B. Heat processing using hot air

15

Dehydration

Dehydration (or drying) is defined as 'the application of heat under controlled conditions to remove the majority of the water normally present in a food by evaporation' (or in the case of freeze drying (Chapter 22) by sublimation). This definition excludes other unit operations which remove water from foods (for example mechanical separations and membrane concentration (Chapter 6), evaporation (Chapter 13) and baking (Chapter 16)) as these normally remove much less water than dehydration.

The main purpose of dehydration is to extend the shelf life of foods by a reduction in water activity (Chapter 1). This inhibits microbial growth and enzyme activity, but the processing temperature is usually insufficient to cause their inactivation. Therefore any increase in moisture content during storage, for example due to faulty packaging, will result in rapid spoilage. The reduction in weight and bulk of food reduces transport and storage costs. For some types of food, dehydration provides a convenient product for the consumer or more easily handled ingredients for food processors. Drying causes deterioration of both the eating quality and the nutritional value of the food. The design and operation of dehydration equipment aim to minimise these changes by selection of appropriate drying conditions for individual foods. Examples of commercially important dried foods are coffee, milk, raisins, sultanas and other fruits, pasta, flours (including bakery mixes), beans, pulses, nuts, breakfast cereals, tea and spices. Examples of important dried ingredients that are used by manufacturers include egg powder, flavourings and colourings, lactose, sucrose or fructose powder, enzymes and yeasts.

15.1 Theory

Dehydration involves the simultaneous application of heat and removal of moisture from foods.[1] Factors that control the rates of heat and mass transfer are described in Chapter 1.

1. Except for osmotic dehydration, in which foods are soaked in concentrated solutions of sugar or salt to remove water using the difference in osmotic pressure as the driving force for moisture transfer. This method is used to produce 'crystallised' or sugared fruits and with salt it is used in some countries as a pre-treatment for fish and vegetables before drying. Further details are given by Torreggiani (1993).

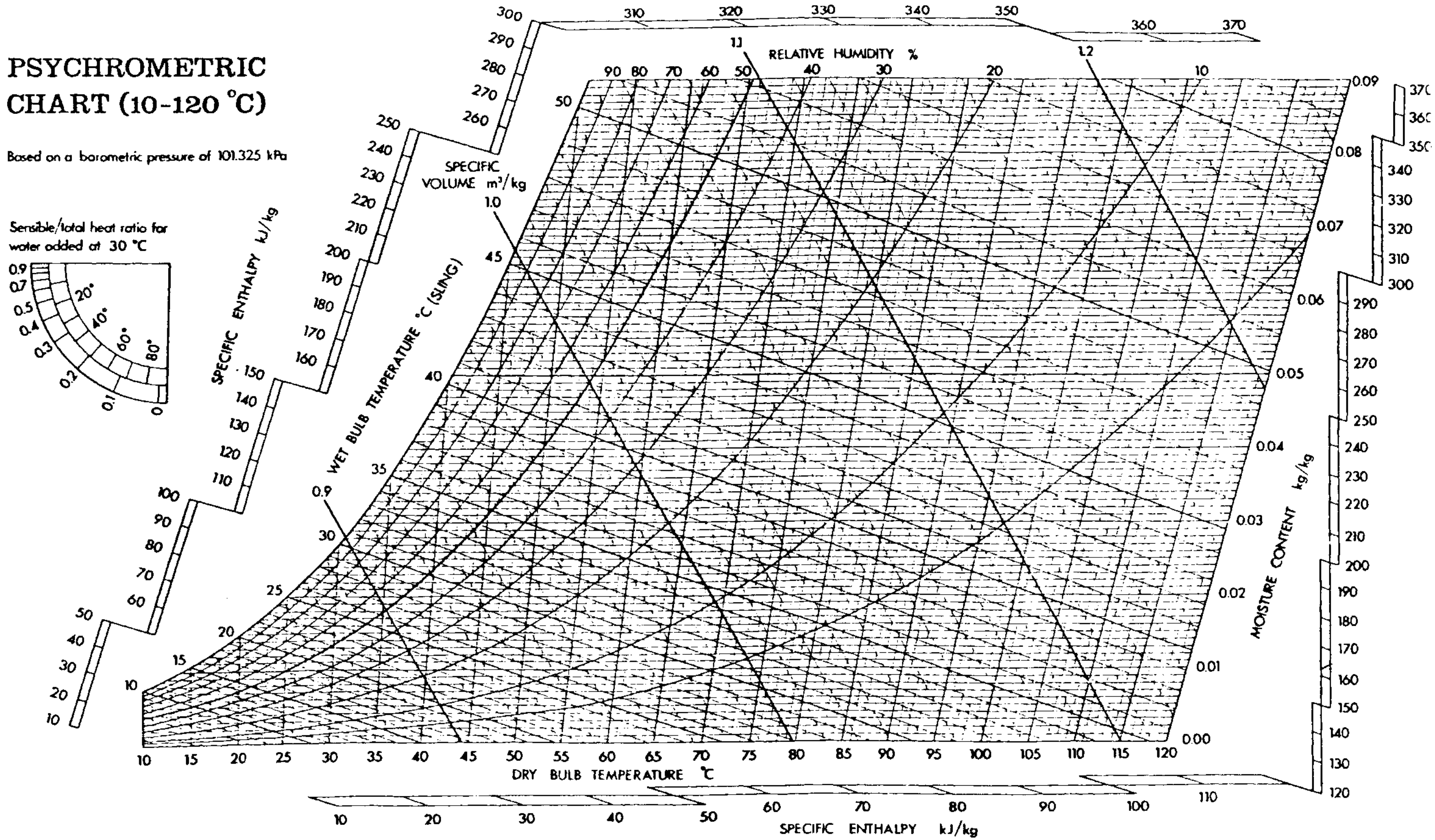

Fig. 15.1 Psychrometric chart (10–120°C) based on barometric pressure of 101.325 kPa. (Courtesy of Chartered Institution of Building Service Engineers.)

Dehydration by heated air or heated surfaces is described in this chapter. Microwave, dielectric and radiant driers are described in Chapter 18 and freeze drying is described in Chapter 22.

There are a large number of factors that control the rate at which foods dry, which can be grouped into the following categories:

- those related to the processing conditions
- those related to the nature of the food
- those related to the drier design.

The effects of processing conditions and type of food are described below and differences in drier design are summarised in Section 15.2.

15.1.1 Drying using heated air

Psychrometrics

There are three inter-related factors that control the capacity of air to remove moisture from a food:

1. the amount of water vapour already carried by the air
2. the air temperature
3. the amount of air that passes over the food.

The amount of water vapour in air is expressed as either *absolute humidity*[2] (termed *moisture content* in Fig. 15.1) or *relative humidity*[3] (RH) (in per cent). Psychrometry is the study of inter-related properties of air–water vapour systems. These properties are conveniently represented on a *psychrometric chart* (Fig. 15.1).

Heat from drying air is absorbed by food and provides the latent heat needed to evaporate water from the surface. The temperature of the air, measured by a thermometer bulb, is termed the *dry-bulb* temperature. If the thermometer bulb is surrounded by a wet cloth, heat is removed by evaporation of water from the cloth and the temperature falls. This lower temperature is called the *wet-bulb temperature*. The difference between the two temperatures is used to find the relative humidity of air on the psychrometric chart. An increase in air temperature, or reduction in RH, causes water to evaporate more rapidly from a wet surface and therefore produces a greater fall in temperature. The *dew point* is the temperature at which air becomes saturated with moisture (100% RH) and any further cooling from this point results in condensation of the water from the air. Adiabatic cooling lines are the parallel straight lines sloping across the chart, which show how absolute humidity decreases as the air temperature increases.

Mechanism of drying

The third factor that controls the rate of drying, in addition to air temperature and humidity, is the air velocity. When hot air is blown over a wet food, water vapour diffuses through a boundary film of air surrounding the food and is carried away by the moving air (Fig. 15.2). A water vapour pressure gradient is established from the moist interior of the food to the dry air. This gradient provides the ‘driving force’ for water removal from the food.

2. Equals the mass of water vapour per unit mass of dry air (in kilograms per kilogram).
3. Defined as ‘the ratio of the partial pressure of water vapour in the air to the pressure of saturated water vapour at the same temperature, multiplied by 100’.

Sample problems 15.1

Using the psychometric chart (Fig 15.1), calculate the following

1. the absolute humidity of air which has 50% RH and a dry-bulb temperature of 60ºC;
2. the wet-bulb temperature under these conditions;
3. the RH of air having a wet-bulb temperature of 45ºC and a dry-bulb temperature of 75ºC;
4. the dew point of air cooled adiabatically from a dry-bulb temperature of 55ºC and 30% RH;
5. the change in RH of air with a wet-bulb temperature of 39ºC, heated from a dry-bulb temperature of 50ºC to a dry-bulb temperature of 86ºC;
6. the change in RH of air with a wet-bulb temperature of 35ºC, cooled adiabatically from a dry-bulb temperature of 70ºC to 40ºC.

Solutions to Sample problems 15.1

1. 0.068 kg per kilogram of dry air (find the intersection of the 60ºC and 50% RH lines, and then follow the chart horizontally right to read off the absolute humidity);
2. 47.5ºC (from the intersection of the 60ºC and 50% RH lines, extrapolate left parallel to the wet-bulb lines to read off the wet-bulb temperature);
3. 20% (find the intersection of the 45ºC and 75ºC lines and follow the sloping RH line upwards to read off the % RH);
4. 36ºC (find the intersection of the 55ºC and 30% RH lines and follow the wet-bulb line left until the RH reaches 100%);
5. 50–10% (find the intersection of the 39ºC wet-bulb and the 50ºC dry-bulb temperatures, and follow the horizontal line to the intersection with the 86ºC dry-bulb line; read the sloping RH line at each intersection (this represents the changes that take place when air is heated prior to being blown over food));
6. 10–70% (find the intersection of the 35ºC wet-bulb and the 70ºC dry-bulb temperatures, and follow the wet-bulb line left until the intersection with the 40ºC dry-bulb line; read sloping RH line at each intersection (this represents the changes taking place as the air is used to dry food; the air is cooled and becomes more humid as it picks up moisture from the food)).

The boundary film acts as a barrier to both heat transfer and water vapour removal during drying. The thickness of the film is determined primarily by the air velocity; if the velocity is low, the boundary film is thicker and this reduces both the heat transfer coefficient and the rate of removal of water vapour. Water vapour leaves the surface of the food and increases the humidity of the surrounding air, to cause a reduction in the water vapour pressure gradient and hence the rate of drying. Therefore the faster the air, the thinner the boundary film and hence the faster the rate of drying. In summary, the three characteristics of air that are necessary for successful drying when the food is moist are:

1. a moderately high dry-bulb temperature
2. a low RH
3. a high air velocity.

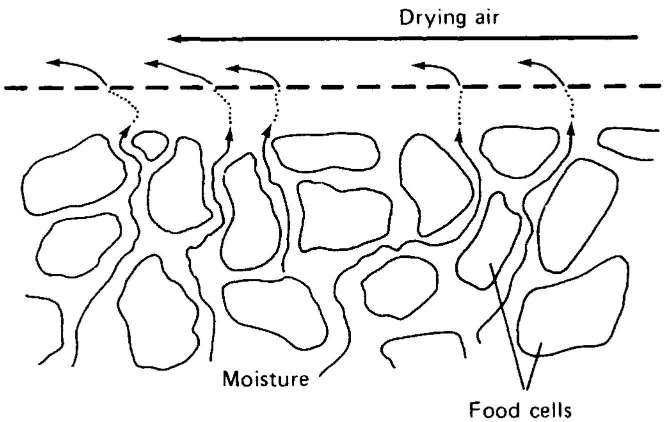

Fig. 15.2 Movement of moisture during drying.

Constant-rate period

When food is placed into a drier, there is a short initial settling down period as the surface heats up to the wet-bulb temperature (A–B in Fig. 15.3(a)). Drying then commences and, provided water moves from the interior of the food at the same rate as it evaporates from the surface, the surface remains wet. This is known as the *constant-rate period* and continues until a certain *critical moisture content* is reached (B–C in Fig. 15.3(a) and (b)). The surface temperature of the food remains close to the wet-bulb temperature of the drying air until the end of the constant-rate period, due to the cooling effect of the evaporating water. In practice, different areas of the food surface dry out at different rates and, overall, the rate of drying declines gradually towards the end of the 'constant'-rate period.

Falling-rate period

When the moisture content of the food falls below the critical moisture content, the rate of drying slowly decreases until it approaches zero at the *equilibrium moisture content* (that is the food comes into equilibrium with the drying air). This is known as the *falling-rate period*. Non-hygroscopic foods (Chapter 1) have a single falling-rate period (C–D in Fig. 15.3(a) and (b)), whereas hygroscopic foods have two or more periods. In the first period, the plane of evaporation moves from the surface to inside the food, and water vapour diffuses through the dry solids to the drying air. The second period occurs when the partial pressure of water vapour is below the saturated vapour pressure, and drying is by desorption.

During the falling-rate period(s), the rate of water movement from the interior to the surface falls below the rate at which water evaporates to the surrounding air, and the surface therefore dries out (assuming that the temperature, humidity and air velocity are unchanged). If the same amount of heat is supplied by the air, the surface temperature rises until it reaches the dry-bulb temperature of the drying air. Most heat damage to food can therefore occur in the falling-rate period and the air temperature is controlled to balance the rate of drying and extent of heat damage. Most heat transfer is by convection from the drying air to the surface of the food, but there may also be heat transfer by radiation. If the food is dried in solid trays, there will also be conduction through the tray to the food. Calculation of heat transfer is therefore often very complex in drying systems.

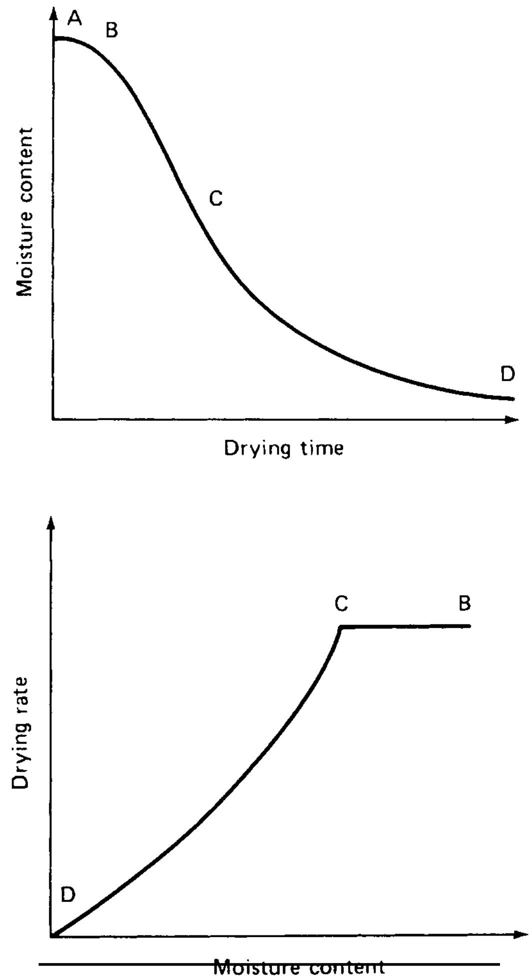

Fig. 15.3 (a) and (b) Drying curves. The temperature and humidity of the drying air are constant and all heat is supplied to the food surface by convection.

The falling-rate period is usually the longest part of a drying operation and, in some foods (for example grain drying) the initial moisture content is below the critical moisture content and the falling-rate period is the only part of the drying curve to be observed. During the falling-rate period, the factors that control the rate of drying change. Initially the important factors are similar to those in the constant-rate period, but gradually the rate of water movement (mass transfer) becomes the controlling factor. Water moves from the interior of the food to the surface by the following mechanisms:

- liquid movement by capillary forces, particularly in porous foods
- diffusion of liquids, caused by differences in the concentration of solutes at the surface and in the interior of the food
- diffusion of liquids which are adsorbed in layers at the surfaces of solid components of the food
- water vapour diffusion in air spaces within the food caused by vapour pressure gradients.

During drying, one or more of the above mechanisms may be taking place and their relative importance can change as drying proceeds. For example, in the first part of the falling-rate period, liquid diffusion may be the main mechanism, whereas in later parts, vapour diffusion may be more important. It is therefore sometimes difficult to predict drying times in the falling-rate period. The mechanisms that operate depend mostly on the temperature of the air and the size of the food pieces. They are unaffected by the RH of the air (except in determining the equilibrium moisture content) and the velocity of the air. The size of food pieces has an important effect on the drying rate in both the constant-rate and falling-rate periods. In the constant-rate period, smaller pieces have a larger surface area available for evaporation whereas in the falling-rate period, smaller pieces have a shorter distance for moisture to travel through the food. Calculation of drying rates is further complicated if foods shrink during the falling-rate period.

Other factors which influence the rate of drying include:

- The *composition and structure* of the food has an influence on the mechanism of moisture removal. For example, the orientation of fibres in vegetables (e.g. celery) and protein strands in meat allow more rapid moisture movement along their length than across the structure. Similarly, moisture is removed more easily from intercellular spaces than from within cells. Rupturing cells by blanching or size reduction increases the rate of drying but may adversely affect the texture of the rehydrated product. Additionally, high concentrations of solutes such as sugars, salts, gums, starches, etc., increase the viscosity and lower the water activity (Chapter 1) and thus reduce the rate of moisture movement.
- The *amount of food* placed into a drier in relation to its capacity (in a given drier, faster drying is achieved with smaller quantities of food).

In practice, the rate at which foods dry may differ from the idealised drying curves described above for these reasons.

Calculation of drying rate

In commercial operation, it is necessary to estimate how quickly a food will dry in a particular drier in order to calculate the amount of production that can be achieved per hour or per day. Where simple drying behaviour is found and data on critical and equilibrium moisture contents or thermal properties of foods are known, drying times can be estimated by calculation. However, this data is not available for many foods and results of pilot scale drying trials are used to estimate drying times.

The moisture content of a food may be expressed on a wet weight basis[4] or a dry weight basis.[5] In the calculations described below, a dry weight basis is used throughout.

The rate of heat transfer is found using:

$$Q = h_S A\,(\theta_a - \theta_s) \qquad \boxed{15.1}$$

The rate of mass transfer is found using:

$$-m_c = K_g A (H_s - H_a) \qquad \boxed{15.2}$$

4. Mass of water per unit mass of wet food.
5. Mass of water per unit mass of dry solids in the food.

Since, during the constant-rate period, an equilibrium exists between the rate of heat transfer to the food and the rate of mass transfer in the form of moisture loss from the food, these rates are related by:

$$-m_c = \frac{h_c A}{\lambda}(\theta_a - \theta_s) \tag{15.3}$$

where Q ($J\,s^{-1}$) = rate of heat transfer, h_c ($W\,m^{-2}\,K^{-1}$) = surface heat transfer coefficient for convective heating, A (m^2) = surface area available for drying, θ_a (ºC) = average dry bulb temperature of drying air, θ_s (ºC) = average wet bulb temperature of drying air, m_c ($kg\,s^{-1}$) = change of mass with time (drying rate), K_g ($kg\,m^{-2}\,s^{-1}$) = mass transfer coefficient, H_s (kg moisture per kg dry air) = humidity at the surface of the food (saturation humidity), H_a (kg moisture per kg dry air) = humidity of air and λ ($J\,kg^{-1}$) = latent heat of vaporisation at the wet bulb temperature.

The surface heat transfer coefficient (h_c) is related to the mass flow rate of air using the following equations: for parallel air flow:

$$h_c = 14.3G^{0.8} \tag{15.4}$$

and for perpendicular air flow:

$$h_c = 24.2G^{0.37} \tag{15.5}$$

where G ($kg\,m^{-2}\,s^{-1}$) = mass flow rate of air per unit area.

For a tray of food, in which water evaporates only from the upper surface, the drying time is found using:

$$-m_c = \frac{h_c}{\rho \lambda x}(\theta_a - \theta_s) \tag{15.6}$$

where ρ ($kg\,m^{-3}$) = bulk density of food and x (m) = thickness of the bed of food. The drying time in the constant rate period is found using:

$$t = \frac{\rho \lambda x (M_i - M_c)}{h_c(\theta_a - \theta_s)} \tag{15.7}$$

where t (s) is the drying time, M_i (kg per kg of dry solids) = initial moisture content, and M_c (kg per kg of dry solids) = critical moisture content.

For water evaporating from a spherical droplet in a spray drier (Section 15.2.1), the drying time is found using:

$$t = \frac{r^2 \rho_1 \lambda}{3h_c(\theta_A - \theta_S)}\,\frac{M_i - M_f}{1 + M_i} \tag{15.8}$$

where ρ ($kg\,m^{-3}$) = density of the liquid, r (m) = radius of the droplet, M_f (kg per kg of dry solids) = final moisture content.

The following equation is used to calculate the drying time from the start of the falling-rate period to the equilibrium moisture content using a number of assumptions concerning, for example, the nature of moisture movement and the absence of shrinkage of the food:

$$t = \frac{\rho x (M_c - M_e)}{K_g(P_s - P_a)} \ln\left(\frac{M_c - M_e}{M - M_e}\right) \tag{15.9}$$

where M_e (kg per kg of dry solids) = equilibrium moisture content, M (kg per kg of dry solids) = moisture content at time t from the start of the falling-rate period, P_s (Torr) =

saturated vapour pressure at the wet bulb temperature and P_a (Torr) = partial water vapour pressure.

Derivations of the above equations are described by Karel (1975), Brennan *et al.* (1990), Barbosa-Canovas (1996) and Hall (1979).

Sample problem 15.2

A conveyor drier (Section 15.2.1) is required to dry peas from an initial moisture content of 78% to 16% moisture (wet-weight basis), in a bed 10 cm deep which has a voidage of 0.4. Air at 85ºC with a relative humidity of 10% is blown perpendicularly through the bed at 0.9 m s^{-1}. The drier belt measures 0.75 m wide and 4 m long. Assuming that drying takes place from the entire surface of the peas and there is no shrinkage, calculate the drying time and energy consumption in both the constant- and the falling-rate periods. (Additional data: the equilibrium moisture content of the peas is 9%, the critical moisture content 300% (dry-weight basis), the average diameter 6 mm, the bulk density 610 kg m^{-3}, the latent heat of evaporation 2300 kJ kg^{-1}, the saturated water vapour pressure at wet-bulb temperature 61.5 Torr and the mass transfer coefficient 0.015 kg m^{-2} s^{-1}.)

Solution to Sample problem 15.2

In the constant-rate period, from equation (15.5),

$$h_c = 24.2(0.9)^{0.37}$$
$$= 23.3\ \mathrm{W\,m^{-2\circ}K^{-1}}$$

From Fig. 15.1 for θ_a = 85ºC and RH = 10%,

$$\theta_s = 42^\circ\mathrm{C}$$

To find the area of the peas,

$$\text{volume of a sphere} = \frac{4}{3}\pi r^3$$
$$= 4/3 \times 3.142(0.003)^3$$
$$= 339 \times 10^{-9}\ \mathrm{m^3}$$

$$\text{volume of the bed} = 0.75 \times 4 \times 0.1$$
$$= 0.3\ \mathrm{m^3}$$

$$\text{volume of peas in the bed} = 0.3(1 - 0.4)$$
$$= 0.18\ \mathrm{m^3}$$

$$\text{number of peas} = \frac{\text{volume of peas in bed}}{\text{volume each pea}}$$
$$\equiv \frac{0.18}{339 \times 10^{-9}}$$
$$\equiv 5.31 \times 10^5$$

$$\text{area of sphere} = 4\pi r^2$$
$$= 4 \times 3.142(0.003)^2$$
$$= 113 \times 10^{-6}\ \mathrm{m^2}$$

and

$$\text{total area of peas} = 5.31 \times 10^5 \times 113 \times 10^{-6}$$
$$= 60\,\text{m}^2$$

From equation (15.3),

$$\text{drying rate} = \frac{23.3 \times 60}{2.3 \times 10^6}(85 - 42)$$
$$= 0.026\,\text{kg s}^{-1}$$

From a mass balance,

$$\text{volume of bed} = 0.03\,\text{m}^3$$
$$\text{bulk density} = 610\,\text{kg m}^{-3}$$

Therefore,

$$\text{mass of peas} = 0.3 \times 610$$
$$= 183\,\text{kg}$$

$$\text{initial solids content} = 183 \times 0.22$$
$$= 40.26\,\text{kg}$$

Therefore,

$$\text{initial mass water} = 183 - 24.15$$
$$= 158.85\,\text{kg}$$

After constant-rate period, solids remain constant and

$$\text{mass of water} = 96.6 - 24.15$$
$$= 72.45\,\text{kg}$$

Therefore,

$$(158.85 - 72.45) = 86.4\,\text{kg water lost}$$

at a rate of $0.026\,\text{kg s}^{-1}$

$$\text{Drying time} = \frac{86.4}{0.026} = 3323 = 55.4\,\text{min}$$

Therefore,

$$\text{energy required} = 0.026 \times 2.3 \times 10^6$$
$$= 6 \times 10^4\,\text{J s}^{-1}$$
$$= 60\,\text{kW}$$

In the falling-rate period, from Section 15.1.1,

$$\text{RH} = \frac{P_A}{P_0} \times 100$$

$$10 = \frac{P}{61.5} \times 100$$

Therefore,

$$P = 6.15\,\text{Torr}$$

The moisture values are

$$M_c = \frac{75}{25} = 3$$

$$M_f = \frac{16}{84} = 0.19$$

$$M_e = \frac{9}{91} = 0.099$$

From equation (15.9),

$$t = \frac{(3 - 0.099)610 \times 0.1}{0.015\,(61.5 - 6.15)} \ln\left(\frac{3 - 0.099}{0.19 - 0.099}\right)$$
$$= 737.7\,\text{s}$$
$$= 12.3\,\text{min}$$

From a mass balance, at the critical moisture content, 96.6 kg contains 25% solids = 24.16 kg. After drying in the falling-rate period, 84% solids = 24.16 kg. Therefore,

$$\text{total mass} = \frac{100}{84} \times 24.16$$
$$= 28.8\,\text{kg}$$

and

$$\text{mass loss} = 96.6 - 28.8$$
$$= 67.8\,\text{kg}$$

Thus,

$$\text{average drying rate} = \frac{67.8}{737.7}$$
$$= 0.092\,\text{kg s}^{-1}$$

and

$$\text{average energy required} = 0.092 \times 2.3 \times 10^6$$
$$= 2.1 \times 10^5\,\text{J s}^{-1}$$
$$= 210\,\text{kW}$$

15.1.2 Drying using heated surfaces

Slurries of food are deposited on a heated steel drum. Heat is conducted from the hot surface, through the food, and moisture is evaporated from the exposed surface. The main resistance to heat transfer is the thermal conductivity of the food (Chapter 1, Table 1.5). Additional resistance arises if the partly dried food lifts off the hot surface, forming a barrier layer of air between the food and the drum. Knowledge of the rheological properties of the food is therefore necessary to determine the thickness of the layer and the way in which it is applied to the heated surface. Equation 1.22 (in Chapter 1) is used to calculate drying rate.

Sample problem 15.3

A single-drum drier (Section 15.2.2) 0.7 m in diameter and 0.85 m long operates at 150ºC and is fitted with a doctor blade to remove food after $\frac{3}{4}$ rev. It is used to dry a 0.6 mm layer of 20% w/w solution of gelatin, pre-heated to 100ºC, at atmospheric pressure. Calculate the speed of the drum required to produce a product with a moisture content of 4 kg of solids per kilogram of water. (Additional data: the density of gelatin feed is 1020 kg m^{-3} and the overall heat transfer coefficient 1200 W m^{-2} K^{-1}; assume that the critical moisture content of the gelatin is 450% (dry weight basis).)

Solution to Sample problem 15.3

First,

$$\begin{aligned}\text{drum area} &= \pi DL \\ &= 3.142 \times 0.7 \times 0.85 \\ &= 1.87\,\text{m}^2\end{aligned}$$

Therefore

$$\begin{aligned}\text{mass of food on the drum} &= (1.87 \times 0.75)\, 0.0006 \times 1020 \\ &= 0.86\,\text{kg}\end{aligned}$$

From a mass balance (initially the food contains 80% moisture and 20% solids),

$$\begin{aligned}\text{mass of solids} &= 0.86 \times 0.2 \\ &= 0.172\,\text{kg}\end{aligned}$$

After drying, 80% solids = 0.172 kg. Therefore

$$\begin{aligned}\text{mass of dried food} &= \frac{100}{80} \times 0.172 \\ &= 0.215\,\text{kg}\end{aligned}$$

$$\begin{aligned}\text{mass loss} &= 0.86 - 0.215 \\ &= 0.645\,\text{kg}\end{aligned}$$

From equation (15.1)

$$\begin{aligned}Q &= 1200 \times 1.87\,(150 - 100) \\ &= 1.12 \times 10^5\,\text{J s}^{-1}\end{aligned}$$

$$\begin{aligned}\text{drying rate} &= \frac{1.12 \times 10^5}{2.257 \times 10^6}\,\text{kg s}^{-1} \\ &= 0.05\,\text{kg s}^{-1}\end{aligned}$$

and

$$\begin{aligned}\text{residence time required} &= \frac{0.645}{0.05} \\ &= 13\,\text{s.}\end{aligned}$$

As only three-quarters of the drum surface is used, 1 rev should take (100/75) $\times$ 13 = 17.3 s. Therefore speed = 3.5 rev min^{-1}.

15.2 Equipment

15.2.1 Hot-air driers

The cost of fuel for heating air is the main economic factor affecting drying operations and commercial driers have a number of features that are designed to reduce heat losses or save energy. Examples from Brennan (1992) include:

- insulation of cabinets and ducting
- recirculation of exhaust air through the drying chamber, provided a high outlet temperature can be tolerated by the product and the reduction in evaporative capacity is acceptable
- recovering heat from the exhaust air to heat incoming air using heat exchangers or thermal wheels (Chapter 1) or fore-warming the feed material
- use of direct flame heating by natural gas and low nitrogen oxide burners to reduce product contamination by the products of combustion
- drying in two stages (e.g fluidised beds followed by bin drying or spray drying followed by fluidised bed drying)
- pre-concentrating liquid foods to the highest solids content possible using multiple effect evaporation (Chapter 13). Energy use per unit mass of water removed in evaporators can be several orders of magnitude less than that required for dehydration
- automatic control of air humidity by computer control.

Further details are given by Zagorzycki (1983), Masters (1972), Grikitis (1986), Heldman and Hartel (1997) and Driscoll (1995) (see also Chapter 2).

The criteria for selection of drying equipment and potential applications are described in Table 15.1. The relative costs of different drying methods from data by Sapakie and Renshaw (1984) are as follows: forced-air drying, 198; fluidised-bed drying, 315; drum drying, 327; continuous vacuum drying, 1840; freeze drying, 3528. Tragardh (1981) compared relative energy consumption (in kilowatt hours per kilogram of water removed) as follows: roller drying, 1.25; pneumatic drying, 1.8; spray drying, 2.5; fluidised-bed drying, 3.5.

Bin driers

Bin driers are large, cylindrical or rectangular containers fitted with a mesh base. Hot air passes up through a bed of food at relatively low velocities (for example $0.5\,m\,s^{-1}$ per square metre of bin area). They have a high capacity and low capital and running costs, and are mainly used for 'finishing' (to 3–6% moisture content) after initial drying in other types of driers. They improve the operating capacity of initial driers by removing the food when it is in the falling-rate period, when moisture removal is most time consuming. The deep bed of food permits variations in moisture content to be equalised and acts as a store to smooth out fluctuations in the product flow between drying and packaging operations. The driers may be several metres high and it is therefore important that foods are sufficiently strong to withstand compression and thus retain spaces between the pieces to permit the passage of hot air through the bed (Table 15.1).

Cabinet driers (tray driers)

These consist of an insulated cabinet fitted with shallow mesh or perforated trays, each of which contains a thin (2–6 cm deep) layer of food. Hot air is blown at $0.5–5\,m\,s^{-1}$ through a system of ducts and baffles to promote uniform air distribution over and/or through each tray. Additional heaters may be placed above or alongside the trays to

Table 15.1 Characteristics of driers

Type of drier	Characteristics of the food: Batch or continuous	Solid/ liquid	Initial moisture content	Heat sensitive	Size of pieces	Should be mechanically strong	Drying conditions: Drying rate	Final moisture content	Typical maximum evaporative capacity ($kg\,h^{-1}$)	Examples of products
Bin	B	S	Low		Int	Yes	Slow	Low	–	Vegetables
Cabinet	B	S	Mod		Int		Mod	Mod	55–75	Fruits, vegetables
Conveyor/band	C	S	Mod		Int		Mod	Mod	1820	Breakfast cereals, fruit products, confectionery, vegetables, biscuits, nuts
Drum	C	S	Mod		Sm		Mod	Mod	410	Slurries, corn syrup, instant potato, gelatin
Foam mat	C	L	–	Yes	–		Fast	Fast	–	Fruit juices
Fluidised bed	B/C	S	Mod		Sm	Yes	Mod	Low	910	Peas, diced or sliced vegetables, grains, powders or extruded foods, fruits, desiccated coconut, herbs
Kiln	B	S	Mod		Int		Slow	Mod	–	Apple rings, slices, hops
Microwave/dielectric	B/C	S	Low		Sm		Fast	Low	–	Bakery products
Pneumatic/ring	C	S	Low	Yes	Sm	Yes	Fast	Low	15 900	Starches, gravy or soup powder, mashed potato
Radiant	C	S	Low		Sm		Fast		–	Bakery products
Rotary	B/C	S	Mod	Yes	Sm	Yes	Mod	Mod	1820–5450	Cocoa beans, nuts, pomace, cooked cereals
Spin flash	C	L	Mod	Yes	Int/Sm		Fast	Low	7800	Pastes, filter cakes, sludges, viscous liquids
Spray	C	S	–		–		Fast	Mod	15 900	Powders, instant coffee, powdered milk
Sun/solar	B	S	Mod		Int		Slow	Mod	–	Fruits, vegetables
Trough	C	S	Mod		Int		Mod	Mod	–	Peas, diced vegetables
Tunnel	C	S	Mod		Int		Mod	Mod	–	Vegetables, fruits
Vacuum band/shelf	C	L	–		–		Fast	Low	18 200	Juices, meat extracts, chocolate crumb

Key: S = Solid, L = Liquid, Mod = Moderate, Int = Intermediate to large (granules, pellets, pieces), Sm = Small (powders).
Data from Barr and Baker (1997).

Table 15.2 Comparison of small and large scale drying technologies

Type of drier	Cost ($US)	Capacity (kg wet food/24 h)	Investment ($US per kg dry capacity)	Fuel efficiency	Labour requirement
'Brace' solar drier	50	10	50	n/a	v.low
Solar cabinet drier	70	30	23	n/a	v.low
'McDowell' drier	170	40	43	v.poor	low
Wood burning cabinet drier	340	80	43	v.poor	low
ITDG batch drier	3 400	240	140	poor	high
ITDG semi-continuous drier	6 800	360	190	medium	v.high
Cabinet drier (small)	85 000	500	1 700	good	high
Cabinet drier (large)	170 000	2 500	680	good	medium
Tunnel drier (12 carriage)	145 000	6 000	240	good	low
Band drier	800 000	48 000	170	v.good	v.low

From Axtell and Bush (1991).

increase the rate of drying. Tray driers are used for small-scale production (1–20 t-day^{-1}) or for pilot-scale work. They have low capital and maintenance costs and are flexible in operation for different foods. However, they have relatively poor control and produce more variable product quality as food dries more rapidly on trays nearest to the heat source. A low cost, semi-continuous mechanism which overcomes this problem by periodically replacing the lowest tray in the stack has been developed by Intermediate Technology Development Group (Axtell and Bush, 1991 and Axtell and Russell, 2000). A comparison of the technology with solar driers and large scale systems is shown in Table 15.2.

Tunnel driers

Layers of food are dried on trays, which are stacked on trucks programmed to move semi-continuously through an insulated tunnel, having one or more types of air flow described in Table 15.3. Food is finished in bin driers. Typically a 20 m tunnel contains 12–15 trucks with a total capacity of 5000 kg of food. This ability to dry large quantities of food in a relatively short time made tunnel drying widely used, especially in the USA. However, the method has now been largely superseded by conveyor drying and fluidised-bed drying as a result of their higher energy efficiency, reduced labour costs and better product quality.

Conveyor driers (belt driers)

Continuous conveyor driers are up to 20 m long and 3 m wide. Food is dried on a mesh belt in beds 5–15 cm deep. The air flow is initially directed upwards through the bed of food and then downwards in later stages to prevent dried food from blowing out of the bed. Two- or three-stage driers (Fig. 15.4) mix and re-pile the partly dried food into deeper beds (to 15–25 cm and then 250–900 cm in three-stage driers). This improves uniformity of drying and saves floor space. Foods are dried to 10–15% moisture content and then finished in bin driers. This equipment has good control over drying conditions and high production rates. It is used for large scale drying of foods (for example up to 5.5 t h^{-1}). Driers may have computer controlled independent drying zones and automatic loading and unloading to reduce labour costs.

A second application of conveyor driers is *foam mat drying* in which liquid foods are formed into a stable foam by the addition of a stabiliser (Appendix C) and aeration with nitrogen or air. The foam is spread on a perforated belt to a depth of 2–3 mm and dried

Table 15.3 Advantages and limitations of parallel flow, counter-current flow, centre-exhaust and cross-flow drying

Type of air flow	Advantages	Limitations
Parallel or co-current type: food → air flow →	Rapid initial drying. Little shrinkage of food. Low bulk density. Less damage to food. No risk of spoliage	Low moisture content difficult to achieve as cool moist air passes over dry food
Counter-current type: food → air flow ←	More economical use of energy. Low final moisture content as hot air passes over dry food	Food shrinkage and possible heat damage. Risk of spoilage from warm moist air meeting wet food
Centre-exhaust type: food → air flow →↑←	Combined benefits of parallel and counter-current driers but less than cross-flow driers	More complex and expensive than single-direction air flow
Cross-flow type: food → air flow ↑↓	Flexible control of drying conditions by separately controlled heating zones, giving uniform drying and high drying rates	More complex and expensive to buy, operate and maintain

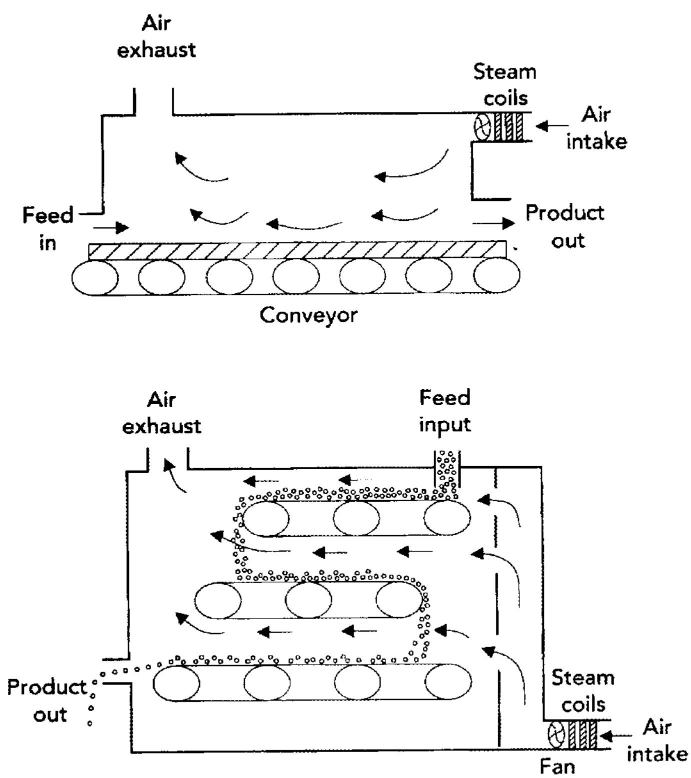

Fig. 15.4 (a) Conveyor drier and (b) three-stage conveyor drier. (From Heldman and Hartel (1997).)

rapidly in two stages by parallel and then counter-current air flows (Table 15.3). Foam mat drying is approximately three times faster than drying a similar thickness of liquid. The thin porous mat of dried food is then ground to a free-flowing powder which has good rehydration properties. Rapid drying and low product temperatures result in a high-quality product, but a large surface area is required for high production rates, and capital costs are therefore high.

A further variation is trough driers (or belt-trough driers) in which small, uniform pieces of food are dried in a mesh conveyor belt which hangs freely between rollers, to form the shape of a trough. Hot air is blown through the bed of food, and the movement of the conveyor mixes and turns the food to bring new surfaces continually into contact with the drying air. The mixing action also moves food away from the drying air, and this allows time for moisture to move from inside the pieces to the dry surfaces. The surface moisture is then rapidly evaporated when the food again contacts the hot air. These driers have high drying rates (for example 55 min for diced vegetables, compared with 5 h in a tunnel drier), high energy efficiencies, good control and minimal heat damage to the product. They operate in two stages, to 50–60% moisture and then to 15–20% moisture before finishing in bin driers.

Fluidised-bed driers

The main features of a fluidised-bed drier are a distributor to evenly distribute the air at a uniform velocity around the bed of material; a plenum chamber below the distributor to produce an homogenous region of air and prevent localised high velocities; and a disengagement or 'freeboard' region above the bed to allow disentrainment of particles thrown up by the air. Air from the fluidised bed is usually fed into cyclones to separate out fine particles, which are then added back to the product or agglomerated (Bahu, 1997). Above the distributor, mesh trays contain a bed of particulate foods up to 15 cm deep. Hot air is blown through the bed, causing the food to become suspended and vigorously agitated (fluidised), exposing the maximum surface area of food for drying (Fig. 15.5). A sample calculation of the air velocity needed for fluidisation is described in Chapter 1 (Sample problem 1.6). These driers are compact and have good control over drying conditions and high drying rates.

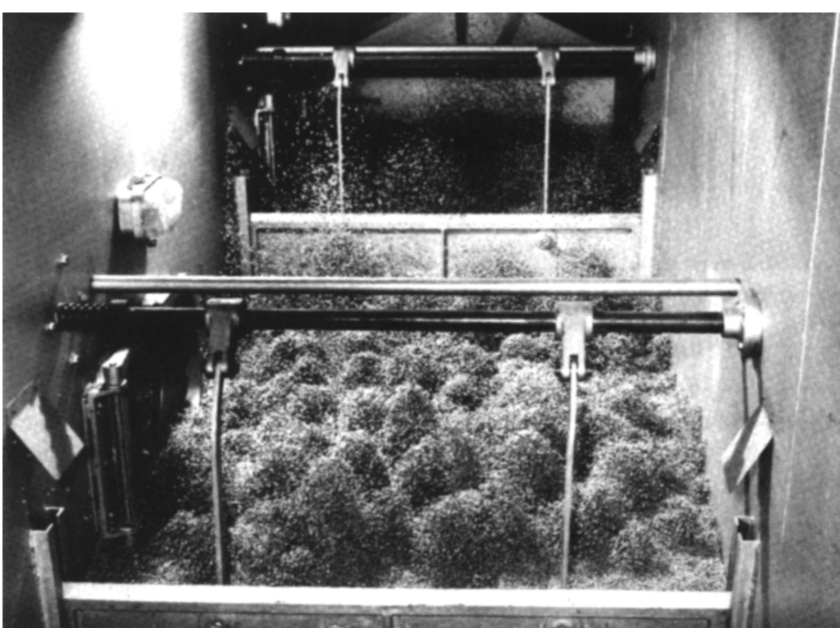

Fig. 15.5 Fluidised-bed drying.
(Courtesy of Petrie and McNaught Ltd.)

In batch operation, the product is thoroughly mixed by fluidisation and this leads to a uniform moisture content. In continuous operation the trays vibrate to move the food under gravity from one tray to the next. There is a greater range of moisture contents in the dried product, and bin driers are used for finishing. The main applications are for small, particulate foods that are capable of being fluidised without excessive mechanical damage, including yeast, desiccated coconut, grain, herbs, instant coffee, sugar and tea (Bahu, 1997).

In a development of the fluidised-bed drier, named the 'Torbed' drier, a fluidised bed of particles is made to rotate around a torus-shaped chamber by hot air blown directly from a burner (Fig. 15.6). The drier has very high rates of heat and mass transfer and substantially reduced drying times. Larger pieces require a period of moisture equilibration before final drying. The drier has microprocessor control and is suitable for agglomeration and puff drying in addition to roasting, cooking and coating applications.

Another development of the fluidised bed principle is the *Spin-flash drier* in which a drying chamber is fitted with a rotor at the base. Hot air enters tangentially and this, together with the action of the rotor, causes a turbulent rotating flow of air up through the chamber. Food pieces, such as crab meat paste, cocoa cake or gums, enter the chamber and become coated in dry powder. The lumps fall to the base where they are fluidised by the air and rotated by the rotor. As they dry the lumps break up and release powder, which is carried up the wall of the chamber and removed through a classification orifice that is changeable for different product particle size ranges. In the *centrifugal fluidised-bed drier* particulate food is filled into a drying chamber which rotates at high speed. Hot air is forced through the bed

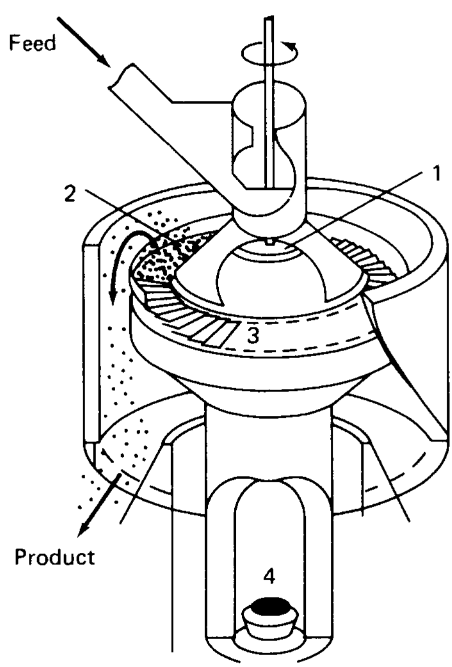

Fig. 15.6 Torbed drier: (1) rotating disc distributor to deliver raw material evenly into processing chamber; (2) rotating bed of particles; (3) fixed blades with hot gas passing through at high velocity; (4) burner assembly.
(Courtesy of Torftech Ltd.)

of food at a velocity that is high enough to overcome the centrifugal force and fluidise the particles. This higher air velocity increases the rate of drying (Cohen and Yang, 1995). Further details of the different types of fluidised-bed driers are given by Bahu (1997).

Kiln driers

These are two-storey buildings in which a drying room with a slatted floor is located above a furnace. Hot air and the products of combustion from the furnace pass through a bed of food up to 20 cm deep. They have been used traditionally for drying apple rings in the USA and hops in Europe, but there is limited control over drying conditions and drying times are relatively long. High labour costs are also incurred by the need to turn the product regularly, and by manual loading and unloading. However the driers have a large capacity and are easily constructed and maintained at low cost.

Pneumatic driers

In these driers, moist powders or particulate foods, usually less than 40% moisture and particle size ranges of 10–500 μm, are metered into metal ducting and suspended in hot air. In vertical driers the air-flow is adjusted so that lighter and smaller particles, which dry more rapidly, are carried to a cyclone separator more rapidly than are heavier and wetter particles, which remain suspended to receive the additional drying required. For products that require longer residence times, the ducting is formed into a continuous loop (*pneumatic ring driers*) and the product is recirculated until it is adequately dried. High temperature short-time ring driers (or *flash driers*) are used to expand the starch in potatoes or carrots to give a rigid, porous structure, which improves both subsequent conventional drying and rehydration rates. Drying takes place within 2–10 s and these driers are therefore suitable for foods that lose moisture rapidly from the surface. Evaporative cooling of the particles prevents heat damage to give high quality products.

Pneumatic driers have relatively low capital and maintenance costs, high drying rates and close control over drying conditions, which make them suitable for heat sensitive foods. Outputs range from 10 kg h^{-1} to 25 t h^{-1} (Barr and Baker, 1997). They are often used after spray drying to produce foods which have a lower moisture content than normal (for example special milk or egg powders and potato granules). In some applications the simultaneous transportation and drying of the food may be a useful method of materials handling (Chapter 26).

Rotary driers

A slightly inclined (up to 5º) rotating metal cylinder is fitted internally with flights to cause the food to cascade through a stream of parallel or counter-current (Table 15.3) hot air as it moves through the drier. The large surface area of food exposed to the air produces high drying rates and a uniformly dried product. The method is especially suitable for foods that tend to mat or stick together in belt or tray driers. However, the damage caused by impact and abrasion in the drier restricts this method to relatively few foods (for example nuts and cocoa beans). To overcome this problem, a variation of the design, named a *Rotary louvre drier*, in which longitudinal louvres are positioned to form an inner drum, has been introduced. The food particles form a partially fluidised rolling bed on the base of this drum and hot air passes through the louvres and the food (Barr and Baker, 1997).

Spray driers

A fine dispersion of pre-concentrated food (40–60% moisture) is first ‘atomised’ to form fine droplets and then sprayed into a co- or counter-current flow of heated air (Table 15.3) at 150–300ºC in a large drying chamber. One of the following types of atomiser is used:

- *Centrifugal atomiser*. Liquid is fed to the centre of a rotating disc or bowl having a peripheral velocity of 90–200 $m\,s^{-1}$. Droplets, 50–60 μm in diameter, are flung from the edge to form a uniform spray.
- *Pressure nozzle atomiser*. Liquid is forced at a high pressure ($700–2000 \times 10^3$ Pa) through a small aperture to form droplet sizes of 180–250 μm. Grooves on the inside of the nozzle cause the spray to form into a cone shape and therefore to use the full volume of the drying chamber.
- *Two-fluid nozzle atomiser*. Compressed air creates turbulence which atomises the liquid. The operating pressure is lower than the pressure nozzle, but a wider range of droplet sizes is produced.
- *Ultrasonic nozzle atomiser*. A two-stage atomiser in which liquid is first atomised by a nozzle atomiser and then using ultrasonic energy to induce further cavitation.

Nozzle atomisers are susceptible to blockage by particulate foods, and abrasive foods gradually widen the apertures and increase the average droplet size.

Studies of droplet drying, including methods for calculating changes in size, density and trajectory of the droplets are described by Charm (1978), Kerkhof and Schoeber (1974) and Masters (1972).

Rapid drying (1–10 s) takes place because of the very large surface area of the droplets. The feed rate is controlled to produce an outlet air temperature of 90–100ºC, which corresponds to a wet-bulb temperature (and product temperature) of 40–50ºC to produce little heat damage to the food. The dry powder is collected at the base of the drier and removed by a screw conveyor or a pneumatic system with a cyclone separator. There are a large number of designs of atomiser, drying chamber, air heating and powder collecting systems which arise from the different requirements of the very large variety of food materials that are spray dried (for example milk, egg, coffee, cocoa, tea, potato, ice cream mix, butter, cream, yoghurt and cheese powder, coffee whitener, fruit juices, meat and yeast extracts, encapsulated flavours (Heath, 1985) and wheat and corn starch products). Detailed designs are described by Masters (1972), Masters (1997) and Kjaergaard (1974). Spray driers may also be fitted with fluidised bed facilities to finish powders taken from the drying chamber. Spray driers vary in size from small pilot-scale models for low-volume high-value products such as enzymes and flavours, to large commercial models capable of producing 10 000 kg of dried milk per hour (Byrne, 1986).

The main advantages are rapid drying, large-scale continuous production, low labour costs and relatively simple operation and maintenance. The major limitations are high capital costs and the requirement for a relatively high-feed moisture content to ensure that the food can be pumped to the atomiser. This results in higher energy costs (to remove the moisture) and higher volatile losses. Conveyor-band driers and fluidised-bed driers are beginning to replace spray driers as they are more compact and energy efficient (Ashworth, 1981). Development work with *ultrasonic drying* has indicated a potential alternative to spray drying. Small droplets are first produced in a liquid by ultrasound (Chapter 4) and then heated to remove the water. Drying takes place very rapidly (sometimes within seconds) and the dried residue is collected. The process works well with low-fat solutions, but less well with oily or fatty foods, which do not dry easily (Cohen and Yang, 1995).

Sun and solar drying

Sun drying (without drying equipment) is the most widely practised agricultural processing operation in the world; more than 250 000 000 t of fruits and grains are dried by solar energy per annum. In some countries, foods are simply laid out in fields or on roofs or other flat surfaces and turned regularly until dry. More sophisticated methods (solar drying) collect solar energy and heat air, which in turn is used for drying. Solar driers are classified into:

- direct natural-circulation driers (a combined collector and drying chamber)
- direct driers with a separate collector
- indirect forced-convection driers (separate collector and drying chamber).

Both solar and sun drying are simple inexpensive technologies, in terms of both capital input and operating costs. Energy inputs and skilled labour are not required and in sun drying, very large amounts of crop can be dried at low cost. The major disadvantages are relatively poor control over drying conditions and lower drying rates than those found in artificial driers, which results in products that have lower quality and greater variability. In addition, drying is dependent on the weather and the time of day and requires a larger labour force than other methods. There are a large number of different designs of solar driers, described in detail by Brenndorfer *et al.* (1985) and Imrie (1997). Small solar driers have been investigated at research institutions, particularly in developing countries, for many years but their often low capacity (Table 15.2) and insignificant improvement to drying rates and product quality, compared to hygienic sun drying, have restricted their commercial use to only three or four applications worldwide. Larger solar driers with photo-voltaic powered fans and having a capacity of 200–400 kg/batch, have been developed by Hohenheim University to a commercial scale of operation. Several hundred driers are now in use in Mediterranean countries to dry fruit to export standards for European markets (Axtell and Russell, 2000). Potential developments using solar energy are likely to include their use in pre-heating air to gain reductions in energy consumption in fuel-fired driers.

15.2.2 Heated-surface (or contact) driers

Driers in which heat is supplied to the food by conduction have two main advantages over hot-air drying:

1. It is not necessary to heat large volumes of air before drying commences and the thermal efficiency is therefore high.
2. Drying may be carried out in the absence of oxygen to protect components of foods that are easily oxidised.

Typically heat consumption is 2000–3000 kJ per kilogram of water evaporated compared with 4000–10 000 kJ per kilogram of water evaporated for hot-air driers. However, foods have a low thermal conductivity (Chapter 1, Table 1.5) which becomes lower as the food dries and a thin layer of food is therefore needed to conduct heat rapidly, without causing heat damage.

Drum driers (roller driers)

Slowly rotating hollow steel drums are heated internally by pressurised steam to 120–170ºC. A thin layer of food is spread uniformly over the outer surface by dipping, spraying, spreading or by auxiliary feed rollers. Before the drum has completed one revolution (within 20 s–3 min), the dried food is scraped off by a ‘doctor’ blade which contacts the drum surface uniformly along its length. Driers may have a single drum (Fig. 15.7(a)), double drums (Fig. 15.7(b)) or twin drums. The single drum is widely used as it

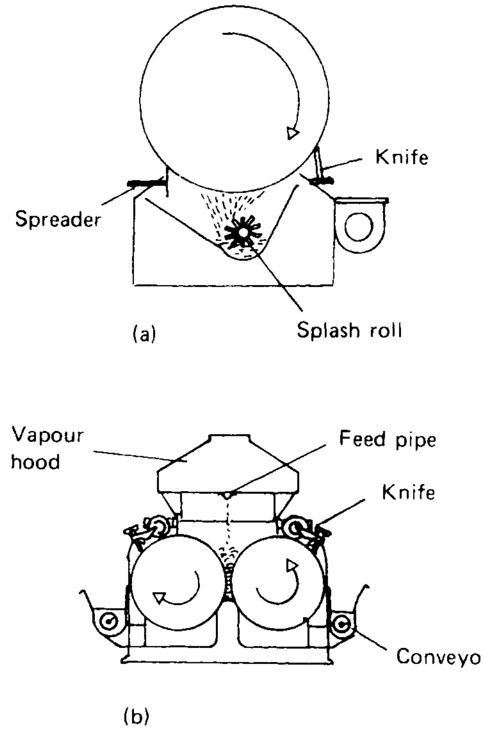

Fig. 15.7 Drum driers: (a) single drum and (b) double drum.
(Courtesy of APV Mitchell Ltd.)

has greater flexibility, a larger proportion of the drum area available for drying, there is easier access for maintenance and no risk of damage caused by metal objects falling between the drums.

Drum driers have high drying rates and high energy efficiencies and they are suitable for slurries in which the particles are too large for spray drying. Drum drying is used to produce potato flakes, pre-cooked cereals, molasses, some dried soups and fruit purees, and whey or distillers' solubles for animal feed formulations. However, the high capital cost of the machined drums and heat damage to sensitive foods caused by high drum temperatures have caused a move to spray drying for many bulk dried foods.

Developments in drum design to improve the sensory and nutritional qualities of dried food include the use of auxiliary rolls to remove and reapply food during drying, the use of high-velocity air to increase the drying rate or the use of chilled air to cool the product. Drums may be enclosed in a vacuum chamber to dry food at lower temperatures, but the high capital cost of this system restricts its use to high-value heat-sensitive foods.

In *ball-drying,* a drying chamber is fitted with a slowly rotating screw and contains ceramic balls that are heated by hot air, blown into the chamber. Particulate foods are dried mainly by conduction as a result of contact with the hot balls and are moved through the drier by the screw, to be discharged at the base. The drying time is controlled by the speed of the screw and the temperature of the heated balls (Cohen and Yang, 1995).

Vacuum band and vacuum shelf driers

A food slurry is spread or sprayed onto a steel belt (or 'band') which passes over two hollow drums, within a vacuum chamber at 1–70 Torr. The food is dried by the first

Table 15.4 Types of contact drier

Type of drier	Batch (B) or continuous (C)	Vacuum (V) or atmospheric (A)	Feed	Production rate	Typical applications
Vacuum tray	B	V	Any	Low	Fruit pieces, meat or vegetable extracts
Vacuum band	C	V	Pastes, solids	Low-medium	Chocolate crumb, meat or vegetable extracts, fruit juices
Plate	C	V or A	Free-flowing solids	Low-medium	Tea, coffee
Thin-film	C	V or A	Liquids	Low-medium	Tomato concentrate, gelatin
Drum	C	V or A	Liquids	Low-medium	Instant potato, corn syrup, baby foods
Rotating batch	B	V	Free-flowing solids	Low-medium	Gravy mix, pectin
Horizontally agitated	B or C	V or A	Liquids, pastes, powders	Low-high	Chocolate crumb, corn meal, confectionery
Indirect rotary	C	A	Free-flowing solids	Medium-very high	Brewer’s grain, starch
Vertical agitated	B	V or A	Liquids, pastes, powders	Low-medium	Plant extracts, food colours, glucose, starch

From Oakley (1997).

Table 15.5 Summary of some novel drying techniques

Technique	Applications	Advantages	Limitations
Microwave and dielectric drying (Chapter 18)	High value products	Low temperature, batch or continuous operation, good quality products	Slow, expensive
Microwave augmented freeze drying (Chapter 22)	High value products	Low temperature, rapid, good quality products	Expensive
Centrifugal fluidised-bed drying	Small particles, vegetable pieces, powders	Rapid, easy to control	Loss of product integrity, noisy
Ball drying	Small particles, vegetable pieces	Low temperature, rapid, continuous operation, good quality products	Loss of product integrity, difficult to control
Ultrasonic drying	Liquids	Rapid	Requires low fat liquids
Explosive puff drying	Produces honeycomb structure in small particles	Rapid, good rehydration of products	Loss of product integrity, high levels of heat

Adapted from Cohen and Yang (1995).

steam-heated drum, and then by steam-heated coils or radiant heaters located over the band. The dried food is cooled by the second water-cooled drum and removed by a doctor blade. Vacuum shelf driers consist of hollow shelves in a vacuum chamber. Food is placed in thin layers on flat metal trays which are carefully made to ensure good contact with the shelves. A partial vacuum of 1–70 Torr is drawn in the chamber and steam or hot water is passed through the shelves to dry the food. Rapid drying and limited heat damage to the food make both methods suitable for heat-sensitive foods. However, care is necessary to prevent the dried food from burning onto trays in vacuum shelf driers, and shrinkage reduces the contact between the food and heated surfaces of both types of equipment. They have relatively high capital and operating costs and low production rates and are used mainly to produce puff-dried foods.

Explosion puff drying involves partially drying food to a moderate moisture content and then sealing it into a pressure chamber. The pressure and temperature in the chamber are increased and then instantly released. The rapid loss of pressure causes the food to expand and develop a fine porous structure. This permits faster final drying and rapid rehydration. Sensory and nutritional qualities are well retained. The technique was first applied commercially to breakfast cereals and now includes a range of fruit and vegetable products. A comparison of different contact driers is given in Table 15.4.

Other developments in drying technologies are described by Cohen and Yang (1995) and are summarised in Table 15.5.

15.3 Effect on foods

All products undergo changes during drying and storage that reduce their quality compared to the fresh material and the aim of improved drying technologies is to minimise these changes while maximising process efficiency. The main changes to dried

Table 15.6 Approximate ratios for drying, shrinkage and rehydration of selected vegetables

Vegetable	Drying ratio	Overall shrinkage ratio	Rehydration ratio
Cabbage	11.5	21.0	10.5
Carrots, sliced	7.5	12.0	7.0
Onions, sliced	7.0	8.0	5.5
Peppers, green	17.0	22.0	8.0
Spinach	13.0	13.5	5.0
Tomato flakes	14.0	20.0	5.0

foods are to the texture and loss of flavour or aroma, but changes in colour and nutritional value are also significant in some foods.

15.3.1 Texture

Changes to the texture of solid foods are an important cause of quality deterioration. The nature and extent of pre-treatments (for example, calcium chloride added to blancher water (Chapter 10), the type and extent of size reduction (Chapter 4), and peeling (Chapter 3)) each affect the texture of rehydrated fruits and vegetables. The loss of texture in these products is caused by gelatinisation of starch, crystallisation of cellulose (see also glass transition, Chapter 1, Section 1.1), and localised variations in the moisture content during drying, which set up internal stresses. These rupture, crack, compress and permanently distort the relatively rigid cells, to give the food a shrunken shrivelled appearance. On rehydration the product absorbs water more slowly and does not regain the firm texture of the fresh material. There are substantial variations in the degree of shrinkage and rehydration with different foods (Table 15.6).

Drying pieces of meat is not common in many countries owing to the severe changes in texture compared with other methods of preservation. These are caused by aggregation and denaturation of proteins and a loss of water-holding capacity, which leads to toughening of muscle tissue.

In general, rapid drying and high temperatures cause greater changes to the texture of foods than do moderate rates of drying and lower temperatures. As water is removed during drying, solutes move from the interior of the food to the surface. The mechanism and rate of movement are specific for each solute and depend on the type of food and the drying conditions used. Evaporation of water causes concentration of solutes at the surface. High air temperatures (particularly with fruits, fish and meats), cause complex chemical and physical changes to solutes at the surface, and the formation of a hard impermeable skin. This is termed *case hardening* and it reduces the rate of drying to produce a food with a dry surface and a moist interior. It is minimised by controlling the drying conditions to prevent excessively high moisture gradients between the interior and the surface of the food.

The textural characteristics of powders are related to their bulk density and the ease with which they are rehydrated. The bulk density of powders depends on the size of the dried particles and on whether they are hollow or solid. This is determined by the nature and composition of the food and the drying conditions (for example the uniformity of droplet size, temperature, solids content and degree of aeration of the feed liquid). Low-fat foods (for example fruit juices, potato and coffee) are more easily formed into free-flowing powders than are whole milk or meat extracts. Powders are 'instantised' by

Table 15.7 Bulk density and moisture content of selected powdered foods

Food	Bulk density ($kg\,m^{-3}$)	Moisture content (%)
Cocoa	480	3–5
Coffee (ground)	330	7
Coffee (instant)	330	2.5
Coffee creamer	470	3
Corn starch	560	12
Egg, whole	340	2–4
Milk, powdered, skimmed	640	2–4
Milk, instant, skimmed	550	2–4
Salt, granulated	960	0.2
Sugar, granulated	800	0.5
Wheat flour	450	12

Adapted from Watt and Merrill (1975) and Peleg (1983).

treating individual particles so that they stick together to form free-flowing agglomerates or aggregates, in which there are relatively few points of contact. The surface of each particle is easily wetted when the powder is rehydrated and the agglomerates break up to allow particles to sink below the surface and disperse rapidly through the liquid. These characteristics are respectively termed *wettability*, *sinkability*, *dispersibility* and *solubility*. For a powder to be considered 'instant', it should complete these four stages within a few seconds. Further details of the properties and handling of powders are given by Lewis (1996).

Agglomeration can be achieved by remoistening particles in low-pressure steam in an agglomerator, and then redrying. Fluidised-bed, jet, disc, cone or belt agglomerators are described by Schubert (1980). Alternatively, 'straight-through' agglomeration is achieved either directly during spray drying or a relatively moist powder is agglomerated and dried in an attached fluidised-bed drier (Masters, 1972). Non-agglomeration methods employ a binding agent (for example lecithin) to bind particles together. This method was previously used for foods with a relatively high fat content (for example whole milk powder) but it has now largely been replaced by agglomeration procedures (Pisecky *et al.*, 1983).

The convenience of instantised powders for retail markets outweighs the additional expense of production, packaging and transport, but many powdered foods are also used as ingredients in other processes, and these are required to possess a high bulk density and a wider range of particle sizes. Small particles fill the spaces between larger ones and thus exclude air to promote a longer storage life. The characteristics of some powdered foods are described in Table 15.7.

15.3.2 Flavour and aroma

Heat not only vaporises water during drying but also causes loss of volatile components from the food and as a result most dried foods have less flavour than the original material. The extent of volatile loss depends on the temperature and moisture content of the food and on the vapour pressure of the volatiles and their solubility in water vapour. Volatiles which have a high relative volatility and diffusivity are lost at an early stage in drying. Foods that have a high economic value due to their characteristic flavours (for example herbs and spices) are dried at low temperatures (Mazza and LeMaguer, 1980).

The open porous structure of dried food allows access of oxygen, which is a second important cause of aroma loss due to oxidation of volatile components and lipids during storage. The rate of deterioration is determined by the storage temperature and the water activity (Chapter 1) of the food. In dried milk the oxidation of lipids produces rancid flavours owing to the formation of secondary products including δ-lactones. Most fruits and vegetables contain only small quantities of lipid, but oxidation of unsaturated fatty acids to produce hydroperoxides, which react further by polymerisation, dehydration or oxidation to produce aldehydes, ketones and acids, causes rancid and objectionable odours. Some foods (for example carrot) may develop an odour of 'violets' produced by the oxidation of carotenes to β-ionone (Rolls and Porter, 1973). These changes are reduced by:

- vacuum or gas packing
- low storage temperatures
- exclusion of ultraviolet or visible light
- maintenance of low moisture contents
- addition of synthetic antioxidants (Appendix C)
- preservation of natural anti-oxidants.

The technical enzyme, glucose oxidase (Chapter 7), is also used to protect dried foods from oxidation. A package which is permeable to oxygen but not to moisture and which contains glucose and the enzyme is placed on the dried food inside a container, to remove oxygen from the head space during storage. Milk powders are also stored under an atmosphere of nitrogen with 10% carbon dioxide (Chapter 20). The carbon dioxide is absorbed into the milk and creates a small partial vacuum in the head space. Air diffuses out of the dried particles and is removed by re-gassing after 24 h.

Flavour changes, due to oxidative or hydrolytic enzymes are prevented in fruits by the use of sulphur dioxide, ascorbic acid or citric acid, by pasteurisation of milk or fruit juices and by blanching of vegetables. Other methods which are used to retain flavours in dried foods include:

- recovery of volatiles and their return to the product during drying
- mixing recovered volatiles with flavour fixing compounds, which are then granulated and added back to the dried product (for example dried meat powders)
- addition of enzymes, or activation of naturally occurring enzymes, to produce flavours from flavour precursors in the food (for example onion and garlic are dried under conditions that protect the enzymes that release characteristic flavours).

15.3.3 Colour

There are a number of causes of colour loss or change in dried foods; drying changes the surface characteristics of a food and hence alters its reflectivity and colour. In fruits and vegetables, chemical changes to carotenoid and chlorophyll pigments are caused by heat and oxidation during drying and residual polyphenoloxidase enzyme activity causes browning during storage. This is prevented by blanching or treatment of fruits with ascorbic acid or sulphur dioxide. For moderately sulphured fruits and vegetables the rate of darkening during storage is inversely proportional to the residual sulphur dioxide content. However, sulphur dioxide bleaches anthocyanins, and residual sulphur dioxide is also linked to health concerns. Its use in dried products is now restricted in many countries.

The rate of Maillard browning in stored milk and fruit products depends on the water activity of the food and the temperature of storage. The rate of darkening increases markedly at high drying temperatures, when the moisture content of the product exceeds 4–5%, and at storage temperatures above 38ºC (Lea, 1958).

15.3.4 Nutritional value

Large differences in reported data on the nutritional value of dried foods are due to wide variations in the preparation procedures, the drying temperature and time, and the storage conditions. In fruits and vegetables, losses during preparation usually exceed those caused by the drying operation. For example Escher and Neukom (1970) showed that losses of vitamin C during preparation of apple flakes were 8% during slicing, 62% from blanching, 10% from pureeing and 5% from drum drying.

Vitamins have different solubilities in water and as drying proceeds, some (for example riboflavin) become supersaturated and precipitate from solution, so losses are small (Table 15.8). Others, for example ascorbic acid, are soluble until the moisture content of the food falls to very low levels and these react with solutes at higher rates as drying proceeds. Vitamin C is also sensitive to heat and oxidation and short drying times, low temperatures, low moisture and oxygen levels during storage are therefore necessary to avoid large losses. Thiamin is also heat sensitive, but other water-soluble vitamins are more stable to heat and oxidation, and losses during drying rarely exceed 5–10%, excluding blanching losses.

Oil-soluble nutrients (for example essential fatty acids and vitamins A, D, E and K) are mostly contained within the dry matter of the food and they are not concentrated during drying. However, water is a solvent for heavy metal catalysts that promote oxidation of unsaturated nutrients. As water is removed, the catalysts become more reactive, and the rate of oxidation accelerates (Fig. 1.15 in Chapter 1). Fat-soluble vitamins are lost by interaction with the peroxides produced by fat oxidation. Losses during storage are reduced by lowering the oxygen concentration and the storage temperature and by exclusion of light.

The biological value and digestibility of proteins in most foods does not change substantially as a result of drying. However, milk proteins are partially denatured during drum drying, and this results in a reduction in solubility of the milk powder and loss of clotting ability. A reduction in biological value of 8–30% is reported, depending on the temperature and residence time in the drier (Fairbanks and Mitchell, 1935). Spray drying does not affect the biological value of milk proteins. At high storage temperatures and at

Table 15.8 Vitamin losses in selected dried foods

	Loss (%)						
Food	Vitamin A	Thiamin	Vitamin B_2	Niacin	Vitamin C	Folic acid	Biotin
Fruits[a]	6	55	0	10	56		
Fig (sun-dried)	–	48	42	37	–	–	–
Whole milk (spray dried)	–	–	–	–	15	10	10
Whole milk (drum-dried)	–	–	–	–	30	10	10
Pork		50–70					
Vegetables[b]	5	< 10	< 10				

[a] Fruits mean loss from fresh apple, apricot, peach and prune.
[b] Vegetables mean loss from peas, corn, cabbage and beans (drying stage only).
Adapted from Rolls (1982) and Calloway (1962).

moisture contents above approximately 5%, the biological value of milk protein is decreased by Maillard reactions between lysine and lactose. Lysine is heat sensitive and losses in whole milk range from 3–10% in spray drying and 5–40% in drum drying (Rolls and Porter, 1973).

15.4 Rehydration

Water that is removed from a food during dehydration cannot be replaced in the same way when the food is rehydrated (that is, rehydration is not the reverse of drying); loss of cellular osmotic pressure, changes in cell membrane permeability, solute migration, crystallisation of polysaccharides and coagulation of cellular proteins all contribute to texture changes and volatile losses and are each irreversible (Rahman and Perera, 1999). Heat reduces the degree of hydration of starch and the elasticity of cell walls, and coagulates proteins to reduce their water-holding capacity. The rate and extent of rehydration may be used as an indicator of food quality; those foods that are dried under optimum conditions suffer less damage and rehydrate more rapidly and completely than poorly dried foods.

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