

Dehydration

Abstract: Dehydration using hot air or heated surfaces removes water from foods and reduces their water activity. This inhibits microbial growth and enzyme activity to extend the shelf-life. Drying can cause deterioration of both the eating quality and the nutritional value of foods, and the design and operation of dehydration equipment aim to minimise these changes. The chapter first looks at psychrometrics, the theory of drying and calculation of drying rates. It then summarises the many different types of hot-air and contact drying equipment and methods used to control their operation. The chapter concludes by describing rehydration and the effects of dehydration on foods and micro-organisms.

Key words: dehydration, psychrometrics, drying rate, hot-air dryers, heated-surface dryers, agglomeration of powders, encapsulation, rehydration.

Dehydration (or drying) is ‘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 by sublimation). This definition excludes other unit operations that remove water from foods (e.g. mechanical separations and membrane concentration (Chapter 5), evaporation (Chapter 14) and baking (Chapter 18)) as these normally remove much less water than dehydration does. This chapter focuses on dehydration using hot air or heated surfaces. Microwave, radio frequency and radiant dryers are described in Chapter 20 and freeze drying is described in Chapter 23 (section 23.1).

The main purpose of dehydration is to extend the shelf-life of foods by a reduction in water activity (Chapter 1, section 1.1.2). 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, can result in rapid spoilage. Drying also causes deterioration of both the eating quality and the nutritional value of the food (section 16.5). The design and operation of dehydration equipment aim to minimise these changes by selection of appropriate drying conditions for individual foods. Details of the chemistry and microbiology of dried foods are given by Hui *et al.* (2007).

The reduction in weight and bulk of dried foods reduces transport and storage costs. Dehydration also provides convenient products that have a long shelf-life at ambient temperature for the consumer, or ingredients that are more easily handled by food processors. Examples of commercially important dried consumer products include baby

foods, beans, pulses, nuts, breakfast cereals, coffee whitener, condiments and spices (e.g. garlic, pepper), egg products, flours (including bakery mixes), instant coffee, instant soups, milk, pasta, powdered cheeses, raisins, sultanas and other fruits, sweeteners and tea. Examples of important dried ingredients that are used by manufacturers include dairy products (milk, whey proteins, cheese, buttermilk, sodium caseinate, butter, ice cream mixes), soy powders, soy protein isolate, whole egg, egg yolk and albumen, encapsulated flavourings and colourings, spray-dried meat purées, fruit and vegetable pulps, pastes and juices, maltodextrins (powdered, granulated or agglomerated), lactose, sucrose or fructose powders, enzymes and yeasts (Deis 1997).

16.1 Theory

Dehydration involves the simultaneous application of heat and removal of moisture by evaporation from foods. Factors that control the rates of heat transfer are described in Chapter 10 (section 10.1.2) and mass transfer due to evaporation is described in Chapter 14 (section 14.1.1). There are a large number of factors that control the rate at which foods dry, which can be grouped into categories related to the processing conditions, the nature of the food and the design of dryers. The effects of processing conditions and type of food are described below and differences in dryer design are summarised in section 16.2.

16.1.1 Drying using heated air

Psychrometrics

Psychrometry is the study of inter-related properties of air–water vapour systems. These properties are conveniently represented on a psychrometric chart (Fig. 16.1) and are described mathematically in a number of food engineering textbooks (e.g. Singh and Heldman 2001a, Toledo 1999). 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; and
- 3 the amount of air that passes over the food.

The amount of water vapour in air is expressed as either absolute humidity (W) (termed ‘moisture content’ in Fig. 16.1 and also known as the ‘humidity ratio’), which equals the mass of water vapour per unit mass of dry air in kg per kg (Equation 16.1), or as relative humidity (RH) (in per cent). This is 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 and can be represented by Equation 16.2:

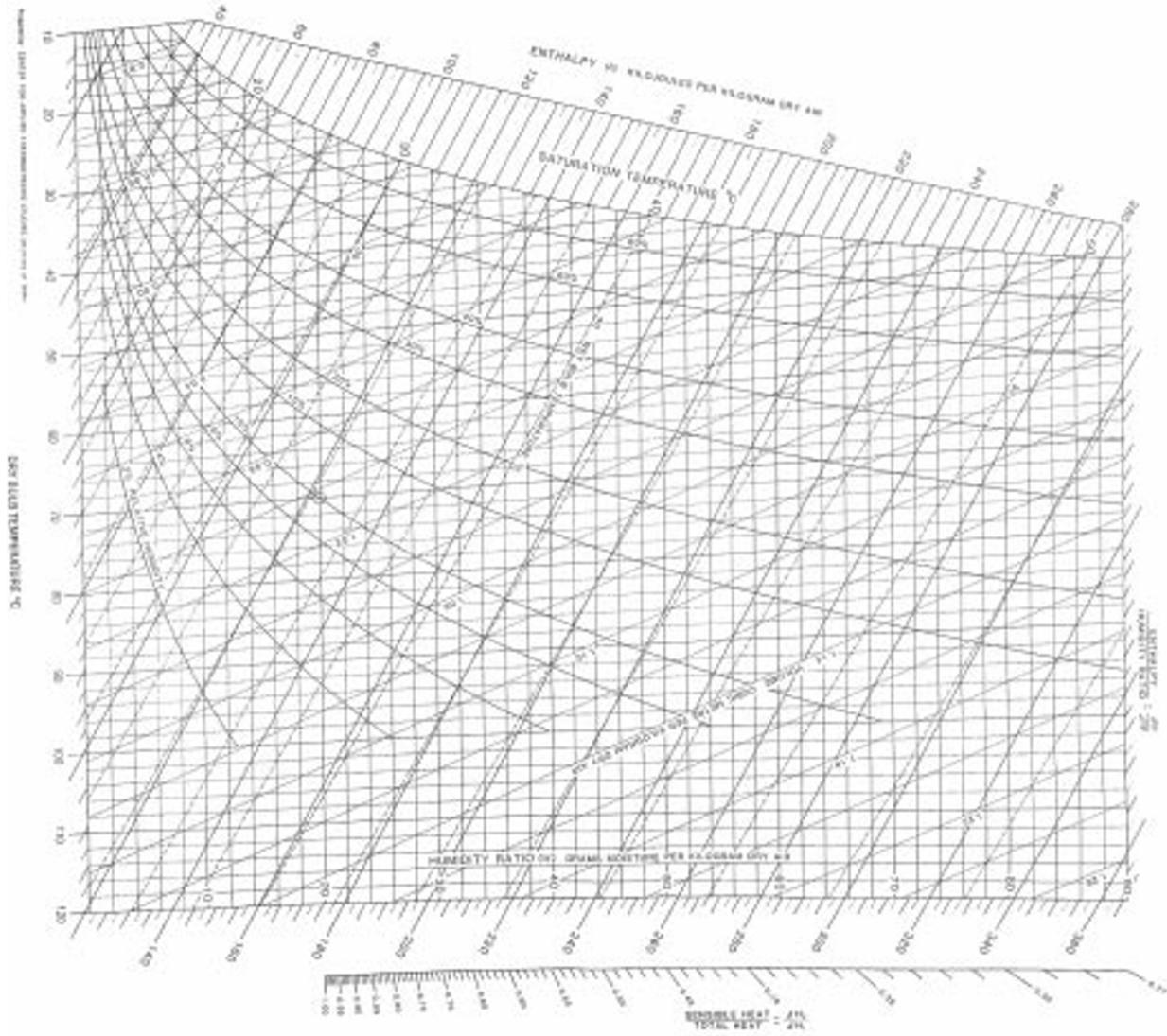
$$W = m_w/m_a \quad \boxed{16.1}$$

where m_w (kg) = mass of water and m_a (kg) = mass of dry air,

$$RH = (\rho_w/\rho_{ws}) \times 100 \quad \boxed{16.2}$$

where ρ_w (kPa) = partial pressure of water vapour in the air and ρ_{ws} (kPa) = saturated water vapour pressure at the same temperature.

The amount of heat needed to raise the temperature of an air–water vapour mixture is known as the ‘humid heat’ and corresponds to sensible heat when heating solids or



ASHRAE PSYCHROMETRIC CHART NO. 3
 HUMAN OCCUPATION: 10°C TO 120°C SEA LEVEL
 STANDARD PRESSURE: 101.325 kPa
 CENTER LINE



Fig. 16.1 Psychrometric chart based on barometric pressure of 101.3 kPa (courtesy of ASHRAE Inc.).

liquids (Chapter 10, section 10.1.2). Other properties of water vapour are described in Chapter 10 (section 10.1.1) and Chapter 14 (section 14.1.1) and details of the factors that control how much vapour can be carried by air are given by Singh and Heldman (2001a).

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, heat will also be conducted through the trays to the food. Heat is absorbed by food and both raises the temperature of the food and provides the latent heat needed to evaporate water from the surface. 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 surface temperature. 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 and air is blown over the cloth, heat is removed by evaporation of water and the temperature falls. This lower temperature is known as the 'wet-bulb' temperature. The difference between the two temperatures is used to find the relative humidity of air on the psychrometric chart (sample problem 16.1).

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 psychrometric chart, which show how absolute humidity decreases as the air temperature increases. The calculations in sample problem 16.1 illustrate how the psychrometric chart is used and further examples are given by Singh and Heldman (2001a) and Toledo (1999).

Sample problem 16.1

Using the psychrometric chart (Fig. 16.1), calculate the following:

- 1 The absolute humidity of air that has RH = 40% and a dry bulb temperature = 60 °C.
- 2 The wet bulb temperature under these conditions.
- 3 The RH of air having a wet bulb temperature = 44 °C and a dry bulb temperature = 70 °C.
- 4 The dew point of air cooled adiabatically from RH = 30% and a dry bulb temperature = 50 °C.
- 5 The change in RH of air with a wet bulb temperature = 38 °C, heated from 50 °C to 86 °C (dry bulb temperatures).
- 6 The change in RH of air with a wet bulb temperature = 35 °C, cooled adiabatically from 70 °C to 40 °C (dry bulb temperatures).
- 7 Food is dried in a co-current dryer (section 16.2.1) from an inlet moisture content of 0.3 kg moisture per kg product to an outlet moisture content of 0.15 kg moisture per kg product. Air at dry bulb temperature = 20 °C and RH = 40% is heated to the dryer inlet temperature = 110 °C. The dry bulb temperature of the exhaust air from the dryer should be at least 10 °C above the dew point to prevent condensation in pipework. Calculate the exhaust air temperature and RH that meets this requirement and the mass of air required (kg h^{-1} (dry basis) per kg h^{-1} of dry solids).

Solutions to sample problems 16.1

- 1 Find the intersection of the 60 °C and 40% RH lines and follow the chart horizontally to the right to read off the absolute humidity (0.0535 kg (or 53.5 g) per kg dry air).

- 2 From the intersection of the 60 °C and 40% RH lines, extrapolate left parallel to the dotted wet bulb lines to read off the wet bulb temperature (43.8 °C).
- 3 Find the intersection of the 44 °C and 70 °C lines and follow the sloping RH line upwards to read off the % RH (25%).
- 4 Find the intersection of the 50 °C and 30% RH lines and follow the dotted wet bulb line left until the RH = 100% (32.6 °C).
- 5 Find the intersection of the 38 °C wet bulb line and the 50 °C dry bulb line, and follow the horizontal line to the intersection with the 86 °C dry bulb line; read the sloping RH line at each intersection. This represents the changes to the air humidity when it is heated (48 – 9.8%).
- 6 Find the intersection of the 35 °C wet bulb line and the 70 °C dry bulb line, and follow the wet bulb line left to the intersection with the 40 °C dry bulb line; read the sloping RH line at each intersection. This represents the changes to air as it dries the food; it is cooled and becomes more humid as it picks up moisture from the food (11 – 73%).
- 7 Find the intersection of the 20 °C dry bulb line and the 40% RH line, and follow the horizontal line left to the dry bulb temperature = 110 °C and read the absolute humidity = 0.006 kg (or 6 g) moisture kg⁻¹ dry air.

At 110 °C the wet bulb temperature = 35.5 °C, follow this line left and find the point at which the dry bulb temperature is 10 °C above the dew point. This occurs when the dry bulb temperature = 44 °C and the dew point = 33.8 °C (the dew point is found by reading horizontally left along the absolute humidity line of 0.034 kg (or 34 g) moisture kg⁻¹ dry air from the point where the 35.5 °C wet bulb temperature and 44 °C dry bulb temperature intersect to RH = 100%).

At point 35.5 °C wet bulb temperature and 44 °C dry bulb temperature, the RH of the exhaust air = 57%.

The air flowrate is found using a mass balance:

$$\text{Moisture lost per kg dry solids} = 1 \times (0.3 - 0.15) \times 1000 = 150 \text{ g h}^{-1}$$

This is the moisture gained by the air, which is also equal to

$$M \times (34 - 6) = M \times 28 \text{ g moisture kg}^{-1} \text{ dry air h}^{-1}$$

where M = mass flow of air. Therefore,

$$M = 150/28 = 5.36 \text{ kg air (dry)/kg dry product}$$

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. 16.2). 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. The boundary film acts as a barrier to both heat transfer and the removal of water vapour. The thickness of the film is determined primarily by the air velocity; low-velocity air produces thicker boundary films that reduce the heat transfer coefficient. When water vapour leaves the surface of the food, it increases the humidity of the air in the boundary film. This reduces the water vapour pressure gradient and hence slows the rate of drying. Conversely, fast-moving air removes humid air more quickly, reduces the boundary film,

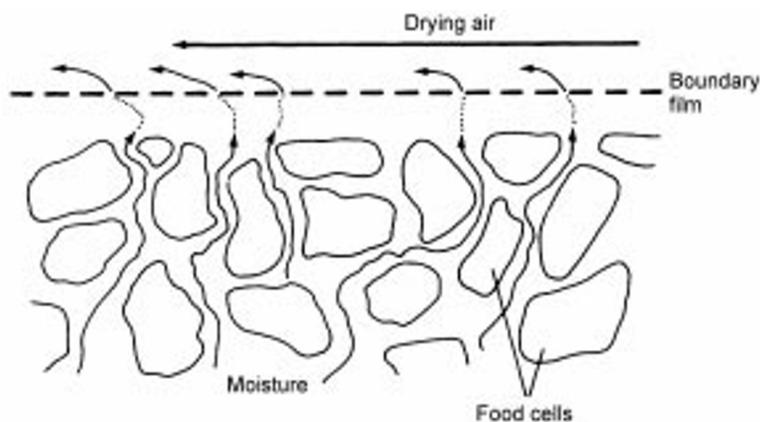


Fig. 16.2 Movement of moisture during drying.

increases the water vapour pressure gradient and hence increases 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; and
- 3 a high air velocity.

Constant rate period

When food is placed in a dryer, there is a short initial settling down period as the surface heats up to the wet-bulb temperature (A–B in Fig. 16.3a). Drying then commences and, provided that 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 Figs 16.3a 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

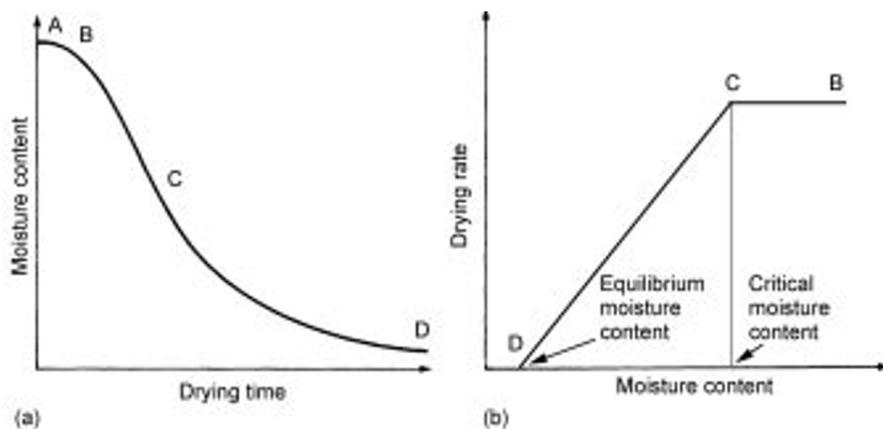


Fig. 16.3 Drying curves. The temperature and humidity of the drying air are constant and all heat is supplied to the food surface by convection.

and, overall, the rate of drying declines gradually towards the end of the 'constant'-rate period. A calculation of the time required to complete the constant rate period is given in sample problem 16.2.

Sample problem 16.2

Diced carrot, having a cube size of 1.5 cm and a moisture content of 88% (w/w basis), is dried in a fluidised bed dryer (section 16.2.1) to a critical moisture content of 38% (w/w basis). During the constant rate period, water is removed at $7 \times 10^{-4} \text{ kg m}^{-2} \text{ s}^{-1}$. Calculate the time taken to complete the constant rate period. Assume that the density of fresh carrot is 840 kg m^{-3} .

Solution to sample problem 16.2

Area of carrot cube available for drying:

$$\begin{aligned} A &= (0.015 \times 0.015) \times 6 \text{ sides (in fluidised bed drying, evaporation of} \\ &\quad \text{moisture can take place from all sides)} \\ &= 1.35 \times 10^{-3} \text{ m}^2 \end{aligned}$$

$$\begin{aligned} \text{Drying rate per cube} &= 0.0007 \times 0.00135 \\ &= 9.45 \times 10^{-7} \text{ kg s}^{-1} \end{aligned}$$

Expressing moisture contents on a dry weight (d/w) basis:

$$\begin{aligned} \text{Initial moisture content} &= 88\% \text{ (w/w basis)} \\ &= 0.88 \text{ kg water per kg product} \\ &\quad \text{(and therefore 0.12 kg solids per kg product)} \end{aligned}$$

$$\begin{aligned} \text{Initial moisture content (d/w basis)} &= 0.88/0.12 \\ &= 7.33 \text{ kg/kg solids} \end{aligned}$$

Similarly the critical moisture content (d/w basis) = $(0.38/0.62) = 0.61 \text{ kg/kg solids}$.

The amount of moisture removed during the constant rate period = $7.33 - 0.61 = 6.72 \text{ kg/kg solids}$.

$$\begin{aligned} \text{The initial mass of one cube} &= \text{density} \times \text{volume} \\ &= 840 \times (0.015)^3 \\ &= 2.84 \times 10^{-3} \text{ kg} \end{aligned}$$

$$\begin{aligned} \text{The initial mass of solids of one cube} &= (2.84 \times 10^{-3}) \times 0.12 \text{ kg solids per kg product} \\ &= 3.4 \times 10^{-4} \text{ kg solids} \end{aligned}$$

$$\begin{aligned} \text{Mass of water removed from one cube} &= 6.72 \times (3.4 \times 10^{-4}) \\ &= 2.28 \times 10^{-3} \text{ kg} \end{aligned}$$

$$\begin{aligned} \text{Time required} &= \frac{\text{mass of water removed}}{\text{drying rate}} \\ &= \frac{2.28 \times 10^{-3}}{9.5 \times 10^{-7}} \\ &= 2412.7 \text{ s} \\ &\approx 40 \text{ min} \end{aligned}$$

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 have a single falling-rate period (CD in Figs 16.3a 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 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 (see also the discussion of 'bound' and 'free' water, water sorption isotherms and water activity in Chapter 1, section 1.1.2).

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. To minimise this, the air temperature is controlled to balance the rate of moisture movement and reduce the extent of heat damage.

The falling-rate period is usually the longest part of a drying operation and, in some foods (e.g. 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 and liquid diffusion may be the main mechanism, whereas in later parts, vapour diffusion may be more important. In summary, 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 that 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.

Equations for the mechanisms of moisture movement by diffusion of water or movement of water vapour are described by Singh and Heldman (2001b).

The mechanisms that operate in the falling-rate period 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. In later stages of the falling-rate period, the temperature of the air determines the rate of heat transfer to the plane of evaporation within the food. Heat is transferred by conduction through the food and the rate is limited by the thermal conductivity of the food (see Chapter 10, section 10.1.1). The amount of heat reaching the liquid surface within the food controls the amount of evaporation that takes place and hence the vapour pressure at the liquid surface. The vapour pressure gradient between the liquid surface and the food surface controls the rate at which moisture is removed from the product.

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 heat and moisture to travel through the food. Other factors that influence the rate of drying include the following:

- The composition and structure of the food, which influence 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 their structure.
- Moisture is removed more easily from intercellular spaces than from within cells.
- Rupturing cells by blanching (Chapter 11) or size reduction (Chapter 3, section 3.1) increases the rate of drying.
- High concentrations of solutes such as sugars, salts, gums, starches, etc., increase the viscosity of a food and reduce the rate of moisture movement.
- The amount of food placed into a dryer in relation to its capacity influences the drying rate (in a given dryer, faster drying is achieved with smaller quantities of food).

For these reasons the rate at which foods dry may differ in practice from the idealised drying curves described above. Calculation of heat transfer rates in drying systems is often very complex and calculation of drying rates is further complicated if foods shrink during the falling-rate period. Mathematical modelling of dehydration systems is used to address these complexities (section 16.3).

Calculation of drying rate

In commercial operations, the speed of drying is often the limiting factor that controls the production rate that can be achieved. Where simple drying behaviour is found and data on critical and equilibrium moisture contents or thermal properties of foods is known, drying times can be estimated by calculation. However, this data is not available for all foods and pilot-scale drying trials are used to estimate drying times.

The moisture content of a food may be expressed on a wet weight basis (mass of water per unit mass of wet food) or a dry weight basis (mass of water per unit mass of dry solids in the food). In the calculations described below, a dry weight basis is used throughout. The moisture content of foods in other sections is given as wet weight basis. Derivations of the following equations are described by Singh and Heldman (2001c), Barbosa-Canovas (1996) Brennan (1994), and Brennan *et al.* (1990).

The rate of heat transfer is found using:

$$Q = h_s A (\theta_a - \theta_s) \quad [16.3]$$

where Q (J s^{-1}) = rate of heat transfer, h_s ($\text{W m}^{-2} \text{K}^{-1}$) = surface heat transfer coefficient, A (m^2) = surface area available for drying, θ_a ($^{\circ}\text{C}$) = average dry bulb temperature of drying air, θ_s ($^{\circ}\text{C}$) = average wet bulb temperature of drying air.

The rate of mass transfer is found using:

$$-m_c = K_g A (H_s - H_a) \quad [16.4]$$

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

$$-m_c = \frac{h_c A}{\lambda} (\theta_a - \theta_s) \quad [16.5]$$

where h_c ($\text{W m}^{-2} \text{K}^{-1}$) = surface heat transfer coefficient for convective heating, m_c (kg s^{-1}) = change of mass with time (drying rate), K_g ($\text{kg m}^{-2} \text{s}^{-1}$) = 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 flowrate of air using the following equations. For parallel air flow:

$$h_c = 14.3G^{0.8} \quad \boxed{16.6}$$

and for perpendicular air flow:

$$h_c = 24.2G^{0.37} \quad \boxed{16.7}$$

where G ($\text{kg m}^{-2} \text{s}^{-1}$) = mass flowrate 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:

$$-m_c = \frac{h_c}{\rho\lambda x} (\theta_a - \theta_s) \quad \boxed{16.8}$$

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:

$$t = \frac{\rho\lambda x(M_i - M_c)}{h_c(\theta_a - \theta_s)} \quad \boxed{16.9}$$

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 dryer (section 16.2.1), the drying time is found using:

$$t = \frac{r^2 \rho_l \lambda}{3h_c(\theta_a - \theta_s)} \frac{M_i - M_f}{1 + M_i} \quad \boxed{16.10}$$

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:

$$t = \frac{\rho\lambda x(M_c - M_e)}{h_c(\theta_a - \theta_s)} \ln \frac{(M_c - M_e)}{(M - M_e)} \quad \boxed{16.11}$$

where ρ (kg m^{-3}) = bulk density of food and x (m) = thickness of the pieces of food, 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.

These straightforward equations are suitable for simple drying systems. More complex models are described by Bahu (1997), Turner and Mujumdar (1996) and Pakowski *et al.* (1991).

Sample problem 16.3

A conveyor dryer (section 16.2.1) is required to dry peas from an initial moisture content of 78% to 16% moisture (wet weight basis), in a bed 10 cm deep that has a voidage of 0.4. Air at 85 °C with a relative humidity of 10% is blown perpendicularly through the bed at 0.9 m s⁻¹. The dryer belt measures 0.75 m wide and 4 m long. Assuming that drying takes place from the entire surface area of the peas and that there is no shrinkage, calculate the drying time and energy consumption in both the constant- and falling-rate periods. (Additional data: the equilibrium moisture content of the peas is 9%, the critical moisture content 100% (dry weight basis), the average diameter 6 mm, the bulk density 610 kg m⁻³ and the latent heat of evaporation 2300 kJ kg⁻¹.)

Solution to sample problem 16.3

In the constant rate period, from Equation 16.7,

$$\begin{aligned} h_c &= 24.2(0.9)^{0.37} \\ &= 23.3 \text{ W m}^{-2} \text{ K}^{-1} \end{aligned}$$

From Fig. 16.1 for $\theta_a = 85^\circ\text{C}$ and $\text{RH} = 10\%$,

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

To find the area of the peas,

$$\begin{aligned} \text{Volume of a sphere} &= \frac{4}{3}\pi r^3 \\ &= 4/3 \times 3.142 (0.003)^3 \\ &= 1.131 \times 10^{-7} \text{ m}^3 \end{aligned}$$

$$\begin{aligned} \text{Volume of the bed} &= 0.75 \times 4 \times 0.1 \\ &= 0.3 \text{ m}^3 \end{aligned}$$

$$\begin{aligned} \text{Volume of peas in the bed} &= 0.3(1 - 0.4) \\ &= 0.18 \text{ m}^3 \end{aligned}$$

$$\begin{aligned} \text{Number of peas} &= \frac{\text{volume of peas in bed}}{\text{volume of each pea}} \\ &= \frac{0.18}{1.131 \times 10^{-7}} \\ &= 1.59 \times 10^6 \end{aligned}$$

$$\begin{aligned} \text{Area of a sphere} &= 4\pi r^2 \\ &= 4 \times 3.142 (0.003)^2 \\ &= 113 \times 10^{-6} \text{ m}^2 \end{aligned}$$

and

$$\begin{aligned} \text{Total area of peas} &= (1.59 \times 10^6) \times (113 \times 10^{-6}) \\ &= 179.67 \text{ m}^2 \end{aligned}$$

From Equation 16.5,

$$\begin{aligned}\text{Drying rate} &= \frac{23.3 \times 179.67}{(85 - 42)} \\ &= 2.3 \times 10^6 \\ &= 0.0782 \text{ kg s}^{-1}\end{aligned}$$

From a mass balance,

$$\begin{aligned}\text{Volume of the bed} &= 0.3 \text{ m}^3 \\ \text{Bulk density} &= 610 \text{ kg m}^3\end{aligned}$$

Therefore,

$$\begin{aligned}\text{Mass of peas} &= 0.3 \times 610 \\ &= 183 \text{ kg} \\ \text{Initial solids content} &= 183 \times 0.22 \\ &= 40.26 \text{ kg}\end{aligned}$$

Therefore,

$$\begin{aligned}\text{Initial mass of water} &= 183 - 40.26 \\ &= 142.74 \text{ kg}\end{aligned}$$

At the end of the constant-rate period, solids remain constant and

$$\begin{aligned}\text{Mass of water remaining} &= 40.26 \times 3 \\ &= 120.78 \text{ kg}\end{aligned}$$

Therefore, during the constant-rate period

$$(142.74 - 120.78) = 21.96 \text{ kg water lost}$$

at a rate of 0.026 kg s^{-1}

$$\begin{aligned}\text{Drying time} &= \frac{21.96}{0.026} \\ &= 844.6 \text{ s} = 14 \text{ min}\end{aligned}$$

Therefore,

$$\begin{aligned}\text{Energy required} &= 0.026 \times 2.3 \times 10^6 \\ &= 5.98 \times 10^4 \text{ J s}^{-1} \\ &\approx 60 \text{ kW}\end{aligned}$$

In the falling-rate period, from section 16.1.1,

$$\begin{aligned}M_c &= 75/25 = 3 \\ M_f &= 16/84 = 0.19 \\ M_e &= 9/91 = 0.099\end{aligned}$$

From Equation 16.11,

$$\begin{aligned}
 t &= \frac{\rho\lambda x(M_c - M_e)}{h_c(\theta_a - \theta_s)} \ln \frac{(M_c - M_e)}{(M - M_e)} \\
 &= \frac{610 \times 2300 \times 0.1 (3 - 0.099)}{23.3 (85 - 42)} \ln \frac{(3 - 0.099)}{(0.19 - 0.099)} \\
 &= \frac{140\,300 \times 2.90}{10\,001.9} \times \ln 31.879 \\
 &= 406.2 \times 3.4619 \\
 &= 1406.35 \text{ s} \\
 &= 23.4 \text{ min}
 \end{aligned}$$

From a mass balance, at 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

$$\begin{aligned}
 \text{Total mass} &= 100/84 \times 24.16 \\
 &= 28.8 \text{ kg}
 \end{aligned}$$

and

$$\begin{aligned}
 \text{Mass loss} &= 96.6 - 28.8 \\
 &= 67.8 \text{ kg}
 \end{aligned}$$

Therefore,

$$\begin{aligned}
 \text{Average drying rate} &= \frac{67.8}{5531} \\
 &= 0.012 \text{ kg s}^{-1}
 \end{aligned}$$

and

$$\begin{aligned}
 \text{Average energy required} &= 0.012 \times (2.3 \times 10^6) \\
 &= 2.76 \times 10^4 \text{ J s}^{-1} \\
 &= 27.6 \text{ kW}
 \end{aligned}$$

16.1.2 Drying using heated surfaces

Slurries of food are deposited on a heated surface and heat is conducted from the hot surface, through the food, to evaporate moisture from the exposed surface. Heat transfer through liquids and solids is described in Chapter 10 (section 10.1.2). The main resistance to heat transfer is the thermal conductivity of the food (Table 10.2 in Chapter 10). Additional resistance arises if the partly dried food lifts off the hot surface to form a barrier layer of air between the food and the hot surface. Knowledge of the rheological properties of the food is necessary to determine the optimum thickness of the layer and the way in which it is applied to the heated surface. Equation 10.20 in Chapter 10 is used to calculate the rate of heat transfer and sample problem 16.4 shows its use.

Sample problem 16.4

A single-drum drier (section 16.2.2) 0.7 m in diameter and 0.85 m long, operates at 150 °C and is fitted with a doctor blade to remove food after three-quarters of a revolution. It is used to dry a 0.6 mm layer of 20% w/w solution of gelatin, pre-heated to 100 °C, 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 = 1020 kg m⁻³, the overall heat transfer coefficient = 1200 W m⁻² K⁻¹, and the latent heat of vaporisation of water = 2.257 kJ kg⁻¹. Assume that the critical moisture content of the gelatin is 450% (dry weight basis).)

Solution to sample problem 16.4

First,

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

Therefore

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

Initially the food contains 80% moisture and 20% solids. From a mass balance,

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

After drying, 80% solids = 0.172 kg. Therefore,

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

$$\begin{aligned}\text{Mass (water) loss} &= 0.86 - 0.215 \\ &= 0.645 \text{ kg}\end{aligned}$$

From Equation 16.3,

$$\begin{aligned}Q &= 1200 \times 1.87 (150 - 100) \\ &= 1.12 \times 10^5 \text{ J s}^{-1} \\ \text{Drying rate} &= \frac{1.12 \times 10^5}{2.257 \times 10^6} \text{ kg s}^{-1} \\ &= 0.05 \text{ kg s}^{-1}\end{aligned}$$

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 revolution should take $(100/75) \times 13 = 17.3$ s. Therefore the speed = 3.5 rpm.

16.1.3 Intermediate moisture foods

Intermediate moisture foods (IMFs) having water activities (a_w) between 0.6 and 0.84 are produced by a number of methods:

- Partial drying of raw foods that have high levels of naturally occurring humectants (e.g. dried fruits such as raisins, sultanas and prunes).
- Osmotic dehydration by soaking food pieces in a more concentrated solution of humectant (commonly sugar or salt). Osmotic pressure causes water to diffuse from the food into the solution to be replaced by the humectant (e.g. 'crystallised' or candied fruits using sugar as the humectant, or salt for fish and vegetables). Further details are given by Torreggiani (1993).
- Dry infusion involves drying the food pieces and then soaking in a humectant solution to produce the required water activity.
- Formulated IMFs have food ingredients, including humectants such as glycerol and propylene glycol, sugar or salt, that are mixed to form a dough or paste that is then extruded, cooked or baked to the required water activity (e.g. traditional products such as jams and confectionery, and newer products such as soft, moist snackfoods and petfoods).

IMFs are compact, convenient to consumers, ready-to-eat and are cheaper to distribute because they require no refrigerated transport or storage. Further details are given by Jayaraman (1995).

16.2 Equipment

The following section describes hot-air and heated-surface dryers. Other types of dryers include infrared, radio frequency and microwave dryers (Chapter 20, section 20.1.2) and freeze dryers (Chapter 23, section 23.1.2). Developments in drying technologies are described by Cohen and Yang (1995).

There are a large number of dryer designs and the characteristics of different types of drying equipment and their applications are summarised in Table 16.1. Details of commercial drying operations are given by Greensmith (1998). 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.

The selection of a dryer depends largely on the type of product, its intended use and its expected quality. For example, different designs are available for solid and liquid foods, for fragile foods that require minimal handling, and for thermally sensitive foods that require low temperatures and/or rapid drying. Batch dryers are most suited to production rates $150\text{--}200\text{ kg h}^{-1}$ dried solids, whereas continuous dryers are used for production rates $>1\text{--}2\text{ t h}^{-1}$. Other considerations include reliability, safety (including protection against fires or explosions for some products), capital and maintenance costs, energy consumption/fuel efficiency and the cost of equipment to ensure that exhaust emissions do not cause dust pollution or nuisance (e.g. from strong odours emitted to the local environment as in garlic or onion drying).

16.2.1 Hot-air dryers

Most commercial-scale dryers use steam to heat the drying air to temperatures $<250^\circ\text{C}$ via fin tube heat exchangers, although electric heaters may be used in small-scale

Table 16.1 Comparison of selected drying technologies

Type of dryer	Characteristics of the food							Drying characteristics				Examples of products
	Batch or continuous	Solid/liquid	Size of pieces	Initial moisture content	Heat sensitive	Mechanically strong	Capacity (kg wet food h ⁻¹)	Drying rate	Final moisture content	Evaporative capacity (kg h ⁻¹)	Labour requirement	
Bin	B	S	Int	Low		Yes		Low	Low	–	Low	Vegetables
Cabinet	B	S	Int	Mod			300–700	Mod	Mod	75	High	Fruits and vegetables
Conveyor/band	C	S	Int	Mod			2000–5000	Mod	Mod	1800	Low	Breakfast cereals, fruits, biscuits, nuts
Drum	C	S	Sm	Mod			600	Mod	Mod	400	Low	Gelatin, potato powder, infant foods, corn syrup
Foam mat	C	L	–	–	Yes		–	High	Low	–	Low	Fruit juices
Fluidised bed	B/C	S	Sm	Mod		Yes	–	Mod	Low	900	Low	Peas, grains, sliced/diced fruits and vegetables, extruded foods, powders
Kiln	B	S	Int	Mod			–	Low	Mod	–	High	Apple rings, hops
Microwave/dielectric	B/C	S	Sm	Low			–	High	Low	–	Low	Bakery products
Pneumatic/ring	C	S	Sm	Low	Yes	Yes	25 000	High	Low	16 000	Low	Gravy powder, potato powder, soup powder
Radiant	C	S	Sm	Low			–	High	Low	–	Low	Bakery products
Rotary	B/C	S	Sm	Mod	Yes	Yes	–	Mod	Mod	5500	Low	Cocoa beans, nuts
Spin flash	C	L	–	–	Yes		–	High	Low	7800	Low	Pastes, viscous liquids
Spray	C	L	–	–			30 000	High	Mod	16 000	Low	Instant coffee, milk powder
Sun/solar	B	S	Int	Mod			–	Low	Mod	–	High	Fruits and vegetables
Trough	C	S	Int	Mod			250	Mod	Mod	–	Low	Peas, diced fruits and vegetables
Tunnel	C	S	Int	Mod			5000	Mod	Mod	–	Mod	Fruits and vegetables
Vacuum band	C	L	–	–	Yes		–	High	Low	150	Low	Chocolate crumb, juices, meat extract
Vacuum tray	B	S,L	–	–	Yes		–	High	Low	–	Mod	Fruit pieces, meat or vegetable extracts

Key: S = solid, L = liquid, B = batch, C = continuous, Sm = small (powders), Int = intermediate to large (granules, pellets, pieces), Mod = moderate. Adapted from Barr and Baker (1997), Axtell and Bush (1991) and Sapakie and Renshaw (1984), Greensmith (1998) and Heldman and Hartel (1997)

equipment (Brennan 1994). Direct heating using burning gas is used in some applications (e.g. spray drying or pneumatic ring drying), which is more thermally efficient than indirect heating but has two main disadvantages: first, moisture is produced by combustion which increases the humidity of the air and hence reduces its moisture-carrying capacity (section 16.1); and secondly, there may be other products of combustion that could contaminate foods, including nitrogen oxides (NOX) which could increase the levels of nitrites/nitrates in the food, and carcinogenic *N*-nitrosamines. Low-NOX burners have been developed to reduce these problems (also Chapter 10, section 10.2).

The cost of fuel for heating air is the main economic factor affecting drying operations, and commercial dryers 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 10, section 10.2.3) or prewarming the feed material;
- drying in two stages (e.g. fluidised beds followed by bin drying, or spray drying followed by fluidised bed drying);
- preconcentrating liquid foods to the highest possible solids content using multiple effect evaporation (Chapter 14, section 14.1.2) – 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 (section 16.3).

Further details of energy efficiency measures in dehydration are given by Heldman and Hartel (1997) and Driscoll (1995).

Bin dryers

Bin dryers are large, cylindrical or rectangular insulated containers fitted with a mesh base. Heated air (40–45 °C) passes up through a bed of food at relatively low velocities (e.g. 0.5 m s⁻¹ per m² of bin area). These dryers have a high capacity and low capital and running costs, and are mainly used for ‘finishing’ products such as cut or whole vegetables (from 10–15% to 3–6% moisture content) after initial drying in other types of dryer. They improve the operating capacity of initial dryers by removing the food when it is in the falling-rate period, when moisture removal is most time consuming. The partial pressure of water vapour in the incoming air must therefore be below the equilibrium vapour pressure of dried food at the drying temperature. The long holding time, typically >36 h, and deep bed of food permit variations in moisture content to be equalised and the dryer acts as a store to smooth out fluctuations in the product flow between drying and packaging operations. The dryers may be several metres high and it is therefore important that foods have sufficient strength to withstand compression. This enables spaces between the pieces to be retained and allow the passage of hot air through the bed. This type of dryer, together with fluidised bed, cabinet, conveyor, trough and kiln dryers (below), are examples of ‘through-flow’ dryers that are described in detail by Sokhansanj (1997).

Cabinet (or tray) dryers

These dryers consist of an insulated cabinet fitted with a stack of shallow mesh or perforated trays, each of which contains a thin (2–6 cm deep) layer of food. Hot air is

blown at $0.5\text{--}5\text{ m s}^{-1}$ 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 increase the rate of drying. Tray dryers are used for small-scale production ($1\text{--}5\text{ t day}^{-1}$) or for pilot-scale work. They have low capital and maintenance costs and have the flexibility to dry different foods. However, they have relatively poor control and produce more variable product quality because food dries more rapidly on trays nearest to the heat source. A low-cost, semi-continuous mechanism which overcomes this problem by periodically moving trays through the stack has been developed (Axtell and Russell 2000, Axtell and Bush 1991).

Conveyor dryers (belt dryers)

Continuous conveyor dryers are up to 20 m long and 3 m wide (Fig. 16.4). 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 downward in later stages to prevent dried food from blowing out of the bed. Two- or three-stage dryers (Fig. 16.5) mix and re-pile the partly dried food into deeper beds (to 15–25 cm and then 250–900 cm in three-stage dryers). This improves the uniformity of drying and saves floor space. For example, potato strips initially piled on a conveyor in a 10 cm deep layer, shrink to a 5 cm layer by the time they reach the end of the first stage. By restacking the material to a depth of 30 cm, the conveyor area needed for the second stage is 20% of that which would have been necessary without restacking. Foods are dried to 10–15% moisture content and then finished in bin dryers. This equipment has good control over drying conditions and high production rates (e.g. up to 5.5 t h^{-1}). It is used for large-scale drying of fruits and vegetables. Dryers may have computer controlled independent drying zones and automatic loading and unloading to reduce labour costs.

A second variation is trough dryers (or belt-trough dryers) in which small, uniform pieces of food are dried on a mesh conveyor belt that 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



Fig. 16.4 Conveyor dryer (courtesy of Aeroglide Corp. at www.aeroglide.com).

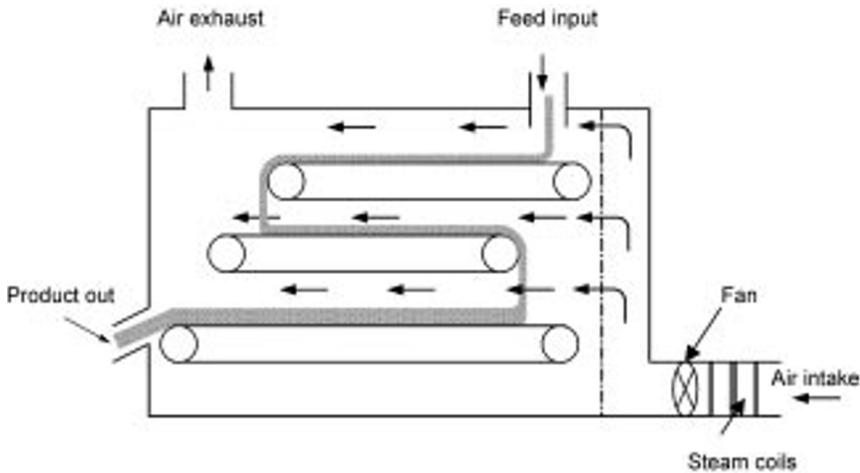


Fig. 16.5 Three-stage conveyor dryer.

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 dryers have high drying rates (e.g. 55 min for diced vegetables, compared with 5 h in a tunnel dryer), 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 dryers.

A further application of conveyor dryers is foam-mat drying in which liquid foods are formed into a stable foam by the addition of a stabiliser or edible surfactant (Chapter 1, section 1.1.2 and Appendix A4) and aeration with nitrogen or air. The foam is spread in a thin layer (2–3 mm) on a perforated belt and dried rapidly in two stages by parallel and then counter-current air flows (Table 16.2). 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 that has good rehydration properties. Examples

Table 16.2 Advantages and limitations of different arrangements of air flow through dryers

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 spoilage.	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.

include milk, mashed potatoes and fruit purées. 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 (see also spray foam drying and vacuum foam mat drying below). The cost of foam mat drying is higher than spray or drum drying but lower than freeze drying.

Explosion puff drying

Explosion puff drying involves partially drying food to a moderate moisture content and then sealing it into a closed, rotating cylindrical pressure chamber. The pressure and temperature in the chamber are increased using superheated steam at $\approx 250^\circ\text{C}$ and $\approx 380\text{ kPa}$ and then instantly released to atmospheric pressure. The rapid loss of pressure causes vapourisation of some of the water and causes the food to expand and develop a fine porous structure. This permits faster final drying (approximately two times faster than conventional methods) particularly for products that have a significant falling-rate period, and also enables more 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.

Fluidised bed dryers

The main features of a fluidised bed dryer are a plenum chamber to produce a homogeneous region of air and prevent localised high velocities, and a distributor to evenly distribute the air at a uniform velocity through the bed of material. 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. 16.6). A sample calculation of the air velocity needed for fluidisation is described in Chapter 1 (sample

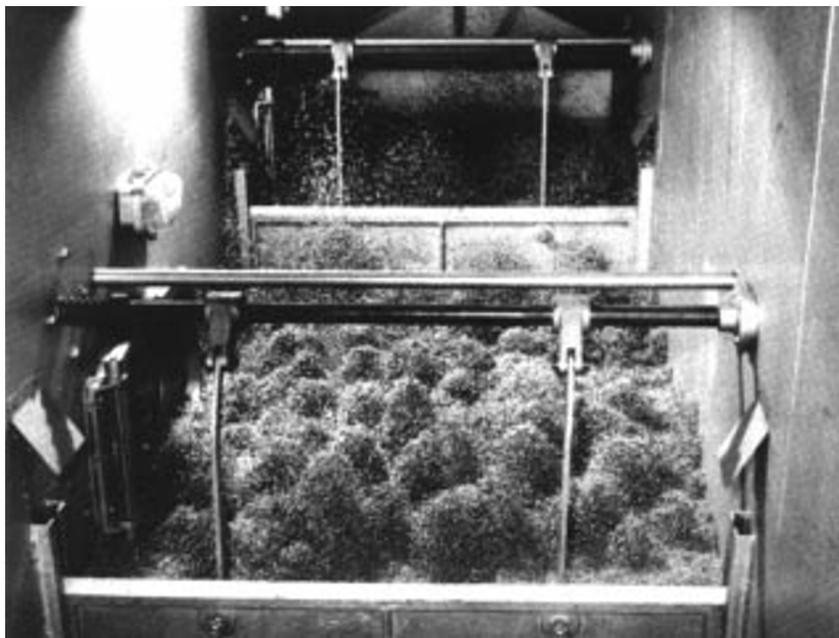


Fig. 16.6 Fluidised bed drying (courtesy of Petrie Technologies at www.petrield.com).

problem 1.7). A disengagement or ‘freeboard’ region above the bed allows disentrainment of particles thrown up by the air. Air from the fluidised bed is fed into cyclones (see Fig. 16.11) to separate out fine particles, which are then added back to the product or agglomerated (Bahu 1997). These dryers are compact and have good control over drying conditions and high drying rates.

In batch operation, the product is thoroughly mixed by fluidisation and this leads to a uniform moisture content. In continuous ‘cascade’ operation the trays vibrate to move the food from one tray to the next, but there is a greater range of moisture contents in the dried product and bin dryers are therefore used for finishing. The main applications are for small, particulate foods that are capable of being fluidised without excessive mechanical damage, including grains, herbs, peas, beans, coffee, sugar, yeast, desiccated coconut, extruded foods and tea.

In a development of the fluidised-bed dryer, named the ‘Toroidal bed’ dryer, a fluidised bed of particles is made to rotate around a torus-shaped chamber by hot air blown directly from a burner. The dryer has very high rates of heat and mass transfer and substantially shorter drying times. Larger pieces require a period of moisture equilibration before final drying. The dryer is also suitable for agglomeration and puff drying in addition to roasting, cooking and coating applications (Anon 2005). Brennan *et al.* (2001) studied the effect of drying and puffing conditions in a toroidal bed dryer on the volume of reconstituted dried puffed potato cubes, their rehydration characteristics and texture. They found that the volume of the dried cubes decreased with increase in initial drying time; the shorter the initial drying time the higher the rehydration ratio; and the hardness, springiness, cohesiveness, chewiness and gumminess of the rehydrated cubes all increased with an increase in drying and puffing time.

Another development of the fluidised bed principle is the ‘spin flash’ dryer (Fig. 16.7), in which a vertical cylindrical drying chamber is fitted with an inverted cone rotor at the base. Hot air from a direct fired gas burner enters tangentially and this, together with the action of the rotor, causes a turbulent rotating flow of air that carries foods up through the chamber. It is used to dry wet cakes or pastes (e.g. filter cakes (Chapter 5, section 5.2) or food pigments). The cake is fed into the drying chamber using a screw conveyor, where the lumps become coated in dry powder. The rotor breaks them into small pieces that are

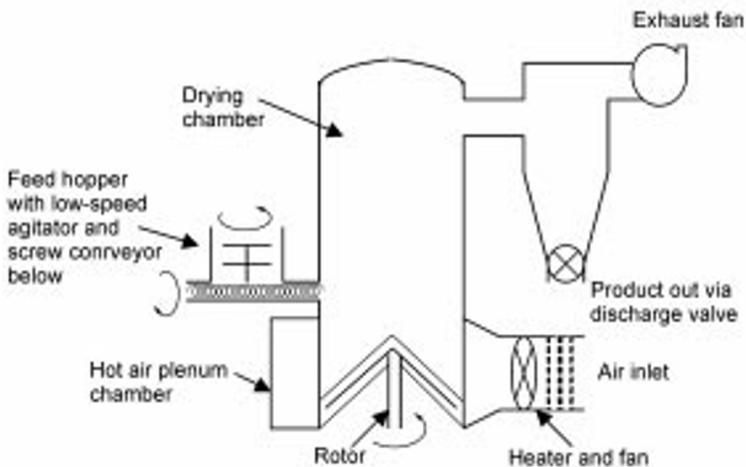


Fig. 16.7 Spin flash dryer (adapted from Anon 2000).

Table 16.3 Comparison of spin flash drying and spray drying, both producing 400 kg h⁻¹ of powder at 0.4% moisture using direct heating

Parameter	Spin flash dryer	Spray dryer
Space requirements		
Chamber diameter (m)	0.8	4.25
Floor area (m ²)	30	60
Building height (m)	5	14
Building volume (m ³)	50	700
Performance		
Feed solids (%)	45	30
Feedrate (kg h ⁻¹)	887	1362
Water evaporation (kg h ⁻¹)	486	961
Gas consumption (m ³ h ⁻¹)	62	125
Power consumption (kW h)	30	40

Adapted from Anon (2000)

then fluidised by the drying air. As they dry, the pieces break up and release powder particles that pass up the walls of the dryer, coating new feed as it enters. The particles are therefore removed from the hot air as soon as they are light enough, and the fluidised bed remains at the wet bulb temperature of the drying air, both of which reduce heat damage to the food. At the top of the dryer, the particles pass through a classification screen that is changeable for different product particle size ranges. Dry particles are carried to a cyclone separator by the fluidising air. A comparison of spin flash drying and spray drying is shown in Table 16.3.

The centrifugal fluidised bed dryer is used to pre-dry sticky foods that have a high moisture content, or to dry diced, sliced and shredded vegetables that are difficult to fluidise and/or are too heat-sensitive to dry in conveyor dryers. Food is filled into a drying chamber, which rotates horizontally at high speed. Hot air is forced through the perforated dryer wall and through the bed of food at a high velocity that overcomes the centrifugal force and fluidises the particles (Cohen and Yang 1995).

The 'spouted bed' dryer is used for particles larger than 5 mm that are not readily fluidised in a conventional fluidised bed dryer. The drying air enters a conical chamber at the base and carries particles up through the dryer in a cyclical pattern. This type of dryer produces high rates of mixing and heat transfer and is used for drying heat-sensitive foods.

Fluidised bed dryers are also used to encapsulate solid particles. The particles have an aqueous solution of coating material sprayed onto them, which then dries to form a protective layer when the water is evaporated. Fluidised bed granulators agglomerate particles by spraying a binding liquid into the fluidised bed of granules. The process has benefits in not producing dust and produces powders having particle sizes in the range of 50–2000 μm (Bahu 1997) (see also types of powders in section on spray drying below).

Impingement dryers

Impingement dryers have been used in paper and textile industries for many years and have more recently been used to dry foods such as coffee or cocoa beans, rice and nuts. Dryers have an array of hot air jets that produce high-velocity air, which impinges perpendicularly to the surface of products. The air almost completely removes the boundary layer of air and water vapour (section 16.1) and therefore substantially increases the rates of heat and mass transfer and reduces processing times. Typically, the air temperature is 100–350 °C and the jet velocity is 10–100 m s⁻¹ (Sarkar *et al.* 2004).

Granular products in particular dry faster and are dried more uniformly because a type of fluidised bed is created by the high air velocity. Moreira (2001) describes the advantages of using superheated steam instead of hot air in impingement dryers, including reduced oxidation of products, improved nutritional value and improved rates of moisture evaporation from the food surfaces.

Kiln dryers

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 dryers have a large capacity and are easily constructed and maintained at low cost.

Pneumatic dryers

In these types of dryer, foods are metered into metal ducting and suspended in hot air. In vertical dryers the air flow is adjusted so that lighter and smaller particles that dry more rapidly are carried to a cyclone separator faster than 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 (known as 'pneumatic ring' dryers) and the product is recirculated until it is adequately dried (Fig. 16.8). Humid air is continuously vented from the dryer and replaced with dry air from the heater. High-temperature short-time ring dryers (or 'flash' dryers) have air velocities from 10 to 40 m s⁻¹. Drying takes place within 0.5–3.5 s if only surface moisture is to be removed, or within a few minutes when internal moisture is removed. These dryers are therefore suitable for foods that lose moisture rapidly from the surface, are not abrasive and do not break easily. Evaporative cooling of the particles prevents heat damage to give high-quality products.

Pneumatic dryers 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 suitable for drying moist free-flowing particles (e.g. milk or egg powders and potato granules), usually partly dried to less than 40% moisture and having uniform particle size and shape over a range from 10–500 μm. They may be used after spray drying to further reduce the moisture content, and in some applications the simultaneous transportation and drying of the food may be a useful method of materials handling (also Chapter 27, section 27.1.2).

Rotary dryers

An inclined, rotating metal cylinder is fitted internally with flights that cause small pieces of food to cascade through a stream of parallel or counter-current hot air (Table 16.2) as they move through the dryer. 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 dryers. However, the damage caused by impact and abrasion in the dryer restricts this method to relatively few foods (e.g. nuts and cocoa beans). To overcome this problem, a variation of the design, named a 'rotary louvre' dryer, has longitudinal louvres positioned to form an inner drum. Hot air passes through the food particles to form a partially fluidised rolling bed on the base of the drum. Further details are given by Barr and Baker (1997).

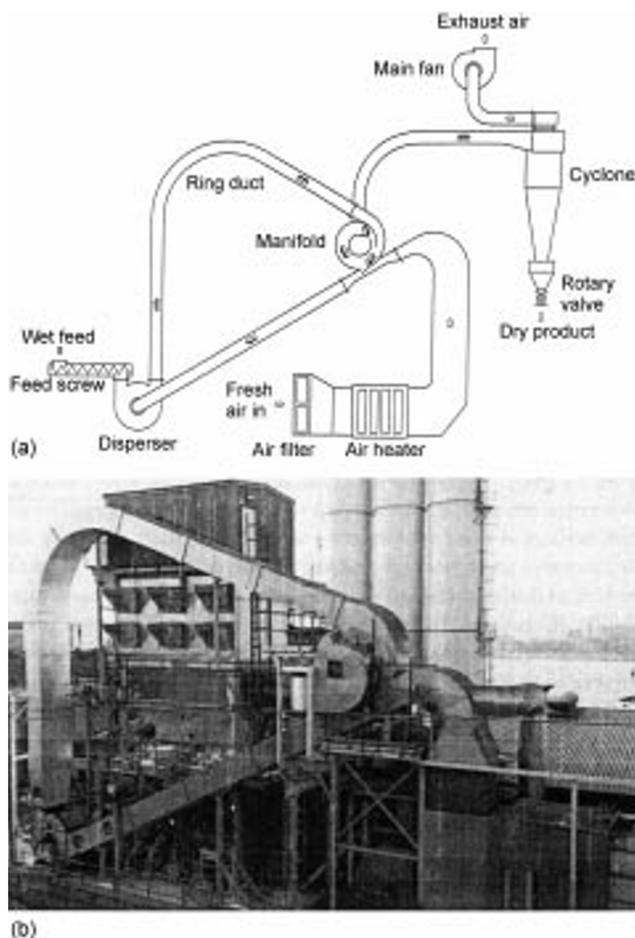


Fig. 16.8 Pneumatic ring dryer: (a) principle of operation (courtesy of Barr Rosin Ltd.); (b) equipment (from Greensmith 1998).

Spray dryers

Spray dryers vary in size from small pilot-scale equipment that can also be used to dry low-volume, high-value products such as enzymes and flavours, to large commercial models capable of producing $10\,000\text{ kg h}^{-1}$ of product (Deis 1997). A dispersion of pre-concentrated food (40–60% moisture) is first ‘atomised’ to form a fine mist of droplets that are sprayed into a co- or counter-current flow of hot air (Table 16.2) in a large drying chamber (Fig. 16.9).

One of the following types of atomiser is used:

- *Centrifugal (rotary, disc or wheel) atomiser*. Liquid is fed to the centre of a rotating disc having a peripheral velocity of $90\text{--}200\text{ m s}^{-1}$. Droplets, $50\text{--}60\ \mu\text{m}$ in diameter, are flung from the edge to form a uniform spray (Fig. 16.10a) that decelerates to $0.2\text{--}2\text{ m s}^{-1}$ as the droplets fall through the drying chamber. It is used for high production rates, unless the feed has a high percentage of fats (e.g. dairy products), when nozzle atomisers are used.
- *Single-fluid (or pressure) nozzle atomiser* (Fig. 16.10b). Liquid is forced at a high pressure ($700\text{--}2000\text{ kPa}$) through a small aperture at $\approx 50\text{ m s}^{-1}$ to form droplet sizes

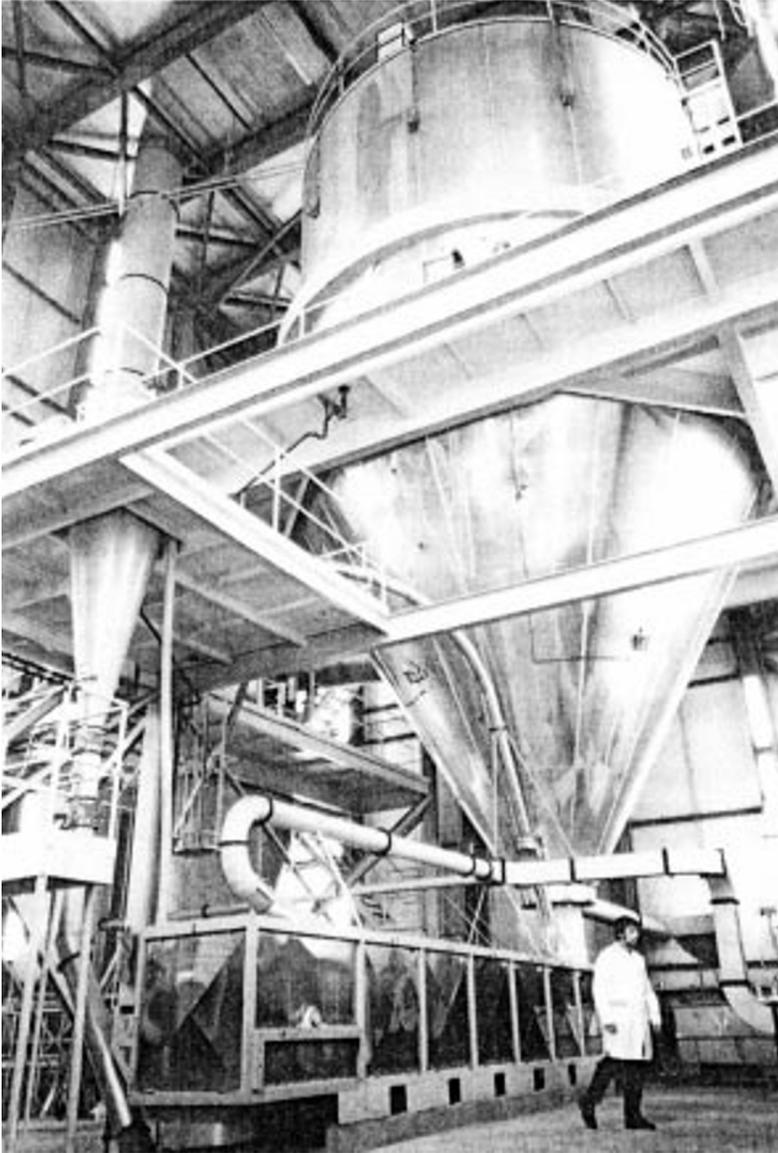


Fig. 16.9 Spray dryer (from Greensmith 1998).

of 180–250 μm . Grooves on the inside of the nozzle cause the spray to form into a cone shape. The spray angle and spray direction can be varied to use the full volume of the drying chamber. However, nozzle atomisers are susceptible to blockage by particulate foods, and abrasive foods gradually widen the apertures and increase the average droplet size.

- *Two-fluid nozzle atomiser.* Compressed air creates turbulence that atomises the liquid. The operating pressure is lower than the pressure nozzle, but a wider range of droplet sizes is produced. They are used for more viscous or abrasive feeds, or for producing small particle sizes that are not possible with a single-fluid nozzle.
- *Ultrasonic nozzle atomiser.* A two-stage atomiser in which liquid is first atomised by a

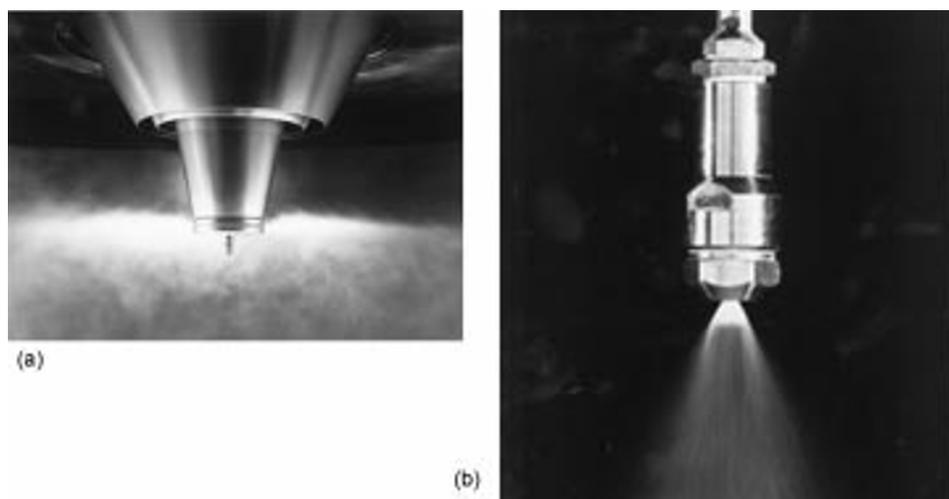


Fig. 16.10 (a) Rotary and (b) nozzle atomisers (courtesy of GEA Niro, Soeborg, Denmark at www.niroinc.com).

nozzle atomiser and then using ultrasonic energy to induce cavitation (also Chapter 9, section 9.6).

The viscosity of the feed material and the presence of particles determine which type of atomiser is most suitable. Frequently, both nozzle and disc atomisers are fitted in the same drying chamber to increase the flexibility of the dryer to handle different foods. Further details of the advantages and limitations of different atomisers are given by Masters (1991, 1997). There are a large number of combinations of atomiser, drying chamber design, air heating and powder collecting systems which arise from the different requirements of the very large variety of food materials that are spray dried (e.g. milk, egg, coffee, cocoa, tea, potato, ice cream mix, butter, cream, yoghurt and cheese powder, coffee whitener, fruit juices, meat and yeast extracts, and wheat and corn starch products). Details are given by Deis (1997). Different chamber designs include cylindrical flat bottom types or conical bottom chambers that are designed for the spray pattern produced by disc atomisers. Rapid drying, within 1–30 s, takes place because of the very large surface area of the droplets. The size of the chamber and flow pattern of moving air within the chamber enable the largest droplets to dry before they contact the wall. This prevents the deposition of partially dried product on the wall.

The temperature of drying depends mostly on the type of food and the required powder quality. The factors that are taken into account when selecting the design of a dryer include:

- properties of the feed material, including temperature sensitivity, viscosity, solids content, presence/absence and size of particulates; and
- properties required in the powdered product, including the moisture content, bulk density, explosion hazard and final particle size.

Most of the residence time of particles in a single-stage dryer is used to remove the final moisture, and the outlet temperature must be sufficiently high to do this. Typically, inlet air at 150–300 °C produces an outlet air temperature of 90–100 °C, which corresponds to a wet-bulb temperature (and product temperature) of 40–50 °C. This produces little heat damage to the food, but higher quality is produced using a lower air

inlet temperature (e.g. 65–70 °C) (Heldman and Hartel 1997). Co-current air flow is most often used with heat-sensitive materials whereas counter-current air flow gives a lower final moisture content (Table 16.2).

The main advantages of spray drying are rapid drying, large-scale continuous production of powders that have closely controlled properties, low labour costs and relatively simple control, operation and maintenance. The major limitations are high capital costs and the requirement for a relatively high moisture content in the feed to ensure that it can be pumped to the atomiser (Table 16.3). This results in higher energy costs (to remove the moisture) and higher volatile losses. Conveyor-band dryers, spin flash dryers and fluidised bed dryers are gaining in popularity, as they are more compact and energy efficient.

The economics of spray dryer operation are influenced by the temperature of drying and the recycling of drying air. Energy efficiency in spray dryers is increased by raising the inlet air temperature as high as possible (e.g. to ≈ 220 °C), and keeping the outlet temperature as low as possible (e.g. ≈ 85 °C) to make maximum use of the energy in the hot air. However, this creates potential risks of heat damage to some products and higher final moisture contents. Therefore a balance is required between the cost of production and product quality. Air recirculation enables up to 25% of the total heat to be reused and air-to-air heat recuperators are also used to recover energy from the exhaust air to further reduce energy costs.

Depending on the design of the dryer, the dry powder and air can be separated in a cyclone separator (Fig. 16.11). Alternatively, the product is separated from exhaust air at the base and removed by either a screw conveyor or a pneumatic system. Fine particles in the air are removed using a cyclone, bag filters, electrostatic precipitators or scrubbers, then bagged or returned for agglomeration.

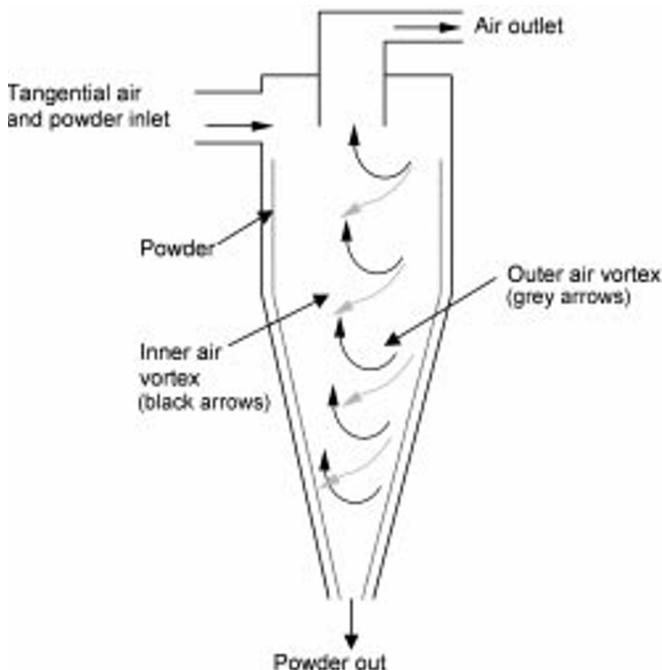


Fig. 16.11 Action of a cyclone separator (adapted from Brennan 1994).

The fluidised spray dryer has a fluidised bed installed in the spray drying chamber. Small particles entrained in the air are recycled from the exhaust system and agglomerated in the fluidised bed. The combination of spray and fluidised bed drying gives efficient use of the drying chamber and produces agglomerated products that have a low bulk density and good instantising characteristics. Further details of these different types of fluidised bed dryers are given by Bahu (1997). A spray dryer with an integrated fluidised bed dryer is an example of a multi-stage dryer. It reduces energy consumption by 15–20% and gives greater control over product quality. Most drying, to 10–15% moisture, takes place in the spray dryer and final drying, to 5% moisture, takes place over a longer time and at a lower temperature in the fluidised bed dryer. The fluidised bed dryer reduces the evaporative load on the spray dryer, which in turn permits a lower outlet air temperature and an increased feedrate to the spray dryer, which leads to higher productivity. As the particles are moist when they enter the fluidised bed, they agglomerate with the dryer particles. An external fluidised bed can also be used for a third cooling stage. Multi-stage drying is also useful for hygroscopic, sticky or high fat products (Deis 1997).

Types of powders

The particle size and bulk density of a powder are important considerations in many applications (Table 16.4). Many powdered foods used as ingredients are required to possess a high bulk density and contain a range of both small and large particles. The small particles fill the spaces between larger ones and thus flow more easily, and also reduce the amount of air in the powder to promote a longer storage life.

There are a number of factors that affect the bulk density of powders:

- Centrifugal atomisers produce smaller droplets and hence higher bulk-density products than nozzle atomisers. Centrifugal atomisers produce more uniform droplet sizes (and hence particle sizes) than nozzle atomisers.
- Aeration of the feed decreases bulk density. Foam spray drying involves making the feed material into a foam using compressed nitrogen or air. Whereas spray-dried particles are hollow spheres surrounded by thick walls of dried material, the foam spray-dried particles have many internal spaces and relatively thin walls, which have typically half the density of spray-dried products.

Table 16.4 Properties of selected powdered foods (reproduced by permission of Elsevier)

Powder	Particle size (μm)	Moisture content (% w/w)	Bulk density (kg m^{-3})	Particle density (kg m^{-3})
Cellulose	43	5	410	1550
Cocoa	7.6	4.4	360	1450
Cornflour	49	9	730	1490
Cornstarch	11.9	10	760	1510
Maltodextrin	55	4.3	600	1390
Salt	12	0.04	1170	2200
Salt	5.8	0.04	870	2210
Soy flour	20.5	6.2	600	1430
Sugar	12	0.06	710	1610
Tea	25	6.6	910	1570
Tomato	320	17.8	890	1490
Wheat flour	51	10	710	1480

Adapted from Fitzpatrick *et al.* (2004)

- Small increases in inlet air temperature decrease bulk density, but an excessively high temperature can also increase bulk density by retaining moisture within case-hardened shells of the particles. During drying in a spray dryer, water evaporates from the surface of particles to form a hard shell, and residual moisture within the shell expands to create porous particles. Maintaining the surface wetness of particles is important for constant-rate drying; if the air temperature is too high, the dried layer at the surface reduces the rate of evaporation.
- If a low bulk density is required, the product should be in contact with the hottest air as it leaves the atomiser, whereas if the outlet air temperature is too low, this increases the moisture content and bulk density of the product.
- Steam injection during atomisation removes air in the centre of the particle and prevents early formation of the shell, to produce a higher bulk density powder.
- More dilute feed material or higher feed temperatures can also increase the bulk density of the powder by forming smaller droplets or by de-aerating them (Deis 1997).
- The nature and composition of the food. Low-fat foods (e.g. fruit juices, potato and coffee) are more easily formed into free-flowing powders than fatty foods such as whole milk or meat extracts.

Fine powders ($<50 \mu\text{m}$) are difficult to handle, may cause a fire or explosion hazard and are difficult to rehydrate (Brennan 1994). Agglomeration is a size enlargement operation in which an open structure is created when particles of powder are made to adhere to each other. It increases the average size of particles from ≈ 100 to $250\text{--}400 \mu\text{m}$ and reduces the bulk density of the powder from ≈ 690 to $\approx 450 \text{ kg m}^{-3}$ (Deis 1997) (Table 16.5). On rehydration, the agglomerated particle sinks below the water surface and breaks apart, allowing the smaller particles to completely hydrate, leading to faster and more complete dispersion of the powder. The characteristics of ‘instantised’ powders are termed ‘wettability’, ‘sinkability’, ‘dispersibility’ and ‘solubility’. For a powder to be considered ‘instant’, it should complete these four stages within a few seconds. The convenience of instantised powders for retail markets outweighs the additional expense of production, packaging and transport and for processors, agglomeration also reduces problems caused by dust. Details of the properties and handling of powders are given by Lewis (1996) and Barbosa-Canovas *et al.* (2005).

Powders can be agglomerated by a number of different methods, described by Zemelman and Kettunen (1992). In the ‘straight-through’ process, fines that are collected in the cyclone are fed back into the feed mist from the atomiser in the spray dryer, where they stick to the moist feed particles to produce agglomerates that are then dried in the dryer. Greater control is achieved using fluidised bed agglomerators: particles are re-

Table 16.5 Differences in reconstitution and physical properties of agglomerated and non-agglomerated skim milk powder

Property	Non-agglomerated powder	Agglomerated powder	
		Integrated spray dryer/ fluidised bed	Re-wetted in fluidised bed
Wettability (s)	>1000	<20	<10
Dispersibility (%)	60–80	92–98	92–98
Insolubility index	<0.1	<0.1	<20
Average particle size (μm)	<100	>250	>400
Bulk density (kg m^{-3})	640–690	450–545	465–500

Adapted from Anon (2000)

moistened under controlled conditions in low-pressure steam, humid air or a fine mist of water and then re-dried in a fluidised bed dryer; or they are discharged from a spray dryer at a slightly higher moisture content (5–8%) onto a fluidised bed dryer. Alternatively, a binding agent (e.g. maltodextrin, gum arabic or lecithin) is used to bind particles together before drying in a fluidised bed. This method has been used for foods with a relatively high fat content (e.g. whole milk powder, infant formulae) as well as fruit extracts, corn syrup solids, sweeteners, starches and cocoa mixes.

Spray drying is the most common means of encapsulation in the food industry. For example, encapsulated flavours are dried by first forming an oil-in-water emulsion (Chapter 3, section 3.2) of the oil-based essence with an aqueous dispersion of a hydrocolloid coating material (e.g. gelatine, dextrin, gum arabic or modified starch). As moisture is evaporated from the aqueous phase, the polymeric material forms a coating around the oily essence. These particles can then be agglomerated to improve dispersability and flowability. Water-soluble materials (e.g. aspartame) are encapsulated by spray coating or fluidised bed coating. Particles are suspended in an upward-moving heated airstream. The coating material is atomised and dries on the particles to coat them uniformly as they are carried up through the dryer several times through a coating cycle. Other ingredients (e.g. powdered shortenings, acidulants, vitamins, solid flavours, sodium bicarbonate or yeast) are encapsulated in a high melting point vegetable fat (e.g. a stearine or wax having melting points of 45–67°C) and spray-cooled using cold air in the drying chamber to harden the fat. If lower melting point fats (32–42°C) are used, the material is spray-chilled at lower temperatures (Deis 1997). Further examples of encapsulation are given in Chapter 24 (section 24.3).

Sun and solar drying

Sun drying (without drying equipment) is the most widely practised agricultural processing operation in the world, and more than 250 000 000 t of fruits and grains are dried annually by solar energy. In some countries, foods are simply laid out in fields or on roofs or other flat surfaces and turned regularly until they are dry. More sophisticated methods (solar drying) use equipment to collect solar energy and heat the air, which in turn is used for drying. There are a large number of different designs of solar dryers, described in detail by Brenndorfer *et al.* (1985) and Imrie (1997). These include:

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

Small solar dryers have been investigated at research institutions, particularly in developing countries, for many years but their often low capacity and insignificant improvement to drying rates and product quality, compared with hygienic sun drying, have restricted their commercial use. Larger solar dryers 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 dryers are now in use to dry fruit to export standards (Axtell and Russell 2000). Both solar and sun drying are simple inexpensive technologies, in terms of capital and operating costs. Purchased 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 fuel-fired dryers, which result in products that have lower quality and greater variability. In addition, drying is dependent on the time of day and the weather. Extended periods when drying does not

occur risks microbial growth on the product. Developments of solar energy include its use to reduce energy consumption in fuel-fired dryers by preheating air and preheating feed water in boilers (Anon 2004). Umesh Hebbar *et al.* (2004) found that a combination of infrared and hot-air drying of carrot and potato reduced the drying time by 48% and consumed 63% less energy compared with drying with hot air alone.

Tunnel dryers

In this equipment, foods are dried on trays that are stacked on trucks, which are programmed to move semi-continuously through an insulated tunnel. Different types of air flow are used depending on the product (Table 16.2). Typically, fruits and vegetables are dried to 15–20% moisture in a 20 m tunnel that contains 12–15 trucks having a total capacity of 5 t of food. The partly dried food is then finished in bin dryers. 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.

Ultrasonic and acoustic dryers

High-power ultrasound (Chapter 9, section 9.6) can accelerate mass transfer processes to remove moisture from foods without significant heating. Heat-sensitive foods can therefore be dried more rapidly and at lower temperatures than in conventional hot-air driers without affecting their quality characteristics. The increases in the rate of moisture evaporation are due to pressure variations at air–liquid interfaces. Mulet *et al.* (2003) describe these effects, including ‘micro-stirring’ at the food interface and rapid alternating contraction and expansion of the material (the ‘sponge effect’), which creates microscopic channels that may make moisture removal easier. The high-intensity acoustic waves also produce cavitation of water molecules in the solid food, which may help remove strongly bound moisture (Gallego *et al.* 1999). García-Pérez *et al.* (2006) and de la Fuente-Blanco *et al.* (2006) report studies of fluidised air drying at 40 °C using a high-intensity ultrasonic field at a frequency of 20 kHz, with a power capacity of ≈ 100 W. They showed that the drying rate is influenced by the air flowrate, ultrasonic power and mass loading of the dryer. However, at high air velocities, the ultrasound acoustic field was disturbed and reduced the effect on drying. Difficulties in the propagation of ultrasound waves in air have led to the development of specially adapted transducers.

Jambrak *et al.* (2007) compared pretreatment of mushrooms, Brussels sprouts and cauliflower by blanching at 80 °C, or treatment using ultrasound with a 20 kHz ultrasound probe or a 40 kHz ultrasound bath before drying. They found that the drying time was shortened for all samples after ultrasound treatment, compared with untreated samples, and that ultrasound-treated samples absorbed more water on rehydration than untreated samples. In ultrasonic spray drying, small droplets are produced by ultrasound and then heated to remove the water. Drying takes place very rapidly (sometimes within seconds) with low-fat solutions, but less well with oily or fatty foods that do not dry easily (Cohen and Yang 1995). Ultrasound has also been used to accelerate mass transfer in osmotic dehydration of apple, and in cheese and meat brining (Mulet *et al.* 2003). An increase in mass transfer is achieved if a threshold power value is achieved for the particular product. However, large-scale commercial development of ultrasound drying has been slow, owing to technical difficulties in transferring acoustic energy from air into the solid material. Although direct contact between the food and the ultrasound transducer

significantly increases the drying rate, its application in conventional hot-air driers has proved difficult and further research is required (Gallego 1998).

In acoustic drying, products are atomised and dried at relatively low temperatures (60–90 °C) using intense low-frequency sound waves that promote liquid–solid separation and increase heat and mass transfer coefficients across the boundary layer of the product. Drying rates in these dryers are 3–19 times faster than those of conventional dryers. The dryer requires sound-proofing because of the loud noise produced during drying. Foods that are difficult to dry by conventional methods have been dried successfully in acoustic dryers; for example, liquids containing 5–78% moisture have been dried to 0.5% moisture content. Products with high fat contents (up to 30%) have also been dried in these dryers. Other products that dry well are high-fructose corn syrups, tomato pastes, lemon juice and orange juice. Because the dryer operates at lower temperatures and is relatively fast, degradation of natural colours, flavours and loss of nutritional quality are reduced.

16.2.2 Heated-surface (or contact) dryers

Dryers in which heat is supplied to the food by conduction have three 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. Contact dryers are usually heated by steam and typically heat consumption is 2000–3000 kJ per kg of water evaporated compared with 4000–10 000 kJ per kg of water evaporated in hot-air dryers.
- 2 Dryers produce small amounts of exhaust air and few entrained particles, thus minimising problems and cost of cleaning air before its release to the atmosphere.
- 3 Drying may be carried out in the absence of oxygen (under vacuum or in a nitrogen atmosphere) to protect components of foods that are easily oxidised.

A comparison of different types of contact dryers is given in Table 16.1.

Ball dryer

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 dryer by the screw to be discharged at the base. The speed of the screw and the temperature of the heated balls control the drying time (Cohen and Yang 1995).

Drum (or roller) dryers

Drum drying involves heat transfer from condensing steam through the metal drums to a layer of product on the outside. This is heated to its boiling point; water is vaporised, the material changes from a liquid to a solid state, and finally the temperature of the product approaches that of the drum. The limiting factor in heat transfer is the thermal resistance of foods caused by their low thermal conductivity (Chapter 10, Table 10.2), which becomes lower as the food dries. Therefore a thin layer of food is needed to conduct heat rapidly without causing heat damage.

Dryers may have a single drum (Fig. 16.12a), double drums (Fig. 16.12b) or twin drums (Fig. 16.12c). In each type of dryer the slowly rotating hollow drums are heated by pressurised steam to 120–170 °C. They are constructed from precision machined, chrome-plated cast iron to provide even heat transfer. The thin layer of food slurry is spread

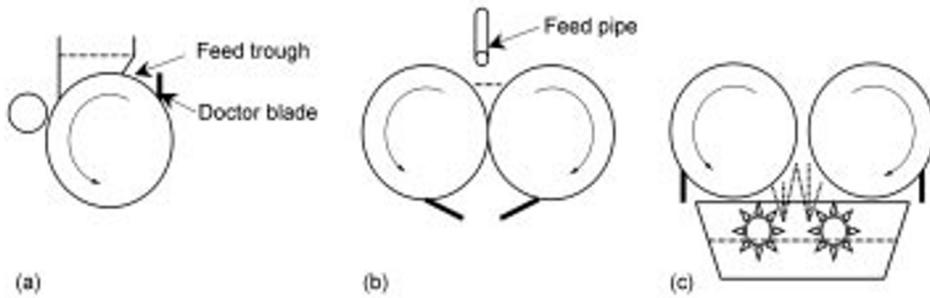


Fig. 16.12 Drum dryers: (a) single drum dryer with top roller feed; (b) double drum dryer with centre feed and bottom discharge; (c) twin drum dryer with splash feed (adapted from Anon 2000).

uniformly over the outer surface by dipping, spraying, spreading, or by auxiliary feed (or applicator) rollers. Feed rollers have advantages when applying wet materials that do not easily form a uniform layer across the drum surface (e.g. starchy materials such as potato pastes). In all types of drum dryers, the dried food is scraped off before the drum has completed one revolution (within 20 s to 3 min) by a 'doctor' blade, which contacts the drum surface uniformly across its width. After removal from the drum, the product is collected by a screw conveyor designed to break up the film or flakes of product into particles. To minimise damage to the surface of the drums, applicator rolls are mounted in spring-loaded assemblies that allow the rolls to lift if a foreign body passes between the rolls and the drum. In twin drum dryers, one drum is fixed and the other is spring loaded to give the same protection. Further information is given by Anon (2008a).

The single drum dryer (Fig. 16.13) is widely used as it has a number of advantages: it has greater flexibility for different products; a larger proportion of the drum area is available for drying; and there is easier access for maintenance. Typical applications include cereal-based breakfast foods, infant foods, pregelatinised starches, potato flakes and fruit pulps. In some designs of double-drum dryers, the drums rotate towards each other and the distance between the drums (the 'nip') determines the thickness of the dried product. Applications include dried yeast and milk products. In twin drum dryers the drums rotate away from each another, and splash feeders apply the wet feed (e.g. gelatine) to the bottom of the drum.



Fig. 16.13 GMF-Gouda single drum dryer showing applicator rolls (manufacturer: GMF-Gouda Processing Solutions at www.gmfgouda.com).

Drum dryers have high drying rates, high energy efficiencies and low labour requirements. They are suitable for slurries in which the particles are too large for spray drying, including a wide range of products that are converted to flakes or powders, which can be quickly rehydrated (e.g. potato flakes, precooked breakfast cereals, some dried soups, fruit purées and whey or distillers' solubles for animal feed formulations). The main disadvantage of drum dryers is that the area available for heat transfer limits the production rate; this is because the surface area : volume ratio decreases with increasing scale, which limits the maximum size of dryers to ≈ 2 m in diameter and ≈ 5 m in length (Anon 2007). Maximum production rates are ≈ 500 – 600 kg h⁻¹. Drum dryers also have higher capital costs than hot-air dryers owing to the cost of the precisely machined drums. 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, or in a nitrogen atmosphere for products that are sensitive to oxidation. However, the high capital cost of these adaptations restricts their use to high-value heat-sensitive foods.

Vacuum band and vacuum shelf dryers

In vacuum band drying a food slurry is spread or sprayed onto a steel belt (or 'band') which passes over two hollow drums inside a vacuum chamber at 0.1–10 kPa. The food is dried by the first 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 dryers consist of hollow shelves in a vacuum chamber. Food is placed in thin layers on flat metal trays that are carefully made to ensure good contact with the shelves. A partial vacuum 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 dryers, and shrinkage reduces the contact between the food and heated surfaces in both types of equipment. They have relatively high capital and operating costs and low production rates.

In vacuum puff drying, a partial vacuum induces foaming in liquid products when dissolved gases are released. The foam is then dried on a heated belt to produce puff-dried foods (see also foam mat drying and foam spray drying using heated air). The increased rate of drying is due to the increase in surface area and the relatively rapid moisture transport through the porous foam structure, compared with the less porous structure of the dried liquid. Heat transfer is less efficient in foam but it is adequate because drying is predominately controlled by the rate of mass transfer. The method reduces damage to heat-sensitive foods such as banana, mango and tomato purées, and the porous structure of the dried foam allows rapid rehydration. Further details are given by Kudra and Ratti (2006).

Vertically agitated dryers

These types of dryers consist of a heated vessel that contains a vertical agitator. The vessel can be either a jacketed cylindrical pan that has a slow-moving paddle to scrape the sides and base, or a jacketed cone that has a vertical screw agitator. The screw rotates about its own axis and also moves around the cone wall on an orbital path. Paddles and agitators provide good mixing of the food and continuously remove food from the wall of the vessel preventing it from over-heating. They are mainly used to dry pastes and slurries, often operating under a partial vacuum (Oakley 1997).

16.3 Control of dryers

The aim of a dryer control system is to produce products that have a uniform moisture content, but this cannot be measured directly on-line and alternative indirect factors are therefore used to control the operation of the dryer. Control of hot-air dryers varies in complexity from simple thermostatic control of air temperature in batch dryers, to more complex feedback control of inlet air and outlet air temperatures and/or humidities. The outlet air temperature is measured using thermocouples or thermistors, air humidity is measured using electronic capacitance or impedance sensors (Pragnell 1993), and air flowrate or product feedrate are measured using flowmeters. A typical control arrangement is to monitor the outlet air temperature and use a programmable logic controller (PLC) (Chapter 27, section 27.2) to adjust the supply of fuel or steam pressure to the air heater. The humidity of the outlet air may also be monitored and used to control vents and dampers to adjust the amount of air that is recirculated. In spray dryers, the outlet air temperature can be used to control the product feedrate to the atomiser (Brennan 1994). Alternatively, the air flow is maintained within a preset range and the inlet air temperature is adjusted to enable the maximum feedrate to be used that produces the required moisture content in the product. In contact dryers the variables are product flowrate, speed of the dryer drum or conveyor, and steam pressure to the dryer. Control of these types of dryer is achieved by monitoring the temperature of the heated surface and using the data to control the steam pressure, keeping the thickness of the feed layer and the drum speed/residence time constant. A process computer linked to a PLC presents real time information to operators, monitors alarms, enables automatic start-up and shut down, and logs data for management and data recording procedures.

Dryers are fitted with alarms to warn operators when a variable exceeds a pre-set condition and interlocks to prevent incorrect operation. Examples of alarm variables include high air inlet or outlet temperatures, high pressure in vacuum dryers and motor failures. Examples of interlocks include stopping the dryer if access doors are opened, preventing feed entering unless the inlet air flow is satisfactory, and preventing the air heater from operating unless the fan is switched on. Further details are given by Gardiner (1997).

The complex nature of drying processes has led to developments in dryer control using neural networks and fuzzy logic control systems. Further details are given in Chapter 27 (section 27.2.3). For example, Qinghua *et al.* (2002) developed an artificial neural network to predict performance indices for rice drying, including energy consumption, final moisture content and moisture removal rate. Inputs to the neural network were four drying parameters: rice layer thickness, hot-air flowrate, hot-air temperature and drying time. A predictive model for heat and mass transfer using a neural network was developed by Hernández-Pérez *et al.* (2004) that can be used for on-line control of drying processes. Other studies of the application of neural networks to dehydration are described by Movagharnejad and Nikzad (2007), Xueqiang *et al.* (2007) and Kaminski *et al.* (1998).

Rodríguez-Jimenes *et al.* (2002) designed an empirically based simulator for a drum dryer and tested an advanced control strategy based on fuzzy logic in order to maintain a constant product moisture content. Zhang and Litchfield (1993) developed a fuzzy logic control system to regulate a continuous crossflow grain dryer. With fuzzy control, similar outlet moisture contents and lower susceptibility of grain to breakage were obtained compared with manually controlled dryer operation. Atthajariyakul and Leephakpreeda (2006) studied optimal conditions for fluidised bed rice drying using fuzzy logic control

of the rice moisture content and heat load of the drying air to quantify rice quality and energy consumption. They produced real-time control of moisture content close to the target level with efficient energy consumption. The control system also enables optimum plant utilisation, control over material and energy costs, process diagnostics, and monitoring for safety and environmental/air pollution (Gardiner 1997).

16.4 Rehydration

Rehydration involves three simultaneous processes: imbibition of water into the dried material, swelling, and leaching of soluble materials. The rate and extent of rehydration depend on the extent of disruption to the cellular structure and chemical changes caused by dehydration. Water that is removed from a food during dehydration cannot be replaced in the same way when the food is rehydrated (i.e. rehydration is not the reverse of drying). The reasons include:

- changes to the structure of a food caused by loss of cellular osmotic pressure;
- changes in cell membrane permeability and solute migration;
- crystallisation of polysaccharides (see also glass transition, Chapter 1, Section 1.4.1); and
- coagulation of cellular proteins, which reduces their water-holding capacity.

Heat also reduces the degree of hydration of starch and the elasticity of cell walls. These factors all contribute to texture changes and each is irreversible (Krokida and Maroulis 2001, Rahman and Perera 1999). Most shrinkage (40–50%) occurs in the initial drying stages, and this can be minimised by low-temperature drying to minimise moisture gradients in the product, or creating a porous structure before drying commences to increase mass transfer and the drying rate. Porous products have faster rehydration, but also reduced storage stability because of the increased surface exposure to air.

Volatile losses and heat-induced chemical changes (e.g. Maillard reactions) may also mean that rehydrated food does not have the same flavour and colour compared with the raw material (Section 16.5.1). The rate and extent of rehydration may be used as an indicator of food quality; those foods that are dried under optimum conditions rehydrate more rapidly and completely than poorly dried foods. Studies of the mechanisms in rehydration and the quality of foods after rehydration are reported by for example Agunbiade *et al.* (2006), Marabi and Saguy (2004) and Lewicki (1998).

16.5 Effect on foods and micro-organisms

16.5.1 Sensory properties

All products undergo changes during drying and storage that reduce their quality compared with the fresh material, and the aim is to minimise these changes while maximising process efficiency. The quality attributes of dried foods are shown in Table 16.6. The main changes to the quality of dried foods are to the texture and flavour or aroma, but changes in colour and nutritional value are also significant in some foods.

Texture

Changes to the texture of solid foods are an important cause of quality deterioration during drying. As a food dries, it becomes more viscous and may pass through a series of rubbery and leathery states until a solid state is achieved when most of the water has

Table 16.6 Changes to quality attributes in dried foods

Attribute	Properties
Appearance	Surface morphology, colour, roughness.
Chemical/biochemical	Oxidation, causing oxidative rancidity, loss of colour, Maillard reactions, causing discoloration, change in texture. Enzymatic, e.g. polyphenoloxidase causing enzymic browning, lipoxygenase causing oxidative rancidity, lipase causing lipolytic rancidity, protease causing gelation and flavour and texture changes.
Microbiological	Numbers of surviving pathogens or spoilage micro-organisms.
Nutritional	Vitamin losses, lipid oxidation, protein denaturation.
Physical	Shrinkage, wetting and rehydration characteristics, density changes, alteration of shape and size, reduced solubility. Moisture movement, causing drying and toughening of texture, hydration and softening of texture, aggregation.
Sensory	Changes to colour, aroma, taste and flavour.
Structural	Glass transitions, cellulose crystal structure, bulk density, porosity.
Textural	Hardness, chewiness, stickiness, viscoelasticity, compressive strength, stress needed to fracture.
Thermal	Glass transition temperature, melting point, thermo-mechanical properties.

Adapted from Mujumdar (1997) and Gould (1995)

been removed. At higher viscosities, foods may become sticky and this has important implications for the design of dryers and selection of operating conditions. For example, in spray drying it is important that there is rapid initial moisture loss so that droplets have passed through the high-viscosity sticky state to prevent them from adhering to the dryer walls. The changes to viscosity can be represented by a glass transition curve on a phase diagram (see Fig. 22.3 in Chapter 22, for similar changes to solutes that take place during freezing). Below the curve, the viscosity of a dry food is sufficiently high to prevent it flowing during the timescales that are required for its shelf-life. This has important implications for the packaging and storage conditions for dried foods; any increase in moisture content or temperature during storage would raise the food above the glass transition curve and lead to stickiness and caking.

The nature and extent of pretreatments (e.g. calcium chloride added to blancher water (Chapter 11), peeling (Chapter 2, section 2.4) and the type and extent of size reduction, (Chapter 3, section 3.1)) each affect the texture of rehydrated fruits and vegetables. The loss of texture in these products is caused by the changes to structural polymeric compounds described in section 16.4 and by Khraisheh *et al.* (2004). Localised variations in the moisture content during drying set up internal stresses, which rupture, crack, compress and permanently distort the relatively rigid cells, to give the food a shrunken, shrivelled appearance (Ratti 1994). Prothon *et al.* (2003) give a detailed review of this textural collapse. 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 density, porosity, degree of shrinkage and rehydration with different foods described by Zogzas *et al.* (1994).

Fully dried meats and fish are commonly produced in some countries (e.g. 'biltong' snack meat in Southern Africa. See also smoked meat and fish in Chapter 17 (section 17.3). Severe changes in texture 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 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 when drying fruits, fish and meats) cause complex chemical and physical changes to solutes at the surface that produce 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. Later migration of moisture to the surface during storage can then promote mould growth. It is minimised by controlling the drying conditions to prevent excessively high moisture gradients between the interior and the surface of the food.

Flavour and aroma

Lipid oxidation during storage of dried foods causes rancidity, development of off-flavours, and the loss of fat-soluble vitamins and pigments in some foods. Factors that affect the rate of oxidation include the product moisture content, types of fatty acid in the food, oxygen content (related to product porosity), storage temperature and exposure to ultraviolet light, the presence of metals or natural antioxidants, and natural lipase activity.

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. Volatiles which have a high relative vapour pressure and diffusivity are lost at an early stage in drying. Foods that have a high economic value due to their characteristic flavours (e.g. herbs and spices) are therefore dried at lower temperatures. The rate of flavour loss during storage is determined by the storage temperature, presence of oxygen and the water activity 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 organic acids, causes rancid and objectionable odours. Some foods (e.g. carrot) may develop an odour of 'violets' produced by the oxidation of carotenes to β -ionone. 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 A4); or
- preservation of natural antioxidants.

The enzyme glucose oxidase (Chapter 6, section 6.5) is also used to protect dried foods from oxidation. A package that is permeable to oxygen but not to moisture, containing glucose and the enzyme, is placed on the dried food inside a container and removes oxygen from the headspace during storage. In modified atmosphere packaging (Chapter 25, section 25.3), milk powders are stored under an atmosphere of nitrogen with 10% carbon dioxide. The carbon dioxide is absorbed into the milk and creates a small partial vacuum in the headspace. Air diffuses out of the dried particles and is removed by re-gassing after 24 h.

Flavour changes caused by oxidative or hydrolytic enzymes are prevented in dried fruits by the use of sulphur dioxide, ascorbic acid or citric acid, by blanching vegetables (Chapter 11) or by pasteurisation of milk and fruit juices (Chapter 12). Other methods that are used to retain flavours in dried foods include:

- recovery of volatiles and their return to the product during drying (see also Chapter 14, section 14.1.2);
- mixing recovered volatiles with flavour fixing compounds, which are then granulated and added back to the dried product (e.g. dried meat powders); and
- addition of enzymes, or activation of naturally occurring enzymes, to produce flavours from flavour precursors in the food (e.g. onion and garlic are dried under conditions that protect the enzymes that release characteristic flavours).

Colour

There are a number of causes of colour changes or losses 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, but most carotene destruction is caused by oxidation and residual enzyme activity during storage. Loss of the green colour of vegetables during the moist heating conditions of initial drying is due to chlorophyll being converted to olive-coloured pheophytin by losing some of the magnesium in the pigment molecules. Shorter drying times and lower drying temperatures, and blanching or treatment of fruits with ascorbic acid or sulphur dioxide, each reduce pigment losses (Krokida *et al.* 2001).

Enzymic reactions by phenolases (e.g. polyphenoloxidase, cresolase, catecholase, tyrosinase) cause browning of some fruits and vegetables (e.g. banana, apple and potato) on exposure to air by oxidation of phenolic compounds (hydroxybenzenes) to brown melanins. This is a particular problem when fruits are prepared for drying by peeling, slicing etc., or when the tissue is bruised during handling (Krokida *et al.* 2000). It can be inhibited by sulphites metabisulphites or bisulphites that maintain a light, natural colour during storage and also inhibit microbial growth. Only free sulphite is effective in retarding the formation of pigment materials or growth of micro-organisms, and the loss of sulphur dioxide therefore determines the practical shelf-life of the dried product. 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. In sulphite-sensitive people, sulphites can provoke asthma and other symptoms of an allergic response such as skin rashes and irritations. Its use in dried products is now restricted in many countries. Packaging under vacuum or nitrogen, or the use of an oxygen scavenger pouch in sealed packs (Chapter 25, section 25.4.3) also reduces browning and flavour changes. The rate of Maillard browning reactions increases at higher temperatures and longer drying times, and at higher solids concentrations (Chapter 1, section 1.2.2). The reaction also makes amino acids unavailable, reducing the nutritional value. The rate of Maillard browning in stored milk and fruit products depends on the water activity of the food and the temperature of storage.

16.5.2 Nutritional value

The loss of moisture as a result of drying increases the concentration of nutrients per unit weight in dried foods compared with their fresh equivalents. Large differences in reported data on the nutritional value of dried foods are due to variations in the composition of raw

materials, differences in preparation procedures, drying temperatures and times, and the storage conditions. In fruits and vegetables, vitamin losses caused by preparation procedures usually exceed those caused by the drying operation. These losses have been studied for many years, and 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 puréeing and 5% from drum drying. Other studies are reported by, for example, Erenturk *et al.* (2005).

Vitamins have different solubility in water and as drying proceeds, some (e.g. riboflavin) become supersaturated and precipitate from solution, so losses are small. Others (e.g. 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, and low moisture and oxygen levels during storage are necessary to avoid large losses. Thiamin is also heat-sensitive and losses are $\approx 15\%$ in blanched tissues, but may be up to 75% in unblanched foods. Lysine is heat-sensitive and losses in whole milk range from 3 to 10% in spray drying and 5–40% in drum drying. Other water-soluble vitamins are more stable to heat and oxidation, and losses during drying rarely exceed 5–10% (excluding preparation and blanching losses).

Oil-soluble nutrients (e.g. 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. 1.11 in Chapter 1). Fat-soluble vitamins are also 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. Ultraviolet light (e.g. during sun or solar drying) causes a reduction in carotene and riboflavin content, as well as increasing the rate of darkening.

The biological value and digestibility of proteins in most foods do 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.

16.5.3 Effect on micro-organisms

Depending on the time–temperature combination used to dry foods, there may be some destruction of contaminating micro-organisms, but the process is not per se lethal, and yeasts, moulds, bacterial spores and many Gram-negative and Gram-positive bacteria can survive in dried foods. Hence most vegetables are blanched (Chapter 11), liquid foods may be pasteurised (Chapter 12) or concentrated by evaporation (Chapter 14) and meat and fish may be treated with salt before drying to inactivate pathogenic bacteria. Dried foods are characterised as having a water activity (a_w) below 0.6, which inhibits microbial growth, provided that the packaging and storage conditions prevent moisture pick-up by the product. If this occurs, xerophilic mould growth at a_w 0.77–0.85 is the most likely form of spoilage, especially by *Eurotium* spp., *Aspergillus* spp., *Penicillium* spp. and *Xeromyces* spp., and also some osmophilic yeasts such as *Saccharomyces rouxii*. Additionally, some types of *Aspergillus* spp. (*A. parasiticus*, *A. nomius* and *A. niger*) produce a range of mycotoxins, which produce acute symptoms that can be fatal and are potent liver carcinogens (Brown 2006).

Most dried foods are cooked before consumption, which reduces the numbers of surviving micro-organisms, but foods such as dried fruits, nuts, herbs and spices may be consumed uncooked. Pepper, paprika, desiccated coconut and cinnamon in particular have been recognised as posing a particular risk for *Salmonella* contamination. Particular care is needed to ensure that these foods are subject to high standards of hygiene and food handling during both preparation for drying and during post-drying treatments. They are also treated with chemical fumigants, modified atmospheres (Navarro *et al.* 1998) and Chapter 21, section 21.2.5), by irradiation (Chapter 7) or by a combination of methods (Wahid *et al.* 1989). These treatments also destroy contaminating insects. (Note: methyl bromide has been discontinued as a chemical fumigant since 2005 because it is an ozone-depleting gas (Anon 2008b).)

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