquid to evaporate. The liquid refrigerant evaporated in the jacket of the condenser, taking heat from the water vapour, causing it to condense [1].

Modern evaporators for fruit juice concentration, work on a high temperature, short time (HTST) principle. They are multiple-effect systems, comprised of up to seven falling film or plate evaporators. The temperatures reached are high enough to inactivate enzymes, but the short residence times limit undesirable changes in the product. They are operated with forward flow or mixed flow feeding patterns. Some designs of this type of evaporator are known as thermally accelerated short time or TASTE evaporators.

Volatile compounds, which contribute to the odour and flavour of fruit juices, are lost during vacuum evaporation, resulting in a concentrate with poor organoleptic qualities. It is common practice to recover these volatiles and add them back to the concentrate. Volatiles may be stripped from the juice, prior to evaporation, by distillation under vacuum. However, the most widely used method is to recover these volatiles after partial evaporation of the water. The vapours from the first effect of a multiple-effect evaporation system consist of water vapour and volatiles. When these vapours enter the heating jacket of the second effect, the water vapour condenses first and the volatiles are taken from the jacket and passed through a distillation column, where the remaining water is separated off and the volatiles are concentrated [20–23].

Orange juice is usually concentrated up to 65% solids, filled into drums or 'bag in box' containers and frozen in blast freezers. Unfrozen concentrated juice may also be transported in bulk in refrigerated tankers or ships' holds. Sulphur dioxide may be used as a preservative. Concentrated orange juice may be UHT treated and aseptically filled into 'bag in box' containers or drums. These concentrates may be diluted back to 12% solids, packed into cartons or bottles and sold as chilled orange juice. They may also be used in the production of squashes, other soft and alcoholic drinks, jellies and many other such products.

A frozen concentrated orange juice may also be marketed as a consumer product. This usually has 42–45% solids and is made by adding fresh juice, *cutback juice*, to the 65% solids concentrate, together with some recovered volatiles. This is filled into cans and frozen. Concentrate containing 65% solids, with or without added sweetener, may be pasteurised and hot-filled into cans, which are rapidly cooled. This is sold as a chilled product. UHT treated concentrate may also be aseptically filled into cans or cartons for sale to the consumer from the ambient shelf.

Juices from other fruits, including other citrus fruits, pineapples, apples, grapes, blackcurrants and cranberries, may be concentrated. The procedures are similar to those used in the production of concentrated orange juice. When clear concentrates are being produced, enzymes are used to precipitate pectins, which are then separated from the juice.

Vacuum evaporation is also applied to the production of concentrated tomato products. Tomatoes are chopped and/or crushed and subjected to heat treatment, which may be the hot break or cold break process [24, 25]. Skin and seeds are removed and the juice extracted in a cyclone separator. The juice is then concentrated by vacuum evaporation. For small-scale production, vacuum pans may be employed. For larger throughputs, two- or three-effect tubular or plate evaporators may be used. If highly concentrated pastes are being produced, agitated thin film evaporators may be used as finishers.

Glucose syrup, skimmed milk and whey are among other food liquids that may be concentrated, to reduce weight and bulk, and so reduce transport and storage costs.

3.2
Dehydration (Drying)

3.2.1
General Principles

Dehydration is the oldest method of food preservation practised by man. For thousands of years he has dried and/or smoked meat, fish, fruits and vegetables, to sustain him during out of season periods in the year. Today the dehydration section of the food industry is large and extends to all countries of the globe. Drying facilities range from simple sun or hot air driers to high capacity, sophisticated spray drying or freeze drying installations. A very large range of dehydrated foods is available and makes a significant contribution to the convenience food market.

In this chapter the terms dehydration and drying are used interchangeably to describe the removal of most of the water, normally present in a foodstuff, by evaporation or sublimation, as a result of the application of heat. The main reason for drying a food is to extend its shelf life beyond that of the fresh material, without the need for refrigerated transport and storage. This goal is achieved by reducing the available moisture, or water activity (a_w; see Section 3.2.16) to a level which inhibits the growth and development of spoilage and pathogenic microorganisms, reducing the activity of enzymes and the rate at which undesirable chemical changes occur. Appropriate packaging is necessary to maintain the low a_w during storage and distribution.

Drying also reduces the weight of the food product. Shrinkage, which occurs often during drying, reduces the volume of the product. These changes in weight and volume can lead to substantial savings in transport and storage costs and, in some cases, the costs of packaging. However, dehydration is an energy intensive process and the cost of supplying this energy can be relatively high, compared to other methods of preservation.

Changes detrimental to the quality of the food may also occur during drying. In the case of solid food pieces, shrinkage can alter the size and shape of the pieces. Changes in colour may also occur. When the food pieces are rehydrated,

their colour and texture may be significantly inferior to those of the fresh material. Dry powders may be slow to rehydrate. Changes in flavour may occur during drying solid or liquid foods, as a result of losing volatile flavour compounds and/or the development of cooked flavours. A reduction in the nutritional value of foods can result from dehydration. In particular, loss of vitamins C and A may be greater during drying than in canning or freezing.

Dehydration is usually described as a simultaneous heat and mass transfer operation. Sensible and latent heat must be transferred to the food to cause the water to evaporate. Placing the food in a current of heated air is the most widely used method of supplying heat. The heat is transferred by convection from the air to the surface of the food and by conduction within the food. Alternatively, the food may be placed in contact with a heated surface. The heat is transferred by conduction to the surface of the food in contact with the heated surface and within the food. There is limited use of radiant, microwave and radio frequency energy in dehydration. Freeze drying involves freezing the food and removal of the ice by sublimation. This is usually achieved by applying heat, by conduction or radiation, in a very low pressure environment. In osmotic drying food pieces are immersed in a hypertonic solution. Water moves from the food into the solution, under the influence of osmotic pressure.

3.2.2
Drying Solid Foods in Heated Air

When a wet material is placed in a current of heated air, heat is transferred to its surface, mainly by convection. The water vapour formed is carried away from the drying surface in the air stream. Consider a model system in which a wet material, consisting of an inert solid wetted with pure water, in the form of a thin slab, is placed in a current of heated air, flowing parallel to one of its large faces. The temperature, humidity and velocity of the air are maintained constant. It is assumed that all the heat is transferred to the solid from the air by convection and that drying takes place from one large face only. If the rate of change of moisture content is plotted against time, as in Fig. 3.4, the drying curve may be seen to consist of a number of stages or periods.
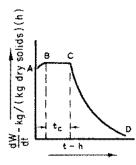

Fig. 3.4 Drying curve for a wet solid in heated air at constant temperature, humidity and velocity; adapted from [1] with permission of the authors.

Period A-B is a settling down or *equilibration period*. The surface of the wet solid comes into equilibrium with the air. This period is usually short compared to the total drying time. Period B-C is known as the *constant rate period*. Throughout this period the surface of the solid is saturated with water. As water evaporates from the surface, water from within the solid moves to the surface, keeping it in a saturated state. The rate of drying during this period remains constant. So also does the surface temperature, at a value corresponding to the wet bulb temperature of the air. By considering heat and mass transfer across the drying surface, a model for the prediction of the duration of the constant rate period of drying can be developed as in Eq. (3.1):

$$t_c = \frac{(W_0 - W_c)\rho_s L_s l}{h_c(\theta_a - \theta_s)} \tag{3.1}$$

where t_c is the duration of the constant rate period, W_0 is the initial moisture content of the wet solid (dry weight basis, dwb), W_c is the moisture content at the end of the constant rate period (dwb), ρ_s is the density of the material, L_s is the latent heat of evaporation at θ_s, l is the thickness of the slab, h_c is heat transfer coefficient for convection heating, θ_a is the dry bulb temperature of the air and θ_s is the wet bulb temperature of the air.

From Eq. (3.1) it can be seen that the main factors that influence the rate of drying during the constant rate period are the air temperature and humidity and the area of the drying surface. The air velocity also has an influence, as the higher this is the greater the value of h_c. As long as this state of equilibrium exists, high rates of evaporation may be maintained, without the danger of overheating the solid. This is an important consideration when drying heat-sensitive foods. Some foods exhibit a constant rate period of drying. However, it is usually short compared to the total drying time. Many foods show no measurable constant rate period.

As drying proceeds, at some point (represented by C in Fig. 3.4) the movement of water to the surface is not enough to maintain the surface in a saturated condition. The state of equilibrium at the surface no longer holds and the rate of drying begins to decline. Point C is known as the critical point and the period C-D is the *falling rate period*. From point C on, the temperature at the surface of the solid rises and approaches the dry bulb temperature of the air as drying nears completion. Hence, it is towards the end of the drying cycle that any heat damage to the product is likely to occur. Many research workers claim to have identified two or more falling rate periods where points of inflexion in the curve have occurred. There is no generally accepted explanation for this phenomenon. During the falling rate period, the rate of drying is governed by factors which affect the movement of moisture within the solid. The influence of external factors, such as the velocity of the air, is reduced compared to the constant rate period. In the dehydration of solid food materials, most of the drying takes place under falling rate conditions.

Numerous mathematical models have been proposed to represent drying in the falling rate period. Some are empirical and were developed by fitting rela-

tionships to data obtained experimentally. Others are based on the assumption that a particular mechanism of moisture movement within the solid prevails. The best known of these is based on the assumption that moisture migrates within the solid by diffusion as a result of the concentration difference between the surface and the centre of the solid. It is assumed that Fick's second law of diffusion applies to this movement. A well known solution to this law is represented by Eq. (3.2):

$$\frac{W - W_e}{W_c - W_e} = \frac{8}{\pi^2} \left[\exp\left\{ -Dt\left(\frac{\pi}{2l}\right)^2 \right\} \right] \tag{3.2}$$

where W is the average moisture content at time t (dwb), W_e is the equilibrium moisture content (dwb), W_c is the moisture content at the start of the falling rate period (dwb), D is the liquid diffusivity and l is the thickness of the slab.

In Eq. (3.2) it is assumed that the value of D is constant throughout the falling rate period. However, many authors have reported that D decreases as the moisture content decreases. Some authors who reported the existence of two or more falling rate periods successfully applied Eq. (3.2) to the individual periods but used a different value of D for each period. Many other factors may change the drying pattern of foods. Shrinkage alters the dimensions of food pieces. The presence of cell walls can affect the movement of water within the solids. The density and porosity of the food material may change during drying. The thermal properties of the food material, such as specific heat and thermal conductivity, may change with a change in moisture content. As water moves to the surface, it carries with it any soluble material, such as sugars and salts. When the water evaporates at the surface, the soluble substances accumulate at the drying surface. This can contribute to the formation of an impervious dry layer at the surface, which impedes drying. This phenomenon is known as case hardening. The diffusion theory does not take these factors into account and so has had only limited success in modelling falling rate drying. Many more complex models have been proposed, which attempt to take some of these changes into account, see [32] as an example [1, 4, 5, 26–32].

3.2.3
Equipment Used in Hot Air Drying of Solid Food Pieces

3.2.3.1 Cabinet (Tray) Drier
This is a multipurpose, batch-operated hot air drier. It consists of an insulated cabinet, equipped with a fan, an air heater and a space occupied by trays of food. It can vary in size from a bench-scale unit holding one or two small trays of food to a large unit taking stacks of large trays. The air may be directed by baffles to flow the across surface of the trays of food or through perforated trays and the layers of food, or both ways. The moist air is partly exhausted from the cabinet and partly recycled by means of dampers. Small cabinet driers are used in laboratories, while larger units are used as industrial driers, mainly for dry-

ing sliced or diced fruits and vegetables. A number of large cabinets may be used in parallel, with a staggered loading sequence, to process relatively large quantities of food, up to 20 000 t day^{-1} of raw material [1, 26, 29, 30, 34].

3.2.3.2 Tunnel Drier

This type of drier consists of a long insulated tunnel. Tray loads of the wet material are assembled on trolleys which enter the tunnel at one end. The trolleys travel the length of the tunnel and exit at the other end. Heated air also flows through the tunnel, passing between the trays of food and/or through perforated trays and the layers of food. The air may flow parallel to and in the same direction as the trolleys, as shown in Fig. 3.5. This is known as a concurrent tunnel. Other designs featuring countercurrent, concurrent-countercurrent and crossflow of air are available. Each pattern of airflow has its advantages and limitations. The trolleys may move continuously through the tunnel. Alternatively, the movement may be semicontinuous. As a trolley full of fresh material is introduced into one end of the tunnel, a trolley full of dried product exits at the other end. Tunnels may be up to 25 m in length and about 2 m×2 m in cross-section. Tunnel driers are mainly used for drying sliced or diced fruits and vegetables [1, 26, 30, 33, 34].

3.2.3.3 Conveyor (Belt) Drier

In this type of drier the food material is conveyed through the drying tunnel on a perforated conveyor, made of hinged, perforated metal plates or wire or plastic mesh. The heated air usually flows through the belt and the layer of food, upward in the early stages of drying and downward in the later stages. The feed is applied to the belt in a layer 75–150 mm deep. The feed must consist of particles that form a porous bed allowing the air to flow through it. Conveyors are typically 2–3 m wide and up to 50 m long. The capacity of a conveyor drier is much less than that of a tunnel drier, occupying the same floor space. As shrinkage occurs during drying, the thickness of the layer of food on the conveyor becomes less. Thus the belt is being used less efficiently as drying proceeds. The use of multistage conveyor drying is common. The product from the first conveyor is redistributed, in a thicker layer, on the second conveyor. This
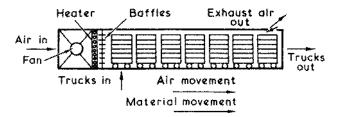

Fig. 3.5 Principle of concurrent tunnel drier; from [1] with permission of the authors.

may be extended to three stages. In this way, the conveyor is used more efficiently, compared to a single-stage unit. On transfer of the particles from one stage to the next, new surfaces are exposed to the heated air, improving the uniformity of drying. The air temperature and velocity may be set to different levels in each stage. Thus, good control may be exercised over the drying, minimising heat damage to the product. However, even when using two or more stages, drying in this type of drier is relatively expensive. Consequently, they are often used to remove moisture rapidly, in the early stages of drying, and the partly dried product is dried to completion in another type of drier. Diced vegetables, peas, sliced beans and grains are examples of foods dried in conveyor driers [1, 26, 30, 33–35].

3.2.3.4 Bin Drier

This is a throughflow drier, mainly used to complete the drying of particulate material partly dried in a tunnel or conveyor drier. It takes the form of a vessel fitted with a perforated base. The partly dried product is loaded into the vessel to up to 2 m deep. Dry, but relatively cool air, percolates up through the bed slowly, completing the drying of the product over an extended period, up to 36 h. Some migration of moisture between the particles occurs in the bin. This improves the uniformity of moisture content in the product [1, 26, 33, 34].

3.2.3.5 Fluidised Bed Drier

This is another throughflow, hot air drier which operates at higher air velocities than the conveyor or bin drier. In this type of drier heated air is blown up through a perforated plate which supports a bed of solid particles. As the air passes through the bed of particles, a pressure drop develops across the bed. As the velocity of the air increases the pressure drop increases. At a particular air velocity, known as the incipient velocity, the frictional drag on the particles exceeds the weight of the particles. The bed then expands, the particles are suspended in the air and the bed starts to behave like a liquid, with particles circulating within the bed. This is what is meant by the term fluidised bed. As the air velocity increases further, the movement of the particles becomes more vigorous. At some particular velocity, particles may detach themselves from the surface of the bed temporarily and fall back onto it. At some higher velocity, known as the entrainment velocity, particles are carried away from the bed in the exhaust air stream. Fluidised bed driers are operated at air velocities between the incipient and entrainment values. The larger and more dense the particles are, the higher the air velocity required to fluidise them. Particles in the size range 20 µm to 10 mm in diameter can usually be fluidised. The particles must not be sticky or prone to mechanical damage. Air velocities in the range 0.2–5.0 m s^{-1} are used. There is very close contact between the heated air and the particles, which results in high rates of heat transfer and relatively short drying times.

Fluidised beds may be operated on a batch or continuous basis. Batch units are used for small-scale operations. Because of the mixing which occurs in such beds, uniform moisture contents are attainable. Continuous fluidised bed driers used in the food industry are of the plug flow type shown in Fig. 3.6. The feed enters the bed at one end and the product exits over a weir at the other. As the particles dry, they become lighter and rise to the surface of the bed and are discharged over the weir. However, if the size, density and moisture content of the feed particles are not uniform, the moisture content of the product may also not be uniform.

The use of multistage fluidised bed driers is common. The partly dried product from the first stage is discharged over the weir onto the second stage and so on. Up to six stages have been used. The temperature of the air may be controlled at a different level in each stage. Such systems can result in savings in energy and better control over the quality of the product, as compared with a single-stage unit. Fluidised beds may be mechanically vibrated. This enables them to handle particles with a wider size range than a standard bed. They can also accommodate sticky products and agglomerated particles better than a standard bed. The air velocities needed to maintain the particles in a fluidised state are less than in a stationary bed. Such fluidised beds are also known as *vibro-fluidisers*. Another design of the fluidised bed is known as the spouted bed drier (see Fig. 3.7). Part of the heated air is introduced into the bottom of the bed in the form of a high velocity jet. A spout of fast-moving particles is formed in the centre of the bed. On reaching the top of the bed, the particles return slowly to the bottom of the bed in an annular channel surrounding the spout. Some of
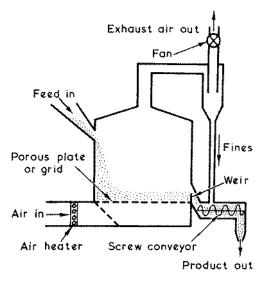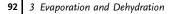

Fig. 3.6 Principle of continuous fluidised bed drier, with fines recovery system; from [1] with permission of the authors.
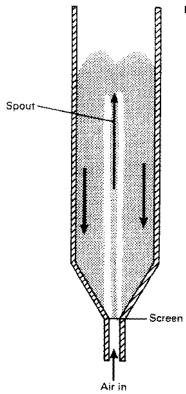
Fig. 3.7 Principle of spouted bed drier.

the heated air flows upward through the slow-moving channel, countercurrent to the movement of the particles. High rates of evaporation are attained in the spout, while evaporative cooling keeps the particle temperature relatively low. Conditions in the spout are close to constant rate drying (see Section 3.2.2). Drying of the particles is completed in the annular channel. This type of drier can handle larger particles than the conventional fluidised bed. In some spouted bed driers the air is introduced tangentially into the base of the bed and a screw conveyor is located at its centre to control the upward movement of the particles. Such driers are suitable for drying relatively small particles. In the toroidal bed drier the heated air enters the drying chamber through blades or louvres, creating a fast-moving, rotating bed of particles (see Fig. 3.8). High rates of heat and mass transfer in the bed enable rapid drying of relatively small particles. Peas, sliced beans, carrots and onions, grains and flours are some foods that have been dried in fluidised bed driers [1, 3, 5, 26, 30, 36–39].
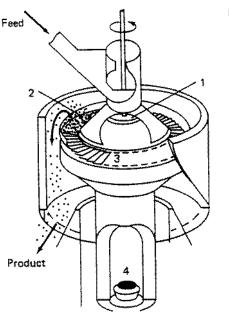
Fig. 3.8 Principle of toroidal bed drier.

Feed

2

1

3

Product

4

3.2.3.6 Pneumatic (Flash) Drier

In this type of drier the food particles are conveyed in a heated air stream through ducting of sufficient length to give the required drying time. It is suitable for relatively small particles and high air velocities are used, in the range 10–40 m s^{-1}. The dried particles are separated from the air stream by cyclone separators or filters. The ducting may be arranged vertically or horizontally. Single vertical driers are used mainly for removing surface moisture. Drying times are short, in the range 0.5–3.5 s and they are also known as flash driers. When internal moisture is to be removed, longer drying times are required. Horizontal pneumatic driers, or vertical driers, consisting of a number of vertical columns in series, may be used for this purpose. The ducting may be in the form of a closed loop. The particles travel a number of times around the loop until they reach the desired moisture content. The dried particles are removed from the air stream by means of a cyclone. Fresh air is introduced continuously into the loop through a heater and humid air is continuously expelled from it. This type of drier is known as a pneumatic ring drier. Grains and flours are the main products dried in pneumatic driers [1, 5, 26, 40].

3.2.3.7 Rotary Drier

The most common design of rotary drier used for food application is known as the direct rotary drier. This consists of a cylindrical shell, set at an angle to the horizontal. The shell rotates at 4–5 rpm. Wet material is fed continuously into

the shell at its raised end and dry product exits over a weir at the lower end. Baffles or flights are fitted to the inner surface of the shell. These lift the material up as the shell rotates and allow it to fall down through a stream of heated air, that may flow concurrent or countercurrent to the direction of movement of the material. The feed material must consist of relatively small particles, which are free-flowing and reasonably resistant to mechanical damage. Air velocities in the range 1.5–2.5 m s^{-1} are used and drying times are from 5 min to 60 min.

One particular design of rotary drier is known as the *louvred drier*. The wall of the shell is made up of overlapping louvre plates, through which the heated air is introduced. As the shell rotates, the bed of particles is gently rolled within it, causing mixing to take place and facilitating uniform drying. The movement is less vigorous than in the conventional rotary drier and causes less mechanical damage to the particles. Grains, flours, cocoa beans, sugar and salt crystals are among the food materials dried in rotary driers [26, 41, 42].

3.2.4
Drying of Solid Foods by Direct Contact With a Heated Surface

When a wet food material is placed in contact with a heated surface, usually metal, the sensible and latent heat is transferred to the food and within the food mainly by conduction. Most of the evaporation takes place from the surface, which is not in contact with the hot surface. The drying pattern is similar to that which prevails during drying in heated air (see Section 3.2.2). After an equilibration period, there a constant rate period, during which water evaporates at a temperature close to its boiling point at the prevailing pressure. The rate of drying will be higher than that in heated air at the same temperature. When the surface begins to dry out, the rate of drying will decrease and the temperature at the drying surface will rise and approach that of the heated metal surface, as drying nears completion. If drying is taking place at atmospheric pressure, the temperature at the drying surface in the early stages will be in excess of 100 °C. There is little or no evaporative cooling as is the case in hot air drying. The temperature of the heated metal surface will need to be well above 100 °C in order to achieve reasonable rates of drying and low product moisture content. Exposure of a heat sensitive food to such high temperatures for prolonged periods, up to several hours, is likely to cause serious heat damage. If the pressure above the evaporating surface is reduced below atmospheric, the evaporation temperature will be reduced and hence the temperature of the heated metal surface may be reduced. This is the principle behind *vacuum drying*.

If it is assumed that drying takes place from one large face only and that there is no shrinkage, the rate of drying, at any time *t*, may be represented by the following equation:

$$\frac{dw}{dt} = \frac{(W_0 - W_f)M}{t} = \frac{K_c A(\theta_w - \theta_e)}{L_e} \tag{3.3}$$

where $\frac{dw}{dt}$ = rate of drying (rate of change of weight) at time t, W_0 is the initial moisture content of the material (dwb), W_f is the final moisture content of the material (dwb), M is the mass of dry solids on the surface, t is the drying time, K_c is the overall heat transfer coefficient for the complete drying cycle, A is the drying area, θ_w is the temperature of the heated metal surface (wall temperature), θ_e is the evaporating temperature and L_e is the latent heat of evaporation at θ_e [1, 5, 26, 43, 44].

3.2.5
Equipment Used in Drying Solid Foods by Contact With a Heated Surface

3.2.5.1 Vacuum Cabinet (Tray or Shelf) Drier
This drier consists of a vacuum chamber connected to a condenser and vacuum pump. The chamber is usually cylindrical and has one or two access doors. It is usually mounted in a horizontal position. The chamber is equipped with a number of hollow plates or shelves, arranged horizontally. These shelves are heated internally by steam, hot water or some other thermal fluid, which is circulated through them. A typical drying chamber may contain up to 24 shelves, each measuring 2.0×1.5 m. The food material is spread in relatively thin layers on metal trays. These trays are placed on the shelves, the chamber is sealed and the pressure reduced by means of the condenser and vacuum pump. Absolute pressures in the range 5–30 kPa are created, corresponding to evaporation temperatures of 35–80 °C. Drying times can range from 4 h to 20 h, depending on the size and shape of the food pieces and the drying conditions. The quality of vacuum dried fruits or vegetables is usually better than air dried products. However, the capital cost of vacuum shelf driers is relatively high and the throughput low, compared to most types of hot air drier [1, 5, 26, 34, 43, 44].

3.2.5.2 Double Cone Vacuum Drier
This type of drier consists of a hollow vessel in the shape of a double cone. It rotates about a horizontal axis and is connected to a condenser and vacuum pump. Heat is applied by circulating steam or a heated fluid through a jacket fitted to the vessel. The pressures and temperatures used are similar to those used in a vacuum shelf drier (see Section 3.2.5.1). It is suitable for drying particulate materials, which are tumbled within the rotating chamber as heat is applied through the jacket. Some mechanical damage may occur to friable materials due to the tumbling action. If the particles are sticky at the temperatures being used, they may form lumps or balls or even stick to the wall of the vessel. Operating at low speeds or intermittently may reduce this problem. This type of drier has found only limited application in the food industry [26, 43, 44].
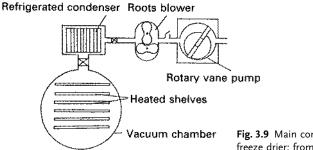
3.2.6
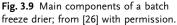### Freeze Drying (Sublimation Drying, Lyophilisation) of Solid Foods

This method of drying foods was first used in industry in the 1950s. The process involves three stages: (a) freezing the food material, (b) subliming the ice (primary drying) and (c) removal of the small amount of water bound to the solids (secondary drying or desorption). Freezing may be carried out by any of the conventional methods including blast, immersion, plate or liquid gas freezing (see Chapter 4). Blast freezing in refrigerated air is most often used. It is important to freeze as much of the water as possible. This can be difficult in the case of material with a high soluble solids content, such as concentrated fruit juice. As the water freezes in such a material, the soluble solids content of remaining liquid increases, and so its freezing point is lowered. At least 95% of the water present in the food should be converted to ice, to attain successful freeze drying.

Ice will sublime when the water vapour pressure in the immediate surroundings is less than the vapour pressure of ice at the prevailing temperature. This condition could be attained by blowing dry, refrigerated air across the frozen material. However, this method has proved to be uneconomic on a large scale. On an industrial scale, the vapour pressure gradient is achieved by reducing the total pressure surrounding the frozen food to a value lower than the ice vapour pressure. The vapour pressure of ice at $-20\,°C$ is about 135 Pa, absolute. Industrial freeze drying is carried out in vacuum chambers operated at pressures in the range 13.5–270.0 Pa, absolute. The main components of a batch freeze drier are a well sealed vacuum chamber fitted with heated shelves, a refrigerated condenser and a vacuum pump or pumps (see Fig. 3.9). The refrigerated condenser removes the water vapour formed by sublimation. The water vapour freezes on to the condenser, thus maintaining the low water vapour pressure in the chamber. The vacuum pump(s) remove the noncondensable gases.

The heated shelves supply the heat of sublimation. Heat may be applied from above the frozen food by radiation or from below by conduction or from both directions.

Once sublimation starts, a dry layer will form on the top surface of the food pieces. Together, the rate at which water vapour moves through this dry layer

Fig. 3.9 Main components of a batch freeze drier; from [26] with permission.

and the rate at which heat travels through the dry layer and/or the frozen layer determine the rate of drying. If a slab-shaped solid is being freeze dried from its upper surface only and if the heat is supplied only from above, through the dry layer, a state of equilibrium will be attained between the heat and mass transfer. Under these conditions, the rate of drying (rate of change of weight, $\frac{dw}{dt}$), may be represented by the following model:

$$\frac{dw}{dt} = \frac{Ak_d(\theta_d - \theta_i)}{L_s l} = \frac{Ab(p_i - p_d)}{l} = A\rho_s(W_0 - W_f)\frac{dl}{dt} \tag{3.4}$$

where A is the drying area normal to the direction of flow of the vapour, k_d is the thermal conductivity of the dry layer, θ_d is the temperature at the top surface of the dry layer, θ_i is the temperature at the ice front, L_s is the heat of sublimation, l is the thickness of the dry layer, b is the permeability of the dry layer to water vapour, p_I is the water vapour pressure at the ice front; p_d is the water vapour pressure at the top surface of the dry layer, ρ_s is the density of the dry layer, W_0 is the initial moisture content of the material (dwb), W_f is the final moisture content of the material (dwb) and $\frac{dl}{dt}$=rate of change of thickness of the dry layer. When heat is supplied from below, or from both above and below, the equilibrium between the heat and mass transfer no longer exists. More complex models representing these situations are available in the literature [30, 45, 46].

The advantages of freeze drying as compared with other methods lie in the quality of the dried product. There is no movement of liquid within the solid during freeze drying. Thus, shrinkage does not occur and solutes do not migrate to the surface. The dried product has a light porous structure, which facilitates rehydration. The temperature to which the product is exposed is lower than in most other methods of drying, so heat damage is relatively low. There is good retention of volatile flavour compounds during freeze drying. However, some damage to the structure may occur during freezing which can result in some structural collapse on rehydration and a poor texture in the rehydrated product. Some denaturation of proteins may occur due to pH changes and concentration of solutes during freezing. Freeze dried food materials are usually hygroscopic, prone to oxidation and fragile. Relatively expensive packaging may be necessary, compared to other types of dried foods. The capital cost of freeze drying equipment is relatively high and so are the energy costs. It is the most expensive method of drying food materials [1, 5, 26, 30, 45–47].

3.2.7
Equipment Used in Freeze Drying Solid Foods

3.2.7.1 Cabinet (Batch) Freeze Drier
This is a batch operated drier. The vacuum chamber is cylindrical, mounted horizontally and fitted with doors front and back. The vacuum is created and maintained by a refrigerated condenser backed up by vacuum pumps (see Fig. 3.9).

Once the frozen food is sealed into the chamber, the pressure must be reduced rapidly to avoid melting of the ice. Once the vacuum is established, the low pressure must be maintained throughout the drying cycle, which may range from 4 h to 12 h. The vacuum system must cope with the water vapour produced by sublimation and noncondensable gases, which come from the food or through leaks in the system. The refrigerated condenser, which may be a plate or coil, is located inside the drying chamber, or in a smaller chamber connected to the main chamber by a duct. The water vapour freezes onto the surface of the plate or coil. The temperature of the refrigerant must be below the saturation temperature, corresponding to the pressure in the chamber. This temperature is usually in the range –10 °C to –50 °C. As drying proceeds, ice builds up on the surface of the condenser. This reduces its effectiveness. If it is not to be defrosted during the drying cycle, then a condenser with a large surface area is required. Defrosting may be carried out during the cycle by having two condensers. These are located in separate chambers, each connected to the main drying chamber via a valve. The condensers are used alternately. While one is isolated from the drying chamber and is defrosting, the other is connected to the main chamber and is condensing the water vapour. The roles are reversed periodically during the drying cycle.

Usually two vacuum pumps are used in series to cope with the noncondensable gases. The first may be a Roots blower or an oil-sealed rotary pump. The second is a gas-ballasted, oil-sealed rotary pump. In the early days of industrial freeze drying, multistage steam ejectors were used to evacuate freeze drying chambers. These could handle both the water vapour and noncondensable gases. However, most of these have been replaced by the system described above, because of their low energy efficiency.

Heat is normally supplied by means of heated shelves. The trays containing the frozen food are placed between fixed, hollow shelves, which are heated internally by steam, heated water or other thermal fluids. Heat is supplied by conduction from below the trays and by radiation from the shelf above. Plates and trays are designed to ensure good thermal contact. Ribbed or finned trays are used to increase the area of the heated surface in contact with granular solids, without impeding with the escape of the water vapour. The use of microwave heating in freeze drying is discussed in Section 3.2.9 [1, 5, 26, 45–48].

3.2.7.2 Tunnel (SemiContinuous) Freeze Drier

This is one type of freeze drier capable of coping with a wide range of piece sizes, from meat and fish steaks down to small particles, while operating on a semicontinuous basis. It is comprised of a cylindrical tunnel, 1.5–2.5 m in diameter. It is made up of sections. The number of sections depends on the throughput required. Entry and exit locks are located at each end of the tunnel. Gate valves enable these locks to be isolated from the main tunnel. To introduce a trolleyload of frozen material into the tunnel, the gate valve is closed, air is let into the entry lock, the door is opened and the trolley pushed into the lock. The

door is then closed and the lock is evacuated by a dedicated vacuum system. When the pressure is reduced to that in the main tunnel, the gate valve is opened and the trolley enters the main tunnel. A similar procedure is in operation at the dry end of the tunnel, to facilitate the removal of a trolleyload of dried product. Fixed heater places are located in the tunnel. The food material, in trays or ribbed dishes, passes between these heater plates as the trolley proceeds through the tunnel. Since both the vacuum and heat requirements decrease as drying proceeds, the vacuum and heating systems are designed to match these requirements. The main body of the tunnel is divided into zones by means of vapour restriction plates. Each zone is serviced by its own vacuum and heating system. Each section of the tunnel can process 3–4 t of frozen material per 24 h [26, 45, 49].

3.2.7.3 **Continuous Freeze Driers**

There are a number of designs of continuous freeze driers suitable for processing granular materials. In one design, a stack of circular heater plates is located inside a vertical, cylindrical vacuum chamber. The frozen granules enter the top of the chamber alternately through each of two entrance locks, and fall onto the top plate. A rotating central vertical shaft carries arms which sweep the top surface of the plates. The arm rotating on the top plate pushes the granules outward and over the edge of the plate, onto the plate below, which has a larger diameter than the top plate. The arm on the second plate pushes the granules inward towards a hole in the centre of the plate, through which they fall onto the third plate, which has the same diameter as the top plate. In this way, the granules travel down to the bottom plate in the stack. From that plate, they fall through each of two exit locks alternately and are discharged from the chamber.

In another design, the frozen granules enter at one end of a horizontal, cylindrical vacuum chamber via an entrance lock, onto a vibrating deck. This carries them to the other end of the chamber. They then fall onto a second deck, which transports them back to the front end of the chamber, where they fall onto another vibrating deck. In this way, the granules move back and forth in the chamber until they are dry. They are then discharged from the chamber through a vacuum lock. Heat is supplied by radiation from heated platens located above the vibrating decks. Another design is similar to the above but conveyor belts, rather than vibrating decks, move the granules back and forth within the chamber [30, 49].

3.2.7.4 **Vacuum Spray Freeze Drier**

A prototype of this freeze drier, developed for instant coffee and tea is described by Mellor [45]. The preconcentrated extract is sprayed into a tall cylindrical vacuum chamber, which is surrounded by a refrigerated coil. The droplets freeze by evaporative cooling, losing about 15% of their moisture. The partially dried par-

ticles fall onto a moving belt conveyor in the bottom of the chamber and are carried through a vacuum tunnel where drying is completed, by the application of radiant heat. The dry particles are removed from the tunnel by means of a vacuum lock.

The production of instant coffee is the main industrial application of freeze drying. Freeze dried fruits, vegetables, meat and fish are also produced, for inclusion in ready meals and soups. However, they are relatively expensive compared to similar dried foods produced by hot air or vacuum drying.

3.2.8
Drying by the Application of Radiant (Infrared) Heat

When thermal radiation is directed at a body, it may be absorbed and its energy converted into heat, or reflected from the surface of the body, or transmitted through the material. It is the absorbed energy that can provide heat for the purposes of drying. Generally, in solid materials all the radiant energy is absorbed in a very shallow layer beneath the surface. Thus radiant drying is best suited to drying thin layers or sheets of material or coatings. Applications include textiles, paper, paints and enamels. In the case of food materials, complex relationships exist between their physical, thermal and optical properties. These in turn influence the extent to which radiant energy is absorbed by foods. The protein, fat and carbohydrate components of foods have their own absorption patterns. Water in liquid, vapour or solid form also has characteristic absorption patterns that influence the overall the absorption of radiant energy. It is very difficult to achieve uniform heating of foods by radiant heat. Control of the heating rate is also a problem. Infrared heating is not normally used, in the food industry, for the removal of water in bulk from wet food materials. It has been used to remove surface moisture from sugar or salt crystals and small amounts of water from low moisture particles such as breadcrumbs and spices. These are conveyed in thin layers beneath infrared heaters. Shortwave lamps are used for very heat-sensitive materials. Longwave bar heaters are used for more heat-resistant materials. Radiant heating is used in vacuum driers and freeze driers, usually in combination with heat transferred by conduction from heated shelves [26, 50].

3.2.9
Drying by the Application of Dielectric Energy

There is some confusion in the literature regarding terminology when describing dielectric and microwave energy. In this section, the term dielectric is used to represent both the radio frequency (RF) and microwave (MW) bands of the electromagnetic spectrum. RF energy is in the frequency range 1–200 MHz and MW from 300 MHz to 300 GHz. By international agreement, specific frequencies have been allocated for industrial use. These are: RF 27.12 MHz and 13.56 MHz, MW 2450 MHz and a band within the range 896–915 MHz. These are known as ISM (industrial, scientific and medical) bands. Dielectric heating is used for cooking,

thawing, melting and drying. The advantages of this form of heating over more conventional methods are that heat generation is rapid and occurs throughout the body of the food material. This is known as volumetric heating. Water is heated more rapidly than the other components in the food. This is an added advantage when it is used for drying foods. The depth to which electromagnetic waves penetrate into a material depends on their frequency and the characteristics of each material. The lower the frequency and so the longer the wavelength, the deeper the penetration. The energy absorbed by a wet material exposed to electromagnetic waves in the dielectric frequency range depends on a characteristic of the material known as its dielectric loss factor, which depends on the distribution of dipoles in the material. The higher the loss factor, the more energy is absorbed by the material. The loss factor of a material is dependent on its moisture content, temperature and, to some extent, its structure. The loss factor of free water is greater than bound water. The loss factors of both free and bound water are greater than that of the dry matter. Heating both by RF and MW methods is mainly due to energy absorbed by water molecules. However, the mechanism whereby this energy is absorbed is different for the two frequency ranges. In RF heating, heat is generated by the passage of an electric current through the water. This is due to the presence of ions in the water, which give it a degree of electrical conductivity. In MW heating, dipolar molecules in the water are stressed by the alternating magnetic field and this results in the generation of heat. At frequencies corresponding to RF heating, the conductivity and hence the energy absorbed increases with increasing temperature. However, in the case of MW frequencies, the loss factor and so the energy absorbed, decreases with increasing temperature. At both RW and MW frequencies, the rapid generation of heat within the material leads to the rapid evaporation of water. This gives rise to a total pressure gradient which causes a rapid movement of liquid water and water vapour to the surface of the solid. This mechanism results in shorter drying times and lower material temperatures, compared to hot air or contact drying. Drying is uniform, as thermal and concentration gradients are comparatively small. There is less movement of solutes within the material and overheating of the surface is less likely than is the case when convected or conducted heat is applied. There is efficient use of energy as the water absorbs most of the heat. However, too high a heating rate can cause scorching or burning of the material. If water becomes entrapped within the material, rupture of solid pieces may occur, due to the development of high pressure within them.

Equipment for the generation of RF and MW is described in the literature [51–53]. Equipment for applying RF and MW differ from each other. A basic RF (platen) applicator consists of two metal plates, between which the food is placed or conveyed. The plates are at different electrical voltages. This is also known as a throughfield applicator and is used mainly for relatively thick objects. In a stray- or fringefield applicator, a thin layer of material passes over electrodes, in the form of bars, rods or plates, of alternating polarity. In a staggered, throughfield applicator, bars are located above and below the product to form staggered throughfield arrays. This type is suitable for intermediate thick-

ness products. In a basic batch MW applicator, microwaves are directed from the generator into a metal chamber via a waveguide or coaxial cable. The food is placed in the chamber. To improve the uniformity of heating, the beam of microwaves may be disturbed by a mode stirrer, which resembles a slow turning fan. This causes reflective scattering of the waves.

Alternatively, the food may be placed on a rotating table in the chamber. In one continuous applicator, known as a leaky waveguide applicator, microwaves are allowed to leak in a controlled manner from slots or holes cut in the side of a waveguide. A thin layer of product passes over the top of the slots. In the slotted waveguide applicator, the product is drawn through a slot running down the centre of the waveguide. This is also suitable for thin layers of material.

Dielectric heating is seldom used as the main source of heat for drying wet food materials. It is mainly used in conjunction with heated air.

Dielectric heating may be used to preheat the feed to a hot air drier. This quickly raises the temperature of the food and causes moisture to rise to the surface. The overall drying time can be reduced in this way. It may also be applied in the early stages of the falling rate period of drying, or towards the end of the drying cycle, to reduce the drying time. It is more usual to use it near the end of drying. RF heating is used in the later stage of the baking of biscuits (postbaking) to reduce the moisture content to the desired level. This significantly shortens the baking time compared to completing the baking in a conventional oven. A similar procedure has been used for breakfast cereals. MW heating is used, in combination with heated air of high humidity, to dry pasta. Cracking of the product is avoided and the drying time is shortened from 8 h to 1 h, compared to drying to completion in heated air. MW heating has been used after frying of potato chips and crisps to attain the desired moisture content, without darkening the product, if the sugar content of the potatoes is high. It has also been used as a source of heat when vacuum drying pasta. The use of MW heating in freeze drying has been the subject of much research. Ice absorbs energy more rapidly than dry matter, which is an advantage. However, ionisation of gases can occur in the very low pressure conditions and this can lead to plasma discharge and heat damage to the food. Using a frequency of 2450 MHz can prevent this. If some of the ice melts, the liquid water will absorb energy so rapidly that it may cause solid food particles to explode. Very good control of the MW heating is necessary to avoid this happening. MW heating in freeze drying has not yet been used on an industrial scale, mainly because of the high cost involved [1, 5, 26, 52–54].

3.2.10
Osmotic Dehydration

When pieces of fresh fruits or vegetables are immersed in a sugar or salt solution, which has a higher osmotic pressure than the food, water passes from the food into the solution under the influence of the osmotic pressure gradient; and the water activity of the food is lowered. This method of removing moisture

from food is known as osmotic dehydration (drying). This term is misleading as the end product is seldom stable and further processing is necessary to extend its shelf life. Osmotic concentration would be a more accurate description of this process. During osmosis the cell walls act as semipermeable membranes, releasing the water and retaining solids. However, these membranes are not entirely selective and some soluble substances, such as sugars, salts, organic acids and vitamins, may be lost from the cells, while solutes from the solution may penetrate into the food. Damage that occurs to the cells during the preparation of the pieces, by slicing or dicing, will increase the movement of soluble solids. The solutes, which enter the food from the solution, can assist in the reduction of the water activity of the food. However, they may have an adverse effect on the taste of the end product.

In the case of fruits, sugars with or without the addition of salt, are used to make up the osmotic solution, also known as the hypertonic solution. Sucrose is commonly used, but fructose, glucose, glucose/fructose and glucose/polysaccharide mixtures and lactose have been used experimentally, with varying degrees of success. The inclusion of 0.5–2.0% of salt in the sugar solution can increase the rate of osmosis. Some other low molecular weight compounds such as malic acid and lactic acid have been shown to have a similar effect. Sugar solutions with initial concentrations in the range 40–70% are used. In general, the higher the solute concentration the greater the rate and extent of drying. The higher the sugar concentration the more sugar will enter the food. This may result in the product being unacceptably sweet. The rate of water loss is high initially, but after 1–2 h it reduces significantly. It can take days before equilibrium is reached. A typical processing time to reduce the food to 50% of its fresh weight is 4–6 h.

In the case of vegetables, sodium chloride solutions in the range 5–20% are generally used. At high salt concentrations, the taste of the end product may be adversely affected. Glycerol and starch syrup have been used experimentally, as solutes for osmotic drying of vegetables.

In general, the higher the temperature of the hypertonic solution the higher the rate of water removal. Temperatures in the range 20–70 °C have been used. At the higher temperatures, there is a danger that the cell walls may be damaged. This can result in excessive loss of soluble material, such as vitamins, from the food. Discoloration of the food may occur at high temperature. The food may be blanched, in water or in the osmotic solution, to prevent browning. This may affect the process in different ways. It can speed up water removal in some large fruit pieces, due to relaxation of the structural bonds in the fruit. In the case of some small fruit pieces, blanching may reduce water loss and increase the amount of solute entering into the fruit from the solution. In general, the lower the weight ratio of food to solution the greater the water loss and solids gain. Ratios of 1:4 to 1:5 are usually employed. The smaller the food pieces the faster the process, due to the larger surface area. However, the smaller the pieces the more cell damage is likely to occur when cutting them and, hence, the greater the amount of soluble solids lost from the food. Promoting movement of the solution relative to the food pieces should result in faster osmosis. However, vigorous mixing is likely to lead

to cell damage. Delicate food pieces may remain motionless in a tank of solution. Some improvement in the rate of drying may be obtained by recirculating the solution through the tank by means of a pump. In large-scale installations, the food pieces may be contained within a basket, which is immersed in the tank of solution. The basket is vibrated by means of an eccentric drive. Alternatively, the food pieces may be packed into a tall vessel and the solution pumped through the porous bed of solids.

Reuse of the hypertonic solution is desirable to make osmotic drying an economic process. Insoluble solids may be removed by filtration and the solution concentrated back to its original soluble solids content by vacuum evaporation. Discoloration may limit the number of times the solution can be reused. A mild heat treatment may be necessary to inactivate microorganisms, mainly yeasts, that may build up in the solution.

As stated above, the products from osmotic drying are usually not stable. In the case of fruits and vegetables, the osmosed products have water activities in the range 0.90–0.95. Consequently, further processing is necessary. Drying in heated air, vacuum drying or freeze drying may be employed to stabilise such products. Alternatively, they may be frozen [26, 30, 55].

3.2.11
Sun and Solar Drying

In this section the term 'sun drying' is used to describe the process whereby some or all of the energy for drying of foods is supplied by direct radiation from the sun. The term 'solar drying' is used to describe the process whereby solar collectors are used to heat air, which then supplies heat to the food by convection.

For centuries, fruit, vegetables, meat and fish have been dried by direct exposure to the sun. The fruit or vegetable pieces were spread on the ground on leaves or mats while strips of meat and fish were hung on racks. While drying in this way, the foods were exposed to the vagaries of the weather and to contamination by insects, birds and animals. Drying times were long and spoilage of the food could occur before a stable moisture content was attained. Covering the food with glass or a transparent plastic material can reduce these problems. A higher temperature can be attained in such an enclosure compared to those reached by direct exposure to the sun. Most of the incident radiation from the sun will pass through such transparent materials. However, most radiation from hot surfaces within the enclosure will be of longer wavelength and so will not readily pass outwards through the transparent cover. This is known as the 'greenhouse effect' and it can result in shorter drying times as compared with those attained in uncovered food exposed to sunlight. A transparent plastic tent placed over the food, which is spread on a perforated shelf raised above the ground, is the simplest form of covered sun drier. Warm air moves by natural convection through the layer of food and contributes to the drying. A simple sun drier of sturdier construction is shown in Fig. 3.10.
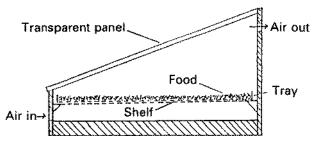
Fig. 3.10 Simple sun drier.

The capacity of such a drier may be increased by incorporating a solar collector. The warm air from the collector passes up through a number of perforated shelves supporting layers of food and is exhausted near the top of the chamber. A chimney may be fitted to the air outlet to increase the rate of flow of the air. The taller the chimney, the faster the air will flow. If a power supply is available, a fan may be incorporated to improve the airflow still further. Heating by gas or oil flames may be used in conjunction with solar drying. This enables heating to continue when sunlight is not available. A facility for storing heat may also be incorporated into solar driers. Tanks of water and beds of pebbles or rocks may be heated via a solar collector. The stored heat may then be used to heat the air entering the drying chamber. Drying can proceed when sunlight is not available. Heat storing salt solutions or adsorbents may be used instead or water or stones. Quite sophisticated solar drying systems, incorporating heat pumps, are also available [26, 30, 56–58].
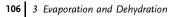
3.2.12
Drying Food Liquids and Slurries in Heated Air

3.2.12.1 Spray Drying
This is the method most commonly used to dry liquid foods and slurries. The feed is converted into a fine mist or spray. This is known as atomisation and the spray forming device as an atomiser. The droplet size is usually in the range 10–200 μm, although for some applications larger droplets are produced. The spray is brought into contact with heated air in a large drying chamber. Because of the relatively small size of the droplets, a very large surface area is available for evaporation of the moisture. Also, the distance that moisture has to migrate to the drying surface is relatively short. Hence, the drying time is relatively short, usually in the range 1–20 s. Evaporative cooling at the drying surface maintains the temperature of the droplets close to the wet bulb temperature of the drying air, i.e. most of the drying takes place under constant rate conditions (see Section 3.2.2). If the particles are removed quickly from the drying chamber once they are dried, heat damage is limited. Hence, spray drying can be used to dry relatively heat sensitive materials.

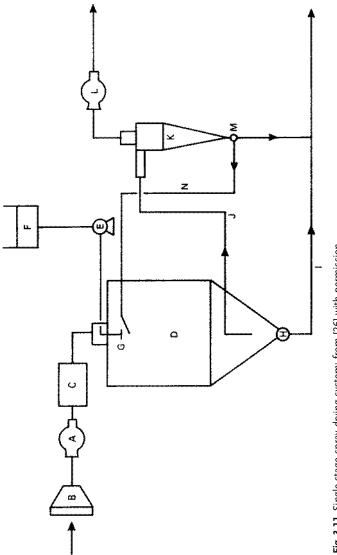The main components of a single stage spray drier are shown in Fig. 3.11.

Fig. 3.11 Single-stage spray drying system; from [26] with permission.

Inlet fan A draws air in through filter B and then through heater C into drying chamber D. Pump E delivers the feed from tank F to the atomiser G. This converts the feed into a spray which then contacts the heated air in drying chamber D, where drying takes place. Most of the dry powder is removed from the chamber through valve H and pneumatically conveyed through duct I to a storage bin. The air leaves the chamber through duct J and passes through one or more air/powder separators K to recover the fine powder carried in the air. This powder may be added to the main product stream through valve M or returned to the wet zone of the drying chamber through duct N.

The air may be heated indirectly through a heat exchanger using oil or gas fuel or steam. In recent years, natural gas has been used to heat the air directly. There is still some concern about possible contamination of the food with nitrate and nitrite compounds, in particular *N*-nitrosodimethylamine, which has been shown to be harmful. The use of low NO_x (nitrogen oxide) burners reduces this problem. However, the quality of the air should be monitored when direct heating is used.

It is important that the droplets produced by the atomiser are within a specified size range. If the droplets vary too much in size, drying may not be uniform. The drying conditions must be set so that the larger droplets reach the desired moisture content. This may result in smaller droplets being overexposed to the heated air. Droplet size can affect some important properties of the dry powder, such as its rehydration behaviour and flow properties. There are three types of atomiser: centrifugal atomiser, pressure nozzle and two-fluid nozzle. A centrifugal atomiser consists of a disc, bowl or wheel on the end of a rotating shaft. The liquid is fed onto the disc near its centre of rotation. Under the influence of centrifugal force, it moves out to the edge of the disc and is spun off, initially in the form of threads, which then break up into droplets. There are many designs of disc in use. An example is shown in Fig. 3.12. Disc diameters range over 50–300 mm and they rotate at speeds in the range 50 000 rpm to 10 000 rpm, respectively. They are capable of producing uniform droplets. They can handle viscous feeds and are not subject to blocking or abrasion by insoluble solid particles in the feed.

A pressure nozzle features a small orifice, with a diameter in the range 0.4–4.0 mm, through which the feed is pumped at high pressure, in the range 5.0–50.0 MPa. A grooved core insert, sited before the orifice, imparts a spinning motion to the liquid, producing a hollow cone of spray. Pressure nozzles are capable of producing droplets of uniform size, if the pumping pressure is maintained steady. However, they are subject to abrasion and/or blocking by insoluble solid particles in the feed. They are best suited to handling homogeneous liquids, of relatively low viscosity.

A two-fluid nozzle, also known as a pneumatic nozzle, features an annular opening through which a gas, usually air, exits at high velocity. The feed exits through an orifice concentric with the air outlet. A venturi effect is created and the liquid is converted into a spray. The feed pumping pressure is lower than that required in a pressure nozzle. Such nozzles are also subject to abrasion

Fig. 3.12 Centrifugal atomiser; by courtesy of Niro.

and blocking if the feed contains insoluble solid particles. The droplets produced by two-fluid nozzles are generally not as uniform in size as those from the other two types of atomiser, especially when handling high viscosity liquids. They are also best suited to handling homogeneous liquids.

There are numerous designs of drying chamber used in industry. Three types are shown in Fig. 3.13. Figure 3.13a depicts a tall cylindrical tower with a conical base. Both heated air and feed are introduced at the top of the chamber and flow concurrently down through the tower. This design is best suited to drying relatively large droplets of heat sensitive liquids, especially if the powder particles are sticky and tend to adhere to the wall of the chamber. The wall of the conical section of the chamber may be cooled to facilitate removal of the powder. Figure 3.13b depicts another concurrent chamber, but featuring a shorter cylindrical body. The air enters tangentially at the top of the chamber and follows a downward, spiral flow path. The feed is introduced into the top of the chamber, through a centrifugal atomiser. Because of the spiral flow pattern followed by the air, particles tend to be thrown against he wall of the chamber. Consequently, this type of chamber is best suited to drying foods, which are not very heat sensitive or sticky. The chamber depicted in Fig. 3.13c features a mixed flow pattern. The heated air is directed upward initially and contacts the spray of liquid from the centrifugal atomiser. The air, containing the droplets, then travels down to the bottom of the chamber. The risk of heat damaging the product is greater than in concurrent chambers. This design is not widely used for food dehydration. Many other designs of spray drying chambers are used in industry including flat-bottomed cylindrical and horizontal boxlike versions.

In industrial spray driers, most of the dry powder is removed from the bottom of the chamber through a rotary valve or vibrating device. Some powders, containing high amounts of sugar or fat, may tend to adhere to the wall of the chamber. Various devices are used to loosen such deposits. Pneumatically operated hammers, which strike the outside wall of the chamber, may be used. Brushes, chains or air brooms may sweep the inner surface of the chamber. The temperature of the wall of the chamber may be reduced by removing some of the insulation or by drawing cool air through a jacket covering some or all of the chamber wall. This can also reduce product build up on the wall.
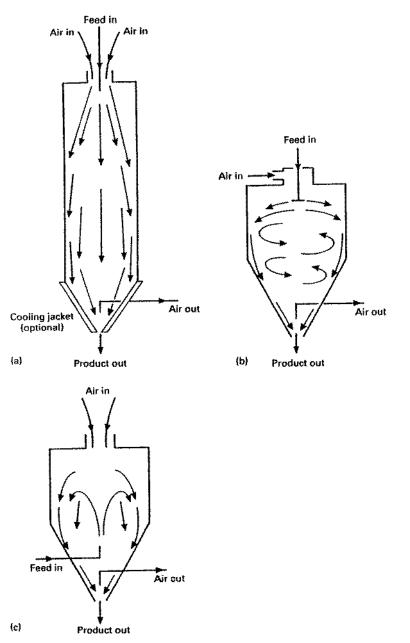
Fig. 3.13 Different designs of spray drying chambers: (a) concurrent with straight-line flow path, (b) concurrent with spiral flow path, (c) mixed flow; from [60] with permission.

The exhaust air from the chamber carries with it some of the fine particles of product. These need to be separated from the air, as they represent valuable product and/or may contaminate the environment close to the plant. Large dry cyclone separators are often used, singly or in pairs in series, for this purpose. Fabric filters are also employed for this duty. Powder particles may be washed out of the exhaust air with water or some of the liquid feed and recycled to the drying chamber. Such devices are known as wet scrubbers. An advantage of this method is that heat may also be recovered from the air and used to preheat or preconcentrate the feed. Electrostatic precipitators could also be used for recovering fines from the air leaving the drying chamber. However, they are not widely employed in the food industry. Combinations of the above separation methods may be used. The air, after passing through the cyclones, may then pass through a filter or scrubber to remove very fine particles and avoid contaminating the outside environment. Fines recovered by cyclones or filters may be added to the main stream of product. However, powders containing large amounts of small particles, less than 50 μm in diameter, are difficult to handle and may have poor rehydration characteristics. When added to a hot or cold liquid, fine particles tend to form clumps which float on the surface of the liquid and are difficult to disperse. It is now common practice to recycle the fines back into the wet zone of the drier where they collide with droplets of the feed to form small agglomerates. Such agglomerates disperse more readily than individual small particles when added to a liquid.

It is now common practice to remove the powder from the spray drying chamber before it reaches its final moisture content and to complete the drying in another type of drier. Vibrating fluidised bed driers are most often used as secondary driers (see Section 3.2.3.5). Some agglomeration of the powder particles occurs in this second stage, which can improve its rehydration characteristics. A second fluidised bed drier may be used to cool the agglomerated particles. Spray driers are available which permit multistage drying in one unit. In the integrated fluidised bed drier, a fluidised bed in the shape of a ring is located at the base of the drying chamber. Most of the drying takes place in the main drying chamber. Drying is completed in the inbuilt fluidised bed [1, 5, 7, 12, 26, 30, 59–61].

3.2.13
Drying Liquids and Slurries by Direct Contact With a Heated Surface

3.2.13.1 Drum (Roller, Film) Drier
The principle of this type of drier is that the feed is applied in a thin film to the surface of a rotating hollow cylinder, heated internally, usually with steam under pressure. As the drum rotates, heat is transferred to the food film, mainly by conduction, causing moisture to evaporate. The dried product is removed by means of a knife which scrapes the surface of the drum. The pattern of drying is similar to that of solids drying in heated air drying i.e. there are constant and falling rate periods (see Section 3.2.2). However, the temperature
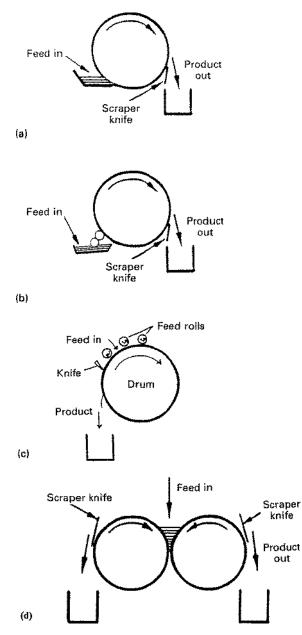
Fig. 3.14 Different designs of drum driers: (a) single drum
with dip feed, (b) single drum with unheated roller feed,
(c) single drum with multiroller feed (d) double drum;
adapted from [26] with permission.

to which the food is exposed is usually higher than in heated air drying, as there is not the same degree of evaporative cooling. Drying times are relatively short, usually in the range 2–30 s. In a single drum drier, the feed may be applied to the drum by different means. The drum may dip into a trough containing the feed (Fig. 3.14a). This feed system is most suited to low viscosity liquids. For more viscous liquids and slurries, unheated rollers may apply the feed to the drum (Fig. 3.14b). A multiple roller system is used for high viscosity liquids and pastes (Fig. 3.14c). The layer of feed becomes progressively thicker as it passes beneath successive feed rollers. The feed may also be sprayed or splashed onto the drum surface. A double drum drier (Fig. 3.14d) consists of two drums rotating towards each other at the top. The clearance between the drums is adjustable. The feed is introduced into the trough formed between the drums and a film is applied to the surface of both drums as they rotate. This type of drum drier is suitable for relatively low viscosity liquids, that are not very heat-sensitive.

Drums are 0.15–1.50 m in diameter and 0.2–3.0 m long. They rotate at speeds in the range 3–20 rpm. They may be made from a variety of materials. For food applications, chromium-plated cast iron or stainless steel drums are mostly used. The drum surface temperature is usually in the range 110–165 °C. As the food approaches these temperatures towards the end of drying, it is likely to suffer more heat damage than in spray drying. For very heat-sensitive materials, one or two drums may be located inside a vacuum chamber operated at an absolute pressure from just below atmospheric down to 5 kPa. The drum is heated by vacuum steam or heated water, with a surface temperature in the range 100 °C to 35 °C. Provision must be made for introducing the feed into and taking the product out of the vacuum chamber and for adjusting knives, feed rollers, etc. from outside the chamber. Such vacuum drum driers are expensive to purchase and maintain and are not widely used in the food industry [1, 5, 26, 43, 62].

3.2.13.2 Vacuum Band (Belt) Drier

In this type of vacuum drier a metal belt or band, moving in a clockwise direction, passes over a heated and cooled drum inside a vacuum chamber (see Fig. 3.15).

The band may be continuous and made of stainless steel or fine stainless steel wire mesh. Alternatively, it may be made of hinged, stainless steel plates. The feed, in the form of a viscous liquid or paste, is applied to the band by means of a roller, after entering the vacuum chamber via a valve. The cooled product is scraped off the band and removed from the chamber through a rotary valve, a sealed screw or into two vacuum receivers, working alternately. Radiant heaters or heated platens, in contact with the belt, supplement the heat supplied by the heated drum. The chamber pressure and band temperature are in similar ranges to those used in vacuum drum driers (see Section 3.2.13.1). A number of bands, positioned one above the other, may be located in one vacuum chamber. Vacuum band driers are expensive to purchase and maintain and
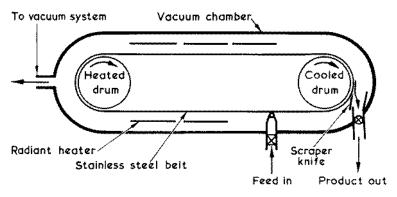
Fig. 3.15 Principle of vacuum band (belt) drier; from [1] with permission of the authors.

are only used for very heat-sensitive materials, which can bear the high costs involved [1, 5, 26, 30, 43].

3.2.14
Other Methods Used for Drying Liquids and Slurries

Concentrated liquids have been dried by heated air on *conveyor driers*, using a technique known as *foam mat drying*. The liquid is made into a foam, by the addition of a small amount, 1% or less, of a foaming agent, such as soya protein, albumin, fatty acid esters of sucrose and glycerol monostearate, and the incorporation of air or other gases by injection or mixing. The foam is spread in thin layers or strips on a wire mesh belt and conveyed through the drier. Relatively rapid drying can be achieved, of the order of 1 h in air at 100 °C, yielding a porous dry product with good rehydration properties [26, 63].

Liquids have been dried in *spouted beds* of inert particles. Metal and glass spheres and various plastic particles have been used as inert material. These have been fluidised with heated air to form spouted beds (see Section 3.2.3.5). The liquid is sprayed onto the particles and is heated by convection from the heated air and conduction from the hot particles, causing moisture to evaporate. When dry, the film is released from the particles by abrasion and impact between particles and separated from the exhaust air by a cyclone separator [57].

Liquids, usually in concentrated form, have been dried in *vacuum cabinet driers* (see Section 3.2.5.1). A technique known as *vacuum puff drying* has been used in this type of drier and in vacuum band driers. The concentrated liquid is spread in a thin layer on trays and placed in the vacuum chamber. When the vacuum is drawn, bubbles of water vapour and entrapped air form within the liquid and expand and the liquid froths up to form a foam. By careful control of pressure, temperature and viscosity of the liquid, it may be made to expand to occupy a space up to 20 times that of the original material. When heat is applied, the foam dries rapidly to form a porous dry product, with good rehydration properties [26, 63].

Concentrated liquids are *freeze dried*. The concentrate is frozen into slabs, which are broken up into pieces and dried in batch or continuous freeze driers (see Section 3.2.6).

3.2.15
Applications of Dehydration

The following are examples of the many foods which are preserved in dehydrated form.

3.2.15.1 Dehydrated Vegetable Products

Many vegetables are available in dehydrated form. A typical process involves:

- ← wet and dry cleaning
- ← peeling, if necessary, by mechanical, steam or chemical methods
- ← slicing, dicing or shredding
- ← blanching
- ← sulphiting, if necessary
- ← dewatering
- ← drying
- ← conditioning, if used
- ← milling or kibbling, if used
- ← screening
- ← packaging

Most vegetables are *blanched* prior to drying. See Chapter 1 for a discussion of the purposes and methods of blanching. Many vegetables are *sulphured* or *sulphited* prior to drying. Again see Chapter 1 for a discussion of this step in the process. Many different types of driers are used for drying vegetables including: cabinets, single or two stage tunnels, conveyor and fluidised bed driers (see Section 3.2.3). Air inlet temperatures vary from product to product but are usually in the range 50–110 °C. Tunnel, conveyor and fluidised bed driers may be divided into a number of drying zones, each zone being controlled at a different temperature, to optimise the process. If the drying is not completed in the main drier, the product may be *finish dried* or *conditioned* in a bin drier, supplied with dry air at 40–60 °C. Among the vegetables dried as outlined above are green beans, bell peppers, cabbage, carrot, celery, leeks, spinach and swedes. Some vegetables such as garlic, mushrooms, green peas and onions are not sulphited. Herbs such as parsley, sage and thyme may be dried without blanching or sulphiting. Vegetables may be dried in vacuum cabinet driers and in freeze driers, to yield products of superior quality to those produced by air drying. However, such products will be more expensive.

Vegetable purees may be dried. Cooked and pureed carrot and green peas maybe drum dried to produce a flaked product. Very finely divided, cooked carrot or green peas may be spray dried to a fine powder [26, 34, 65, 66].

A number of dried potato products are available. Dehydrated, diced potato is produced by a process similar to that outlined above. After blanching the potato pieces should be washed with a water spray to remove gelatinised starch from their surfaces. In addition to sulphite, calcium salts may be added to increase the firmness of the rehydrated dice. Cabinet, tunnel or conveyor driers may be used to dry the potato. Conveyor driers are most widely used. In recent years, fluidised bed driers have been applied to this duty. Finish drying in bins is often practiced. Potato flakes are produced by drum drying cooked, mashed potatoes. Two-stage cooking is followed by mashing or ricing. Sufficient sulphite is mixed with the mash to give 150–200 ppm in the dried product. An emulsion is made up containing, typically, monoglyceride emulsifier, sodium acid pyrophosphate, citric acid and an antioxidant and mixed into the mash. In some cases milk powder may also be added. The mash is then dried on single drum driers equipped with a feed roll and up to four applicator rolls. Steam at 520–560 kPa, absolute, is used to heat the drums. After drying, the dried sheet is broken up into flakes. Potato flour is made from poor quality raw potatoes which are cooked, mashed, drum dried and milled. Potato granules may also be produced from cooked, mashed potatoes. After cooking, the potato slices are carefully mashed. Some dry granules may be 'added back' to the mash, which then has sulphite added to give 300–600 ppm in the dried product. A second granulation stage then follows. It is important that as little as possible rupture of cells occurs at this stage. The granules are cooled to 15.5–26.5 °C and held at that temperature for about 1 h. During this 'conditioning' some retrogradaton of the starch occurs. A further gentle granulation then takes place and the granules are dried in pneumatic and/or fluidised bed driers to a moisture content of 6–7% (wwb [26, 34, 67]).

Sliced tomatoes may be sun dried. The slices are exposed to the fumes of burning sulphur in a chamber or dipped in, or sprayed with sulphite solution before sun drying. In recent years, there has been an increase in demand for sun dried tomatoes which are regarded as being of superior quality to those dried by other means. Tomato slices are also air dried in cabinet or tunnel driers to a moisture content of 4% (wwb). The dried slices tend to be hygroscopic and sticky. They are usually kibbled or milled into flakes for inclusion in dried soup mixes or dried meals.

Tomato juice may be spray dried. The juice is prepared by the 'hot or cold break process' (see Section 3.1.5.3) and concentrated by vacuum evaporation up to 26–48% total solids content, depending on the preparation procedure, before it is spray dried. The powder is hygroscopic and sticky when hot and tends to adhere to the wall of the drying chamber. A tall drying chamber downward, concurrent flow may be used. Alternatively, a chamber with a shorter body featuring a downward, concurrent, spiral flow path may be used. The wall of the chamber is fitted with a jacket through which cool air is circulated, to reduce wall deposition. An air inlet temperature in the range 140–150 °C is used and the product has a moisture content of 3.5% (wwb [12, 26, 34]).

3.2.15.2 **Dehydrated Fruit Products**

Many fruits are sun dried, including pears, peaches and apricots. However, hot air drying is also widely applied to fruits such as apple slices, apricot halves, pineapple slices and pears in halves or quarters. A typical process for such fruits involves:

- ← Washing
- ← grading
- ← peeling/coring, if required
- ← trimming, if required
- ← sulphiting
- ← cutting
- ← resulphiting
- ← drying
- ← conditioning, if required
- ← packing

Fruits are not usually blanched. However, a procedure known as dry-blanch-dry is sometimes used for some fruits such as apricots, peaches and pears. After an initial drying stage, in which the fruit is reduced to about half its initial weight, it is steam blanched for 4–5 min. It is then further dried and conditioned down to its final moisture content. Fruits are usually sulphured by exposure to the fumes of burning sulphur.

Cabinet or tunnel driers are most commonly used at the drying stage(s). Air inlet temperatures in the range 50–75 °C are used. Tunnel driers may be divided into two or three separate drying zones, each operating at a different air temperature.

Grapes are sun dried on a large scale to produce raisins or sultanas. They are also dried in heated air in cabinet or tunnel driers. The grapes are dipped in a hot 0.25% NaOH bath, washed and heavily sulphured. prior to drying down to a moisture content of 10–15% (wwb). They are usually conditioned in bins or sweat boxes to attain a uniform moisture content. Fumigation may be necessary during conditioning to kill any infestation. The 'golden bleached' appearance of the raisins or sultanas is due to the high SO_2 content which is in the range 1500–2000 ppm.

Whole plums are dried in cabinet or tunnel driers to produce prunes. The fruits are not sulphured. They are dried down to a moisture content in the range 16–19% (wwb) but may be 'stabilised' by rehydration in steam to a moisture content of 20–22% (wwb).

Fruit purees may drum dried to produce a flake or powder product. Bananas may treated with SO_2, pulped, pasteurised, further treated with SO_2, homogenised and dried on a single drum drier to a moisture content of 4% (wwb). Other fruit purees may be drum dried, including apricot, mango and peach. Some of these products are hygroscopic and sticky. Additives, such as glucose syrup, may have to be mixed into the puree to facilitate removal of the product from the drum and its subsequent handling.

Fruit juices may be spray dried. Concentrated orange juice is an example. To avoid the powder sticking to the wall of the drying chamber, additives are used. The most common one is liquid glucose with a dextrose equivalent in the range 15–30. It may be added in amounts up to 75% of the concentrate, calculated on a solids basis. Other additives such as skim milk powder and carboxymethyl celluloses have been used. However, these limit the uses to which the dry powder can be put. It is important that the concentrated juice is well homogenised, if it contains insoluble solid particles. Both centrifugal and nozzle atomisers are used. Tall chambers, featuring downward, concurrent flow patterns are favoured. The dried powder may be cooled on a fluidised bed to facilitate handling. Volatiles, separated from the juice before or after concentration, may be added to the powder to enhance its flavour. Other fruit juices which may be spray dried include lemon, mango, peach and strawberry [26, 34, 64, 68, 69].

3.2.15.3 **Dehydrated Dairy Products**

Skim or separated milk is mainly produced by spray drying. The raw whole milk is centrifuged to yield skim milk with 0.05% fat. The skim milk is then heat treated. The degree of heat treatment at this stage determines whether the powder produced is classed as low-heat, medium-heat or high-heat powder. The more severe the heat treatment, the lower the amount of soluble whey proteins (albumin and globulin) that remain in the powder. Low-heat powder is used in recombined milk products such as cheese and baby foods. Medium-heat powder is used in the production of recombined concentrated milk products. High-heat powder is mainly used in the bakery and chocolate industries. The milk is then concentrated to a total solids content in the range 40–55%, by multiple-effect evaporation. Falling film evaporators are most widely used in recent years. Various designs of spray drying chamber and atomiser can be used for drying skim milk, as it not a difficult material to dry. Air inlet and out temperatures used are in the ranges 180–230 °C and 80–100 °C, respectively. The moisture content of the powder is in the range 3.5–4.0% (wwb). It is common practice to recycle the fine powder from the separators into the wet zone of the drier. The powder may be removed from the drying chamber at a moisture content of 5–7% (wwb) and the drying completed in a vibrated fluidised bed drier. This promotes some agglomeration of the powder particles and improves its rehydration characteristics. Instant milk powder may be produced by rewetting the powder particles, usually with steam, mixing them to promote agglomeration and redrying them down to a stable moisture content. This can be carried out in a fluidised bed. The powder may be cooled in a second fluidised bed to facilitate handling.

Whole milk powder is also produced by spray drying in a similar manner to skim milk. Air inlet and outlet temperatures are usually in the ranges 175–200 °C and 75–95 °C, respectively. Whole milk powder is rather sticky when hot and can form a deposit on the chamber wall. Hammers, which are located outside the chamber and tap the wall of the chamber at intervals, may be used to assist in the removal of the powder. Whole milk powder may be agglomer-

ated. However, this may not be as effective as in the case of skim milk powder. Fat may migrate to the surface of the particles. This reduces their wettability. The addition of small quantities of lecithin, a surface active agent, to whole milk powder, can improve its rehydration characteristics, particularly in cold liquids.

Other dairy products which are spray dried are buttermilk and whey. Whey powder is hygroscopic and difficult to handle, as the lactose is in a amorphous state. A crystallisation process before and/or after drying can alleviate this problem.

Relatively small amounts of milk and whey are drum dried. Double drum driers are usually used. The dry products are mainly used for animal feed. However, because of its good water binding properties, drum dried milk is used in some precooked foods [7, 9–12, 26, 60].

3.2.15.4 Instant Coffee and Tea

These products are produced by spray drying or freeze drying. The extract from ground roasted beans (see Section 3.1.5.2) is preconcentrated by vacuum evaporation before drying. Tall spray drying chambers, featuring a downward, concurrent flow pattern and a nozzle atomiser, are favoured as the powder is sticky. Air inlet and outlet temperatures in the ranges 250–300 °C and 105–115 °C, respectively, are used. Fine powder from the separators is recycled into the wet zone of the drier. Agglomeration may be attained in a fluidised bed. As an alternative to spray drying, the preconcentrated extract may be frozen into slabs, the slabs broken into pieces and freeze dried in batch or continuous equipment.

Instant tea may also be produced by spray drying the extract from the leaves. Similar equipment to that used for instant coffee is employed but at lower air inlet temperatures (200–250 °C). The concentrated extract may be freeze dried in a similar manner to coffee extract.

3.2.15.5 Dehydrated Meat Products

Cooked minced meat may be hot air dried in cabinet, conveyor, fluidised bed and rotary driers, down to a moisture content of 4–6% (wwb). Chicken, beef, lamb and pork may be dehydrated in this way. Chicken meat is the most stable in dried form, while pork is the least stable. The main cause of deterioration in such dried products is oxidation of fat leading to rancidity. Cooked minced meat may also be dried in vacuum cabinet driers to give better quality products, than hot air dried meat, but at a higher cost. Both raw and cooked meat in the form of steaks, slices, dice or mince may be freeze dried down to a moisture content of 1.5–3.0% (wwb), at a still higher cost. Dehydrated meat products are mainly used as ingredients in dried soup mixes, sauces and ready meals. They are also used in rations for troops and explorers [26, 34].

3.2.15.6 Dehydrated Fish Products

The traditional methods of extending the shelf life of fish are salting and smoking. Salting could be regarded as a form of osmotic drying whereby salt is introduced into the flesh of fish to reduce its water activity (see Section 3.2.16). Some water may evaporate during or after salting. Smoking involves exposure of the fish to smoke from burning wood. This may be done at relatively low temperature, c. 30 °C, and is known as cold smoking. A moisture loss of 10–11% may occur during smoking. Cold smoked fish products can be chilled, which gives them a shelf life of about 7 days. Hot smoking is carried out at temperatures up to 120 °C. Hot smoked products may have a sufficiently low water activity to be stable without refrigeration. Unsalted and unsmoked fish may be hot air dried in cabinet and tunnel driers, using relatively low air temperatures, down to 30 °C. However, this is not widely practised commercially. Freeze dried fish products are also available. Because of the high cost of freeze drying, only relatively expensive fish products, such as prawns and shrimps, are dried in this way. Dried fish products are used as ingredients in soup mixes and ready meals. Many fishery byproducts are produced in dried form, including fish hydrolysate, fish meal and fish protein concentrate [26, 71, 72].

3.2.16
Stability of Dehydrated Foods

When considering the stability of dehydrated foods it is not the total moisture content that is critical but rather the amount of moisture that is available to support microbial growth, enzymic and chemical activity. It is generally accepted that a proportion of the total moisture present in a food is strongly bound to individual sites on the solid components and an additional amount is less firmly bound, but is still not readily available as a solvent for various soluble food components. In studying the availability of water in food, a fundamental property known as water activity, a_w, is measured. This property is defined by the expression:

$$a_w = \frac{p_v}{p_w} \tag{3.5}$$

where p_v is the water vapour pressure exerted by a solution or wet solid and p_w is the vapour pressure of pure water at the same temperature. This expression also describes the relative humidity of an air-water vapour mixture. A plot of moisture content as a function of water activity, at a fixed temperature, is known as a sorption isotherm (Fig. 3.16). Isotherms may be prepared either by adsorption, i.e. placing a dry material in contact with atmospheres of increasing relative humidity, or by desorption, i.e. placing a wet material in contact with atmospheres of decreasing relative humidity. Thus two different curves may be obtained from the same material. This hysteresis effect is typical of many foods.

Food isotherms are often divided into three regions, denoted by A, B and C in Fig. 3.16. In region A, water molecules are strongly bound to specific sites on
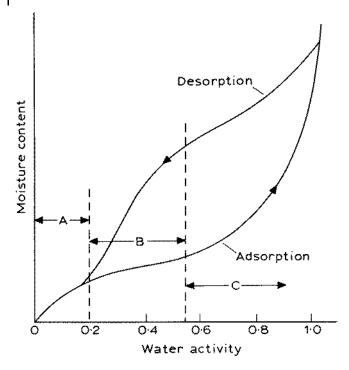
Fig. 3.16 Adsorption and desorption isotherms showing hysteresis; from [1].

the solid. Such sites may be hydroxyl groups in polysaccharides, carbonyl and amino groups in proteins and others on which water is held by hydrogen bonding, ion-dipole bonds or other strong interactions. This bound water is regarded as being unavailable as a solvent and hence does not contribute to microbial, enzymic or chemical activity. It is in the a_w range 0–0.35, and is known as the monomolecular or monolayer value. Monolayer moisture content in foods is typically in the range 0.05–0.11 (dwb). Above region A, water may still be bound to the solid but less strongly than in region A. Region B is said to consist of a multilayer region and region C is one in which structural and solution effects account for the lowering of the water vapour pressure. However, this distinction is dubious, as these effects can occur over the whole isotherm. Above region A, weak bonding, the influence of capillary forces in the solid structure and the presence of soluble solids in solution all have the effect of reducing the water vapour pressure of the wet solid. All these effects occur at a moisture content below 1.0 (dwb). Most foods exhibit a water vapour pressure close to that of pure water when the moisture content is above 1.0 (dwb). Temperature affects the sorption behaviour of foods. The amount of adsorbed water at any given value of a_w decreases with increase in temperature. Knowledge of the sorption characteristics of a food is useful in predicting its shelf life. In many cases the most stable moisture content corresponds to the monolayer value (Fig. 3.17).
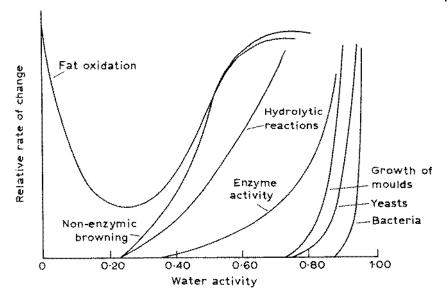
Fig. 3.17 Influence of water activity on the stability of foods; adapted from [70].

In many foods the rate of oxidation of fat is minimum in the a_w range 0.20–0.40. The rate of nonenzymic browning is highest in the a_w range 0.40–0.60. Below this range, reaction is slow due to the lack of mobility of the water. Hydrolytic reactions are also most rapid in the a_w range 0.40–0.70. The activity of enzymes starts to increase above the monolayer region and, at an a_w value above 0.80, it accelerates rapidly. Most moulds will not grow below an a_w value of 0.70, yeasts below 0.80. Most bacteria will not grow below an a_w of 0.90. Halophilic (salt loving) bacteria can grow at lower a_w. It is important to note that many other factors influence the activity of microorganisms including temperature, pH and availability of oxygen and nutrients and these may affect their behaviour at different a_w levels [1, 4, 5, 26, 70].

References

1 Brennan, J.G., Butters, J.R., Cowell, N.D., Lilly, A.E.V. **1990**, *Food Engineering Operations*, 3rd edn, Elsevier Applied Science, London.

2 Haywood, R.W. **1990**, *Thermodynamic Tables in SI (metric) Units*, 3rd edn, Cambridge University Press, Cambridge.

3 Hartel, R.A. **1992**, Evaporation and Freeze Concentration, in *Handbook of Food Engineering*, ed. D.R. Heldman, D.B. Lund, Marcel Dekker, New York.

4 Singh, R.P., Heldman, D.R. **1993**, *Introduction to Food Engineering, 2nd edn*, Academic Press, London.

5 Fellows, P. **2000**, *Food Processing Technology, 2nd edn*, Woodhead Publishing, Cambridge.

6 Burkart, A., Wiegand, B. **1987**, Quality and Economy in Evaporator Technology,

in *Food Technology International Europe*, ed. A. Turner, Sterling Publications International, London, pp. 35–39.

7 Pisecky, J. **1995**, Evaporation and Spray Drying, in *Handbook of Industrial Drying*, vol. 1, 2nd edn, ed. A. S. Mujumdar, Marcel Dekker, New York.

8 Walstra, P., Geurts, T. J., Jellema, A., van Boekel, M. A. J. S. **1999**, *Dairy Technology, Principles of Milk Properties and Processes,* Marcel Dekker, New York.

9 Knipschild M. E., Anderson G. G. **1994**, Drying of Milk and Milk Products, in *Modern Dairy Technology*, vol. 1, ed. R. K. Robinson, Chapman & Hall, London, pp. 159–254.

10 Early R. **1998**, Milk Concentrates and Milk Powders, in *The Technology of Dairy Products,* 2nd edn, ed. R. Early, Blackie Academic & Professional, Glasgow, pp. 228–300.

11 Lawley, R. **2001**, *LFRA Microbiology Handbook – Dairy Products*, 2nd edn, Leatherhead Food RA, Leatherhead.

12 Masters, K. **1991**, *Spray Drying Handbook*, 5th edn, Longman Scientific and Technical, New York.

13 Clarke, R. J. **1987**, Extraction, in *Coffee Technology*, vol. 2, ed. R. J. Clarke, R. Macrae, Elsevier Applied Science, London, pp. 109–145.

14 Clarke, R. J. **1987**, Drying, in *Coffee Technology*, vol. 2, ed. R. J. Clarke, R. Macrae, Elsevier Applied Science, London, pp. 147–199.

15 McGinnis, R. A. (ed.) **1971**, *Beet-Sugar Technology*, 2nd edn, Beet Sugar Development Foundation, Fort Collins.

16 Meade, G. P., Chen, J. C. P. **1977**, *Cane Sugar Handbook*, 10th edn, John Wiley & Sons, New York.

17 Perk, C. G. M. **1973**, *The Manufacture of Sugar from Sugarcane*, C. G. M. Perk, Durban.

19 Hugot, E. **1986**, *Handbook of Cane Sugar Engineering*, 3rd edn, Elsevier, Amsterdam.

20 Rao, M. A., Vitali, A. A. **1999**, Fruit Juice Concentration and Preservation, in *Handbook of Food Preservation*, ed. M. S. Rahman, Marcel Dekker, New York, pp. 217–258.

21 Nelson, P. E., Tressler, D. K. **1980**, *Fruit and Vegetable Juice Processing Technology*, 3rd edn, AVI Publishing Company, Westport.

22 Rebeck, H. M. **1990**, Processing of Citrus Juices, in *Production and Packaging of Non-Carbonated Fruit Juices and Fruit Beverages*, ed. P. R. Ashurst, Blackie Academic and Professional, Glasgow, pp. 221–252.

23 Kale, P. N., Adsule, P. G. **1995**, Citrus in *Handbook of Fruit Science and Technology*, ed. D. K. Salunkhe, S. S. Kadam, Marcel Dekker, New York, pp. 39–65.

24 Goose, P. G., Binsted, R. **1973**, *Tomato Paste and Other Tomato Products,* Food Trade Press, London.

25 Madhavi, D. L., Salunkhe, D. K. **1998**, Tomato in *Handbook of Vegetable Science and Technology*, Marcel Dekker, New York, pp. 171–201.

26 Brennan, J. G. **1994**, *Food Dehydration – a Dictionary and Guide*, Butterworth-Heinemann, Oxford.

27 Okos, M. R., Narsimhan, G., Singh, R. K., Weitnauer A. C. **1992**, Food Dehydration, in *Handbook of Food Engineering*, ed. D. R. Heldman, D. B. Lund, Marcel Dekker, New York, pp. 437–562.

28 Mujumdar, A. S. **1997**, Drying Fundamentals, in *Industrial Drying of Foods*, ed. C. G. J. Baker, Blackie Academic & Professional, London, pp. 7–30.

29 Sokhansanj, S., Jayes, D. S. **1995**, Drying of Foodstuffs, in *Handbook of Industrial Drying*, 2nd edn, ed. A. S. Mujumdar, Marcel Dekker, New York, pp. 589–625.

30 Barbosa-Canovas, G. V., Vega-Mercado, H. **1996**, *Dehydration of Foods*, Chapman & Hall, New York.

31 Toledo, R. T. **1991**, *Fundamentals of Food Process Engineering*, 2nd edn, Van Nostrand Reinhold, New York.

32 Wang, N., Brennan, J. G. **1994**, A Mathematical Model of Simultaneous Heat and Moisture Transfer During Drying of Potato, *Journal of Food Engineering*, 24, 47–60.

33 Brown, A. H., Van Arsdel, W. B., Lowe, E., Morgan Jr, A. I. **1973**, Air Drying and Drum Drying, in *Food Dehydration*, vol. 1, 2nd edn, ed. W. B. Van Arsdel,

M. J. Copley, A. I. Morgan Jr., AVI Publishing Company, Westport, pp. 82–160.

34 Greensmith, M. **1998**, *Practical Dehydration*, 2nd edn, Woodhead Publishing, Cambridge.

35 Sturgeon, L. F. **1995**, Conveyor Dryers, in *Handbook of Industrial Drying*, vol. 1, 2nd edn, ed. A. S. Mujumdar, Marcel Dekker, New York, pp. 525–537.

36 Hovmand, S. **1995**, Fluidised Bed Drying, in *Handbook of Industrial Drying*, vol. 1, 2nd edn, ed. A. S. Mujumdar, Marcel Dekker, New York, pp. 195–248.

37 Pallai, E., Szentmarjay, T., Mujumdar, A. S. **1995**, Spouted Bed Drying, in *Handbook of Industrial Drying*, vol. 1, 2nd edn, ed. A. S. Mujumdar, Marcel Dekker, New York, pp. 453–488.

38 Brennan, R. J. G. **2003**, Fluidized Bed Drying, in *Encyclopedia of Food Science and Nutrition*, 2nd edn, ed. B. Caballero, L. C. Trugo, P. M. Finglas, Academic Press, London, pp. 1922–1929.

39 Bahu, R. E. **1997**, Fluidized Bed Dryers, in *Industrial Drying of Foods*, ed. C. G. J. Baker, Blackie Academic and Professional, London, pp. 65–88.

40 Kisakurek, B. **1995**, Flash Drying, in *Handbook of Industrial Drying*, vol. 1, 2nd edn, ed. A. S. Mujumdar, Marcel Dekker, New York, pp. 503–524.

41 Kelly, J. J. **1995**, Rotary Drying, in *Handbook of Industrial Drying*, vol. 1, 2nd edn, ed. A. S. Mujumdar, Marcel Dekker, New York, pp. 161–184.

42 Barr, D. J., Baker, C. G. J. **1997**, Specialized Drying Systems, in *Industrial Drying of Foods*, ed. C. G. J. Baker, Blackie Academic and Professional, London, pp. 179– 209.

43 Oakley, D. **1997**, Contact Dryers, in *Industrial Drying of Foods*, ed. C. G. J. Baker, Blackie Academic and Professional, London, pp. 115–133.

44 Anon **1992**, Dryers: Technology and Engineering, in *Encyclopedia of Food Science and Technology*, vol. 1, ed. Y. H. Hui, John Wiley & Sons, Chichester, pp. 619–656.

45 Mellor, J. D. **1978**, *Fundamentals of Freeze-Drying*, Academic Press, New York.

46 Athanasios, I., Liapis, I., Bruttini, R. **1995**, Freeze Drying, in *Handbook of Industrial Drying*, vol. 1, 2nd edn, ed. A. S.

Mujumdar, Marcel Dekker, New York, pp. 309–344.

47 Snowman, J. W. **1997**, Freeze Dryers, in *Industrial Drying of Foods*, ed. C. G. J. Baker, Blackie Academic and Professional, London, pp. 134–155.

48 Dalgleish, J. McN. **1990**, *Freeze-Drying for the Food Industries*, Elsevier Applied Science, London.

49 Lorentzen, J. **1975**, Industrial Freeze Drying Plants for Food, in *Freeze Drying and Advanced Food Technology*, ed. S. A. Goldblith, L. Rey, H. H. Rothmayr, Academic Press, London, pp. 429–443.

50 Ratti, C., Mujumdar, A. S. **1995**, Infrared Drying, in *Handbook of Industrial Drying*, vol. 1, 2nd edn, ed. A. S. Mujumdar, Marcel Dekker, New York, pp. 567–588.

51 Edgar, R. H. **2001**, Consumer, Commercial, and Industrial Microwave Ovens and Heating Systems, in *Handbook of Microwave Technology for Food Applications*, ed. A. K. Datta, R. C. Anantheswaran, Marcel Dekker, New York, pp. 215–277.

52 Schiffmann, R. F. **1995**, Microwave and dielectric drying, in *Handbook of Industrial Drying*, vol. 1, 2nd edn, ed. A. S. Mujumdar, Marcel Dekker, New York, pp. 345–372.

53 Jones, P. L., Rowley, A. T. **1997**, Dielectric Dryers, in *Industrial Drying of Foods*, ed. C. G. J. Baker, Blackie Academic & Professional, London, pp. 156–178.

54 Schiffmann, R. F. **2001**, Microwave Processes for the Food Industry, in *Handbook of Microwave Technology for Food Applications*, ed. A. K. Datta, R. C. Anantheswaran, Marcel Dekker, New York, pp. 215–299.

55 Lewicki, P. P., Das Gupta, D. K. **1995**, Osmotic Dehydration of Fruits and Vegetables, in *Handbook of Industrial Drying*, vol. 1, 2nd edn, ed. A. S. Mujumdar, Marcel Dekker, New York, pp. 691–713.

56 Bolin, H. R., Salunkhe, D. K. **1982**, Fluid Dehydration by Solar Energy, *CRC Critical Reviews in Food Science and Technology*, 16, 327–354.

57 Brennan, J. G. **1989**, Dehydration of Foods, in *Water and Food Quality*, ed. T. M. Hardman, Elsevier Applied Science, London, pp. 33–70.

58 Imrie, L. **1997**, Solar Dryers, in *Industrial Drying of Foods*, ed. C. G. J. Baker, Blackie Academic & Professional, London, pp. 210–241.

59 Masters, K **1997**, Spray Dryers, in *Industrial Drying of Foods*, ed. C. G. J. Baker, Blackie Academic & Professional, London, pp. 90–114.

60 Brennan, J. G. **2003**, Spray Drying, in *Encyclopedia of Food Science and Nutrition*, 2nd edn, ed. B. Caballero, L. C. Trugo, P. M. Finglas, Academic Press, London, pp. 1929– 1938.

61 Filkova, I., Mujumdar, S. S. **1995**, Industrial Spray Drying Systems, in *Handbook of Industrial Drying*, vol. 1, 2nd edn, ed. A. S. Mujumdar, Marcel Dekker, New York, pp. 263–308.

62 Moore, J. G. **1995**, Drum Dryers, in *Handbook of Industrial Drying*, vol. 1, 2nd edn, ed. A. S. Mujumdar, Marcel Dekker, New York, pp. 249–262.

63 Salumkhe, D. K., Bolin, H. R., Reddy, N. R. **1991**, *Storage, Processing and Nutritional Quality of Fruits and Vegetables*, vol. 2, 2nd edn, CRC Press, Boca Raton.

64 Jayaraman, K. S., Das Gupta, D. K. **1995**, Drying of Fruits and Vegetables, in *Handbook of Industrial Drying*, vol. 1, 2nd edn, ed. A. S. Mujumdar, Marcel Dekker, New York, pp. 643–690.

65 Luh, B. S., Woodruff, J. G. **1975**, *Commercial Vegetable Processing*, AVI Publishing Company, Westport.

66 Feinberg, B. **1973**, Vegetables, in *Food Dehydration*, vol. 2, 2nd edn, ed. W. B. Van Arsdel, M. J. Copley, A. I. Morgan, AVI Publishing Company, Westport, pp. 1–82.

67 Talburt, W. F., Smith, O. **1975**, *Potato Processing*, 3rd edn, AVI Publishing Company, Westport.

68 Woodroof, J. G., Luh, B. S. **1975**, *Commercial Fruit Processing*, AVI Publishing Company, Westport.

69 Nury, F. S., Brekke, J. E., Bolin, H. R. **1973**, Fruits, in *Food Dehydration*, vol. 2, 2nd edn, ed. W. B. Van Arsdel, M. J. Copley, A. I. Morgan, AVI Publishing Company, Westport, pp. 158–198.

70 Labuza, T. P. **1977**, The Properties of Water in Relationship to Water Binding in Foods. A Review, *Journal of Food Processing and Preservation*, 1, 176–190.

71 Aitken, A., Mackies, I. M., Merritt, J. H., Windsor, M. L. **1981**, *Fish Processing and Handling*, 2nd edn, Her Majesty's Stationary Office, Edinburgh.

72 Windsor, M., Barlow, S. **1981**, *Introduction to Fishery By-products*, Fishing News Books, Farnham.