Chapter 8
Food Dehydration Equipment

8.1 Introduction

Food dehydration, a traditional method of food preservation, is also used for the production of special foods and food ingredients and for the utilization of food plant wastes. A wide variety of industrial food drying equipment is used, developed mostly empirically but continuously improved by recent advances in drying technology and food engineering. In addition to the basic process engineering requirements, food dryers must meet the strict standards for food quality and food hygiene and safety.

Removal of water from the food materials is usually accomplished by thermal evaporation, which is an energy-intensive process, due to the high latent heat of vaporization of water (e.g., 2.26 MJ/kg at 100 °C).

Part of the water in "wet" food products can be removed by inexpensive nonthermal processes, like mechanical pressing/expression, filtration, centrifugation, or osmotic dehydration. Mechanical pressing is used effectively to remove 20–30 % of free water from solid food wastes, before thermal drying.

Dehydration of liquid foods, such as milk and soluble coffee, is normally preceded by efficient thermal evaporation. Energy-saving systems, such as multiple-effect and vapor recompression evaporators, which are very efficient in evaporation, cannot be applied to food dehydration.

The diversity of drying processes and equipment used in food processing is caused by the difficulty of handling and processing solid materials and the special requirements for the various food products. In addition, economics (investment and operation) is an important factor, especially for large-volume, low-cost products, such as dried skim milk. The equipment ranges from crude solar dryers to sophisticated spray dryers or freeze dryers.

Most food products are dehydrated in convective dryers, in which air is utilized for heating the product and removing the evaporated water. In contact dryers, heat is transported to the product through the walls (e.g., shelves) of the equipment.

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In some dryers, heat may be transferred through radiation (infrared microwave). Osmotic dehydration, an alternative to thermal dehydration, is in the development stage.

8.2 Principles of Drying

The physical and engineering principles of drying are discussed by Mujumdar and Menon (1995). The process calculations used in the design and operation of industrial dryers are reviewed by Pakowski and Mujumdar (1995).

8.2.1 Psychrometric Calculations

The properties of air/water vapor mixtures are of fundamental importance to calculations of air-drying processes (convective drying). They can be calculated from material and energy balances or obtained from psychrometric charts (Fig. 8.1) or from computer programs, such as DryPACK (Pakowski 1998). The normal psychrometric charts refer to atmospheric pressure (1.013 bar). Psychrometric charts are available in the low-temperature region (used in refrigeration) and in the medium or high temperatures (used in air conditioning or drying).

The psychrometric chart is a graphical representation of the hygroscopic properties of the air, i.e., the dry and wet bulb temperatures (T, T_w), the moisture content Y (kg/kg dry air), the relative humidity (% RH), the specific enthalpy H (kJ/kg dry air), and the specific volume V (m^3/kg dry air). Psychrometric data can be obtained also from the Mollier diagram, used in Europe. Figure 8.1 shows a chart in the temperature range of 30–100 °C, of interest to air-drying of foods. This chart, based on material and energy balance equations, was developed by Zogzas (2001).

Figure 8.2 shows a representation on the psychrometric chart of the process path of air in an adiabatic convective dryer. Fresh air enters the system at state (A) and it is heated at constant moisture content (Y) to state (B), increasing its enthalpy by DH (kJ/kg dry air). The hot air is passed through the dryer at constant wet bulb temperature and enthalpy (H), picking up moisture, and it is rejected at a higher moisture and lower dry bulb temperature (point C). In this process, the air is humidified, picking up moisture DY (kg/kg dry air). The psychrometric chart shows also the specific volume of air/water mixtures at various states, e.g., at points A, B, and C.

The process (ABC), shown in Fig. 8.2, represents a once-through process, i.e., without air recirculation. In several drying operations, air recirculation is often practiced for the purpose of recovering part of the rejected energy in the exhaust air. However, it is evident from the psychrometric chart that the capability of the air to absorb moisture is diminished as the air is humidified and the moisture content of the air is increased. The psychrometric chart and the computer programs allow the

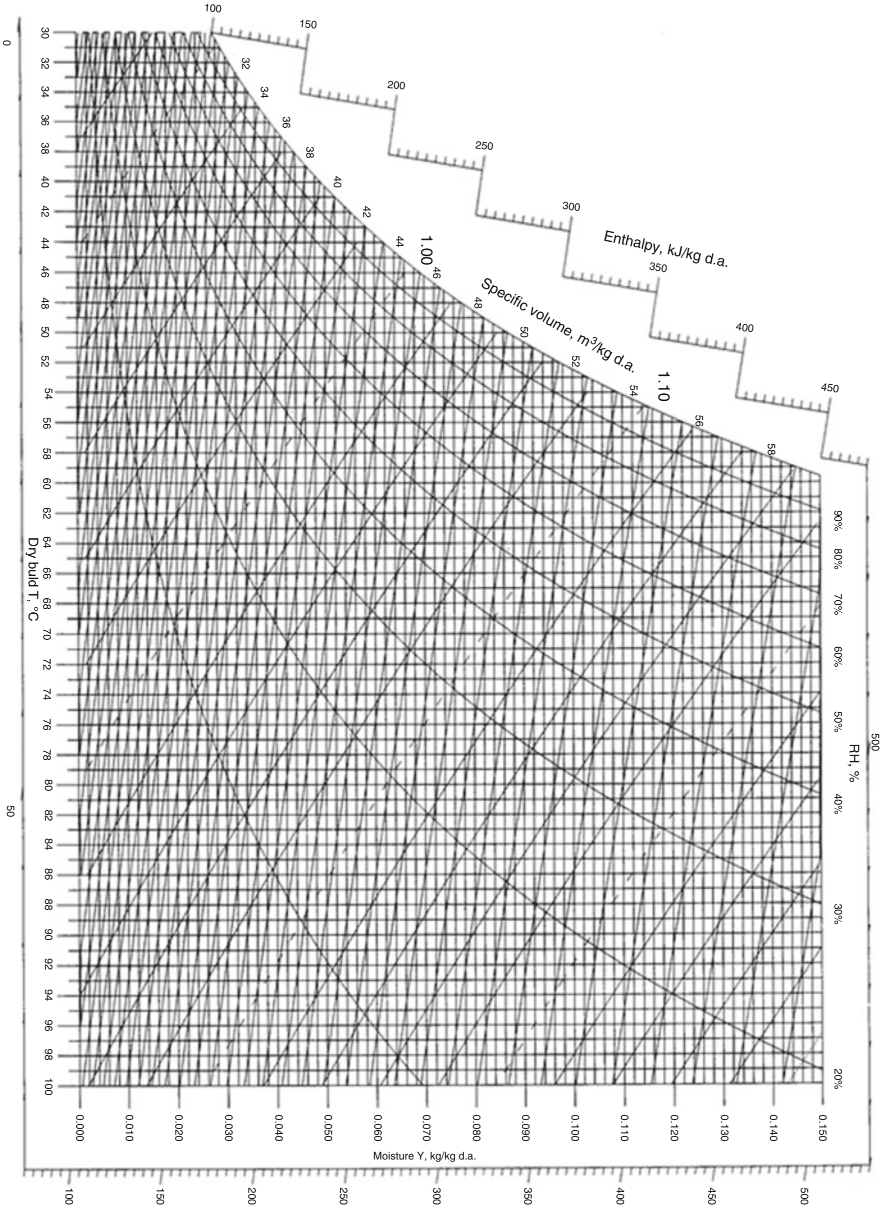


Fig. 8.1 Psychrometric chart in the range 30–100 °C (atmospheric pressure)

calculation of humidities and enthalpies of various mixtures of exhaust and fresh air.

The graphical or computer calculations of hygroscopic properties of the air are essentially representations of material and energy balances in the various streams of a drying system.

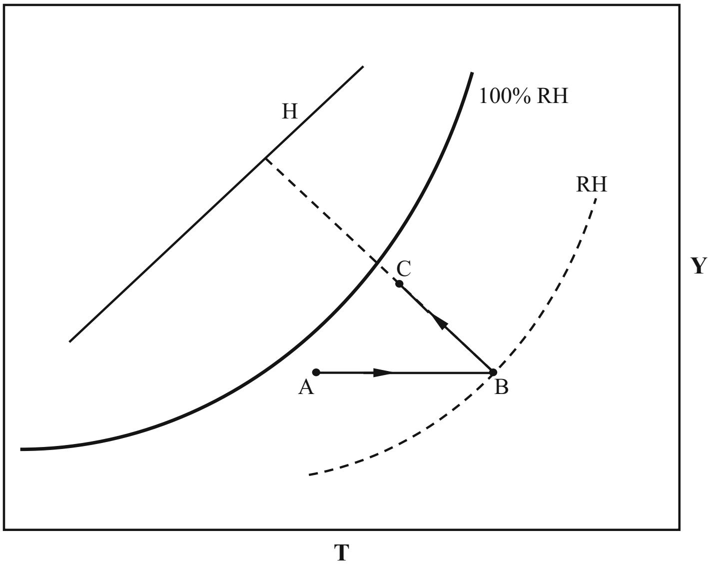


Fig. 8.2 Process path of air in an adiabatic dryer: *AB* heating at constant humidity, *Y*; *BC* adiabatic humidification at constant wet bulb temperature (constant enthalpy, *H*); *RH* relative humidity

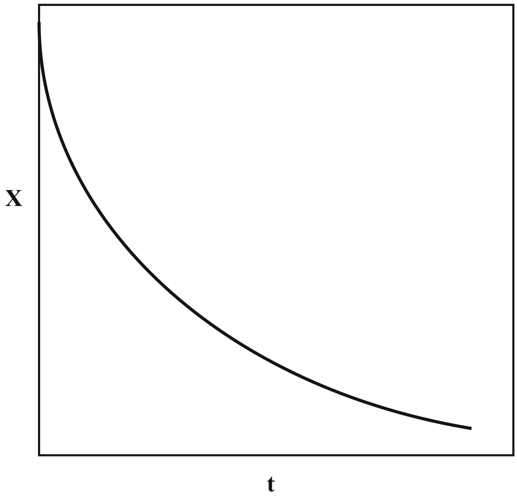
8.2.2 Drying Rates

The drying rates of food materials are usually determined experimentally, since it is very difficult to predict accurately the heat and mass transport rates on purely theoretical grounds (Molnar 1995). The drying tests are normally carried out on a layer of material, placed in an experimental dryer, which is operated under controlled conditions of temperature, air velocity, and humidity. The weight and the temperature of the sample are monitored by appropriate instrumentation as a function of time, obtaining the basic drying curve of moisture content X (kg/kg dry basis) versus time t (Fig. 8.3). The drying rate curve (dX/dt vs. X) is obtained by differentiating the original drying curve (Fig. 8.4).

The drying rate curve may indicate a constant rate period, during which mass transfer from the surface of the material controls the drying process, depending mainly on the external conditions (air velocity, temperature, and humidity). Short constant drying rates may be observed in air-drying food materials of high moisture content or in washed products, containing free surface water. However, most food materials do not show any constant rate and they dry entirely in the falling rate period, during which mass transfer is controlled by the transport (diffusion) of water through the material to the surface of evaporation.

The drying rate of a food material during the falling rate period can be expressed by the empirical equation of thin-layer drying (Saravacos and Maroulis 2001):

Fig. 8.3 Experimental drying curve



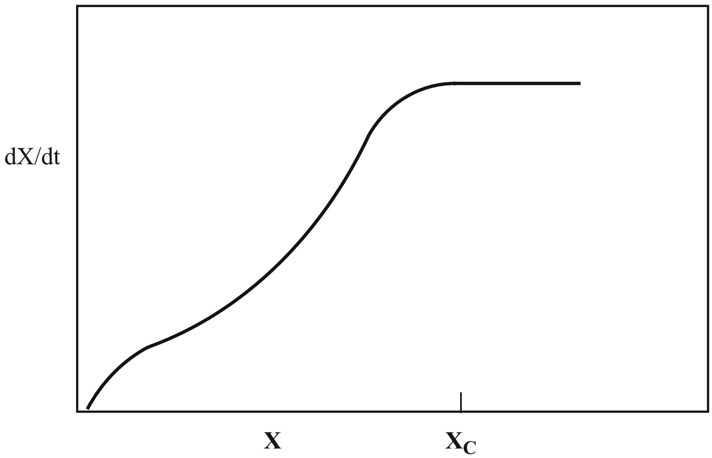


Fig. 8.4 Drying rate curve

$$\mathrm{d}X/\mathrm{d}t = -K(X - X_\mathrm{e}) \tag{8.1}$$

where X is the moisture content (dry basis) at time (t), X_e is the equilibrium moisture content, and K (1/s) is the drying constant.

Integration of (8.1), assuming that K is constant, yields the empirical drying equation

$$\log[(X_\mathrm{o} - X)/(X_\mathrm{o} - X_\mathrm{e})] = Kt \tag{8.2}$$

The experimental drying data of Fig. 8.3 are usually plotted on semilog coordinates, obtaining the curve of drying ratio R vs. t, where $R = (X_\mathrm{o} - X)/(X_\mathrm{o} - X_\mathrm{e})$.

The equilibrium moisture content of the food material at the drying temperature can be taken from the literature (Iglesias and Chirife 1983; Wolf et al. 1985), determined experimentally, or estimated from empirical equations of the sorption isotherm of the material, such as the GAB equation (Saravacos 1995).

The empirical drying constant (K) depends on the material and the (dry bulb) temperature of the air.

Actually, the drying constant of several food materials may change during the drying process, due to the significant changes in the physical structure of the material and, consequently, in the mass transport mechanism within the material. Water may be transported mainly by diffusion (liquid or vapor) or hydrodynamic/capillary flow.

From the changes of the slope of the drying ratio curve, two or more falling rate periods may be identified, obtaining two or more drying constants (K_1, $K_2, \ldots$). However, in general, K varies continuously with the moisture content (X), and some empirical K (X) relationship may be used.

The drying constant (K) increases exponentially with the temperature, and empirical models have been proposed for various materials (Marinos-Kouris and Maroulis 1995). Thus, the (K) of shelled corn increases from about 0.2 1/h at 20 °C to 0.5 1/h at 60 °C.

Assuming that water transport within the food material can be expressed by the diffusion (Fick) equation, the effective moisture diffusivity (D) can be estimated from the slope of the experimental drying ratio curve (Fig. 8.5). For a constant slope, the drying constant is related to the diffusivity D (m^2/s) and the thickness L (m) of the material (slab or plate) by the diffusion-derived equation (Saravacos and Maroulis 2001)

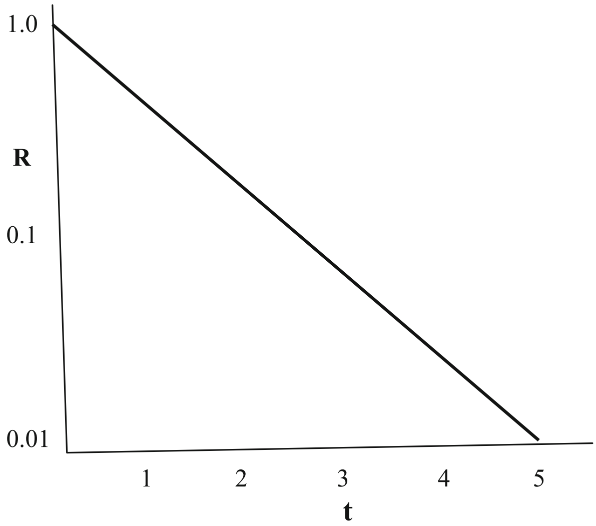


Fig. 8.5 Drying ratio curve. $R = (X - X_e)/(X_o - X_e)$; X_o, X_e, X moisture contents, initial, equilibrium, and after time (t)

$$K = p^2 D / L^2 \tag{8.3}$$

Thus, if the effective moisture diffusivity (D) of the material is known at the given temperature and moisture content, the drying constant (K) of the material at the given thickness (L) of the slab can be estimated. For a spherical material, (8.3) becomes

$$K = p^2 D / r^2 \tag{8.4}$$

where r (m) is the radius of the sphere.

Equations (8.3) and (8.4) are rough approximations, which should be applied with caution. They are based on mass transport by diffusion, in which the rate is proportional to the square of thickness of the material. Actually, the diffusion mechanism may not be applicable to some food materials, due to their physical structure.

For diffusion-controlled drying, the thickness (or diameter) of the material should be as low as possible, i.e., drying of thin layers or particles of small diameter is desirable. At the same time, higher effective diffusivities are required to achieve short drying times.

Table 8.1 shows typical effective moisture diffusivities (D) of some classes of food materials (Saravacos and Maroulis 2001). The energy of activation for diffusion is also given in the table, since it is a good measure of the effect of temperature on (D).

High energies of activation for diffusion (strong temperature effects) are characteristic of liquid diffusion in nonporous food materials, while low energies indicate vapor diffusion in porous materials.

The following two examples of approximate calculations show the required times to dry a layer of 1 cm and a particle of diameter 1 mm of food material from 80 to 10 % moisture content:

For the 1-cm food layer, the effective diffusivity (D) at the drying temperature is assumed 10×10^{-10} m^2/s (Table 8.1), a rather high value, justified by the high bulk porosity of the material (Saravacos and Maroulis 2001). According to (8.3), the drying constant will be $K = p^2 \times 10 \times 10^{-10}/(0.01)^2 = 9.86 \times 10^{-5}$ 1/s or $K = 0.355$ 1/h. The material is dried from 80 % ($X_o = 4$ kg/kg db) to 10 % ($X = 0.11$) moisture content. Assuming constant K value, the required drying time will be (8.2) $t = [\log (4/0.11)]/(0.355)$ or $t = 4.4$ h, which is a reasonable drying time. It should be noted that the effective moisture diffusivity of the material could

Table 8.1 Typical values of effective moisture diffusivity (D) and energy of activation for diffusion (E_D) of food materials

Food material	D ($\times 10^{-10}$ m^2/s)	E_D (kJ/mol)
Highly porous	50	15
Porous	10	25
Nonporous starch/sugar	1	40
Nonporous protein/starch	0.1	50

be increased substantially by increasing the bulk porosity, for example, by puffing or extrusion cooking.

For the drying of porous food particles of 1 mm diameter, assuming $D = 10 \times 10^{-10}$ m^2/s, the drying constant will be $K = p^2 \times 10 \times 10^{-10}/(0.0005)^2 = 0.04$ 1/s. The drying time for $(X_o/X) = 4/0.11 = 36.4$ will be $t = [\log(36.4)]/(0.04) = 39$ s. This is a reasonable residence time for a flash or spray drying system. However, if a nonporous particle of the same diameter is going to be dried in the same moisture ratio, the diffusivity will be lower, e.g., $D = 1 \times 10^{-10}$ m^2/s for a starch/sugar nonporous material, and the drying time will be $t = 39 \times 10 = 390$ s or 6.5 min. This is a very long time for a flash or spray dryer, and a fluid bed dryer may be more appropriate.

8.2.3 Food Dehydration Technology

The technology of food dehydration was developed largely from practical experience, but during the recent years, the principles of food science and chemical (process) engineering are used increasingly to analyze and improve this old technology. The technological aspects of food dehydration are discussed in specialized books, such as Van Arsdel et al. (1973), Barbosa-Canovas and Vega-Mrcado (1996), Baker (1997), and Greensmith (1998). Details on the dehydration of specific food products are presented by Mujumdar (1995) in the *Handbook of Industrial Drying*, i.e., Sokhansanj and Jayas (drying of foodstuffs), Raghavan (drying of agricultural products), Jayaraman and Das Gupta (drying of fruits and vegetables), Lewicki and Lenart (osmotic dehydration), and Pisecky (drying of dairy products). The dehydration technology of fruits and vegetables is discussed by Woodroof and Luh (1986), Luh and Woodroof (1988), Salunkhe et al. (1991), and Saravacos (1993).

The major dehydrated food products are fruits and vegetables, dairy products (milk, whey), soluble coffee, tea, and soups (MacCarthy 1986). Fruit and vegetable dehydration has received special attention due to the diversity of the raw materials, the sensitivity of food products, and the various types of drying equipment used for these products.

The terms "drying" and "dehydration" are used interchangeably in process engineering and in this book. However, in food science and technology, the term "drying" is traditionally used for thermal removal of water to about 15–20 % moisture (dry basis), which is approximately the equilibrium moisture content of dried agricultural products (e.g., fruits and grains) at ambient (atmospheric) air conditions. The term "dehydration" is traditionally used for drying foods down to about 2–5 %, e.g., dehydrated vegetables, milk, and coffee. The dehydrated foods usually require special packaging to protect them from picking up moisture during storage. The term "evaporated" is used sometimes for dried fruits, such as apples, of about 20 % moisture. The term "intermediate moisture foods" (IMFs) is used for semimoist dried foods (fruits, meat, etc.) of 20–30 % moisture content.

The main drying processes used for fruits and vegetables are sun drying, convective (air) drying, fluid bed drying, spray drying, and drum drying. Specialized drying processes include vacuum drying, freeze-drying, puff drying, and foam-mat drying.

Pre-drying treatments of fruits include slicing and sulfuring, while peeling and blanching are applied to vegetables. Dipping of grapes in alkali solutions, containing ethyl oleate, increases substantially the drying rate. Sulfuring (gaseous SO_2 or sulfurous solutions), used to preserve fruit color, may be replaced by other treatments, which are safer to the consumers.

Dried and dehydrated foods are generally microbiologically stable, i.e., microbial growth is prevented by the low water activity ($a_w < 0.70$). Protective packaging and some acceptable additives may be required to preserve the quality of the product (color, flavor, structure).

IMFs are dried to water activities of 0.90–0.70, corresponding to moisture contents 30–20 %, which prevent the growth of spoilage bacteria. The growth of yeasts and molds may be controlled by additives, such as sorbic acid (Davies et al. 1976). IMF foods are produced either by convective drying under mild conditions or by osmotic dehydration.

Process and storage calculations require knowledge of the equilibrium moisture properties (moisture sorption isotherms) of the dried food materials (Iglesias and Chirife 1983; Wolf et al. 1985; Saravacos 1995). The quality of dehydrated foods, especially fruit products, is affected strongly by the retention of characteristic volatile aroma components during the drying operation. Some dehydration processes result in improved aroma retention, e.g., vacuum drying and freeze-drying, spray drying, and osmotic dehydration (Saravacos 1993, 1995).

Figure 8.6 shows a process block diagram for the dehydration of diced potato (Greensmith 1998), which is useful for material and energy balances and for preliminary sizing of the process equipment.

The equipment used in the pre- and post-drying operations (washers, peelers, blanchers, and packaging machinery) is discussed in various chapters of this book.

8.3 Design and Selection of Food Dryers

The design of industrial dryers in food processing is based mainly on practical experience, since handling and processing of solid and semisolid food materials cannot be described adequately by mathematical models and computer simulations. Recent advances in the application of transport phenomena, particle technology, and computer technology to food engineering can improve markedly the design and operation of food dryers.

Food dehydration is a heat and mass transfer process, involving handling of solids and particles. The drying process must be cost-effective and preserve or improve the quality of the product. Particular attention must be given to the safety, nutritional quality, and consumer acceptance (convenience) of the dehydrated food products.

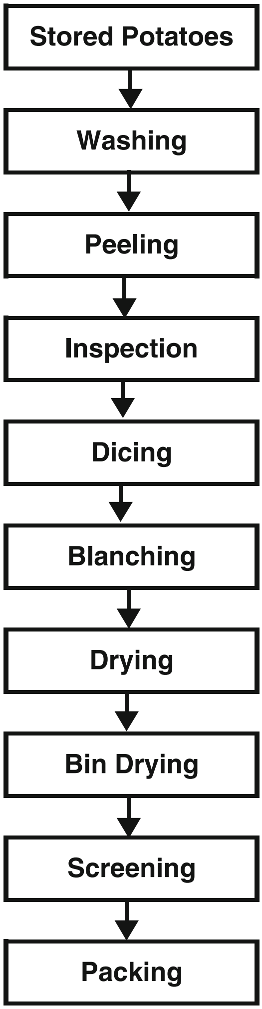


Fig. 8.6 Process block diagram of dehydration of diced potatoes

A detailed discussion of drying technology is presented by Mujumdar (1995) in the *Handbook of Industrial Drying*. A comprehensive list of definitions and terms used in drying was published (in German with English translation of terminology) by the German Society of Process Equipment (VDMA 1999a).

8.3.1 Heat and Mass Transfer

Heat and mass transport within the food materials (internal transport) controls the drying rate of most food. The internal transport properties, i.e., mass diffusivity (moisture and solutes) and thermal conductivity/diffusivity, affect strongly the drying rate, and they should be known or determined experimentally for each food material. A detailed discussion on the transport properties of foods, with particular emphasis on the drying processes, is presented by Saravacos and Maroulis (2001). Table 8.1 shows some typical effective moisture diffusivities of food materials of interest to drying. In general, both mass and thermal transport properties are affected strongly by the physical structure (porosity) of the material and to a lesser degree by the temperature and the moisture content. Detailed data on the thermal transport properties are presented by Rahman (1995).

Interphase (surface) heat and mass transfer is important in the early stages of drying, when the external drying conditions (air velocity, temperature, and humidity) have a decisive effect on the drying rate.

The surface heat transfer coefficient h (W/m^{2}K) in a drying operation is defined by the equation

$$Q/A = h\text{DT} \tag{8.5}$$

where Q/A is the heat flux (W/m^2) and (DT) is the temperature difference between the heating medium and the heated surface of the material (K).

The surface mass transfer coefficient h_{M} (kg/m^2 s) is defined by an analogous equation

$$J = h_{\text{M}}\text{DY} \tag{8.6}$$

where J is the mass transfer rate (kg/m^2 s) and DY is the difference of moisture content (kg/kg dry air) between the material's surface and the bulk of the drying medium (air).

The mass transfer coefficient k_{c} (m/s), also used in the literature, is based on the driving force of concentration difference DC (kg/m^3), according to the equation

$$J = k_{\text{c}}\text{DC} \tag{8.7}$$

The two mass transfer coefficients are interrelated by the equation

$$h_{\text{M}} = k_{\text{c}}r \tag{8.8}$$

where r (kg/m^3) is the density of the transfer medium, i.e., the air.

For air–moisture systems of normal drying conditions (atmospheric pressure, temperature less than 100 °C), the air density is approximately 1 kg/m^3 and, therefore, the two coefficients are numerically equal:

$$h_{\text{M}}\left(\text{kg/m}^2\text{s}\right) \approx k_{\text{c}}(\text{m/s}) \tag{8.9}$$

The interphase transfer coefficients are affected by the air velocity and temperature and the geometry of the transfer system. Approximate values of the coefficients are given in the literature (Rahman 1995; Green and Perry 1997).

The transfer coefficients are correlated by empirical equations for various systems, using the known dimensionless numbers Reynolds ($Re = (u\ r\ d)/h$), Prandtl ($Pr = (C_p\ h)/l$), Nusselt ($Nu = h\ d/l$), Schmidt ($Sc = h/r\ D$), and Sherwood ($Sh = (k_c\ d)/D$).

The thermophysical and transport properties used in these numbers are the density r (kg/m^3), specific heat C_p (J/kg K), velocity u (m/s), (equivalent) diameter d (m), thermal conductivity l (W/mK), viscosity h (Pa s), mass diffusivity D (m^2/s), heat transfer coefficient h (W/m^{2}K), and mass transfer coefficient k_c (m/s).

The Colburn analogies are employed to relate the heat and mass transfer coefficients, using the dimensionless heat and mass transfer factors (j_H and j_M), defined by the following equations (Geankoplis 1993):

$$j_H = j_M \tag{8.10}$$

where $j_H = St_H\ (Pr)^{2/3}$ and $j_M = St_M\ (Sc)^{2/}$

The Stanton numbers for heat and mass transfer, St_H and St_M, are defined as

$$St_H = Nu/Re\,Pr = h/u\rho C_p \quad \text{and} \quad St_M = Sh/Re\,Sc = h_M/u\rho = k_c/u \tag{8.11}$$

The Colburn heat and mass transfer analogy can be applied to air–moisture systems at atmospheric pressure for comparing the two transfer coefficients (Geankoplis 1993):

$$h/h_M = C_p \quad \text{or} \quad h\ /\ k_c = rC_p \tag{8.12}$$

For air at atmospheric pressure, $r = 1$ kg/m^3 and $C_p = 1000$ J/kg K. Therefore, the two coefficients are numerically identical, if expressed in appropriate units:

$$h\left(\mathrm{W/m^2K}\right) \approx h_M\left(\mathrm{g/m^2s}\right) \approx k_c(\mathrm{mm/s}) \tag{8.13}$$

The Colburn analogies can be simplified by assuming that the heat and mass transfer factors (j_H and j_M) are functions of the Reynolds number only (Saravacos and Maroulis 2001). Regression analysis of several literature data has yielded the following two empirical equations:

$$j_H = aRe^n \quad \text{and} \quad j_M = bRe^m \tag{8.14}$$

where a, b, m, and n are empirical constants. For convective (air) drying, (8.14) become

$$j_H = 1.04 \times Re^{-0.45} \quad \text{and} \quad j_M = 23.5Re^{-0.88} \tag{8.15}$$

Figure 8.6 shows typical regression lines of literature data on the transfer factors j_H and j_M for the convective drying of corn and rice.

Using the data of Fig. 8.7, the calculated heat and mass transfer coefficients shown on Table 8.2 were obtained. Equations (8.10) and (8.11) were used with the

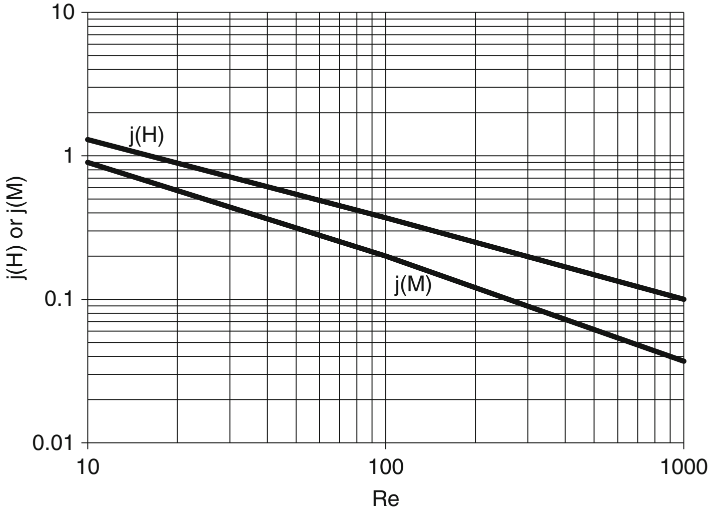


Fig. 8.7 Regression lines of literature data on heat and mass transfer factors (j_H and j_M) for convective drying of corn and rice

Table 8.2 Heat and mass transfer coefficients (h, h_M/k_c) in convective (air) drying of corn and rice

Re	u (m/s)	h (W/m K)	h_M (g/m^2 s) or k_c (mm/s)
10	0.1	30	97
100	1	104	292
1000	10	364	810

Re Reynolds number, u air velocity

following thermophysical and transport properties of the air at 60 °C: $r = 1$ kg/m, $C_p = 1000$ J/kg K, $h = 22$ mPa s, $l = 0.03$ W/mK, and $D = 3 \times 10^{-5}$ m^2/s. The calculated Prandtl and Schmidt numbers are $Pr = 0.81$ and $Sc = 0.81$.

The data on Fig. 8.7 and Table 8.2 show an analogy between the two transfer coefficients (h, h_M). Although of the same order of magnitude, the numerical values of the two coefficients are not the same, as predicted by the Colburn equation (8.10). This difference may be caused by the effect of food solids in the drying system, since the Colburn equation was derived for heat and mass transfer in gaseous systems.

8.3.2 Modeling and Simulation of Dryers

Mathematical modeling and simulations, used extensively in chemical engineering, especially in the processing of gases and liquids, are difficult to apply to complex drying operations involving handling and processing of solids and semisolids.

Nevertheless, these computer-based methods are useful in analyzing and optimizing drying processes for cost and product quality.

A generalized approach to the use of modeling in the design of convective dryers (conveyor belt, fluid bed, and rotary) was presented by Kiranoudis et al. (1994, 1996a, b). The mathematical model of each drying section involves material and energy balances, heat and mass transfer rates with constraints of temperature, product quality, and equipment construction characteristics.

Simplified models are used for heat and mass transfer in the dryer, and the drying rate (K) is estimated from assumed values of effective moisture diffusivity (8.3). The effect of temperature was modeled by the Arrhenius equation with a typical energy of activation for diffusion, 35 kJ/mol (Table 8.1).

Simplified models were used for the estimation of the total and operating costs of the drying operation. The operating cost at various production capacities showed that the rotary dryer is the most economical unit, followed by the conveyor belt and the fluid bed dryers. However, the rotary dryer was the most expensive to build. Conveyor belt dryers appear to be the most appropriate drying equipment for food dehydration.

Modeling and simulation of dryers used in the processing of rice and vegetable slurries was presented by Bakker-Arkema (1986). Three types of dryers were considered: countercurrent flow packed bed dryer, concurrent flow rotary dryer, and cocurrent flow spray dryer. The models utilize moisture sorption isotherms, internal moisture transport, and external moisture transfer.

The modeling of convective dryers is based on the experimental values of the physical and transport properties and the drying kinetics (drying rate) of the material (Tsotsas 1998). Drying kinetics should be determined on both the single (small) particles and the bulk (integral) of the material. In addition to the basic heat and mass transport phenomena, the product quality should be considered. For example, mechanical damage to the product during drying, such as cracking and shrinkage, should be controlled.

Modeling has been applied to optimize the drying conditions of pasta (de Cindio et al. 1994). Internal moisture transport (diffusion) and mechanical stresses are causing cracking of the product, which can be controlled by increasing the air humidity in the dryer. A similar modeling, applied to rice fissure during drying, suggests high temperature but low drying rate to improve the quality (Abud-Archila et al. 2000).

Food process simulators, like OVENSIM (baking bread in a tunnel oven) (Skjoldebrandt et al. 1994), could be developed for dying processes. The computer program is useful for optimizing the food process and for training the plant operators.

Computational fluid dynamics (CFD) has been used to simulate and improve the operation of spray dryers, e.g., by reducing wall depositions (Langrish 1996). Commercial CFD packages,)suggested for drying applications, include PHOENICS, FLOW 3D, FIDAP, and FLUENT (Chap. 1).

8.3.3 Design of Industrial Dryers

The design of industrial dryers is based largely on empirical knowledge, while modeling and simulation can generalize and improve the design procedure. The diversity of drying processes and dried products has resulted in a multitude of drying equipment, specific for each class of products. Thus, selection of a particular dryer becomes as important as the engineering design of the equipment.

The principles of dryer design are outlined in process engineering books, like Mujumdar (1995), Keey (1978), Strumillo and Kudra (1987), Walas (1988), Green and Perry (1997), Krischer (1963), and Kroll (1976). Practical aspects of dryer design and selection were presented by Williams-Gardner (1971), Bhatia (1983), Lee (1983), Cook and DuMont (1991), and Van't Land (1991). The scale-up of dryers in the process industries is an important aspect of drying technology (Genskow 1994).

The thermophysical, transport, and equilibrium (isotherms) properties of the material are very important in specifying the proper dryer and drying conditions. Mechanical properties of solids and solid particles are important in handling and processing of the various materials. Drying rates (kinetics of moisture removal) are useful for preliminary estimation of the drying time (8.2). The estimated time is taken as the approximate mean residence time in the dryer, an important parameter in dryer design.

The specifications of an industrial dryer should be listed in an equipment specification form (Chap. 2) and should include the properties of the wet and dried material, the temperature sensitivity and water activity of the product, the capacity and evaporation duty (kg/h), the energy supply and cost, the environmental impact, and the relationship to the other plant operations.

There are about 40 classes and over 100 subclasses of dryers, which are classified by different methods, based on type of operation (batch, continuous), type of feed (liquid, suspension, paste, granules, fibrous solids, porous solids, dense solids, and sheets), heating method (convection, contact, radiation, dielectric), and product sensitivity (vacuum, low temperature). The size of dryers can be small (up to 50 kg/h), medium (50–1000 kg/h), and large (above 1000 kg/h) (Walas 1988).

The capacity of the dryers can be expressed also as (kg) water evaporated per unit surface and unit time, which is very high in rotary dryers (about 50 kg/m^2 h) and low in tray dryers (about 1 kg/m^2 h).

The cost of drying is an important factor in dryer design, especially for large-volume products of relatively low value. Energy (fuel) is the major cost in drying operations (62 %), followed by capital and labor costs (Bhatia 1983).

The major energy use is for the evaporation of water (moisture), which varies considerably for the different dryers, e.g., from 3 MJ/kg water (spray dryers) to 6 MJ/kg (tray dryers). The energy efficiency of the dryers (ratio of the heat of evaporation to the heat input to the dryer) depends strongly on the type of dryer. It is higher in contact than convective drying, e.g., 40–80 % versus 20–40 %. Rotary dryers are more efficient than tray, fluid bed, and spray dryers (Walas 1988).

Four categories of industrial dryer problems have been identified by Kemp and Gardiner (2000): (a) underperforming (corrected by performing material and energy balances, by drying kinetics, and by applying moisture equilibria), (b) materials handling, (c) product quality, and (d) mechanical breakdown.

8.3.4 Selection of Industrial Dryers

Simple empirical methods for dryer selection were proposed by Williams-Gardner (1971), Keey (1978), Strumillo and Kudra (1987), Van't Land (1991), and Papagiannes (1992). These methods are qualitative and they do not cover the wide range of available industrial dryers. Selection of the optimal dryer type and size should satisfy all process and product requirements at minimum cost. On the other hand, selection of the wrong dryer may create serious difficulties in producing the desired quantity and quality of dried product.

Recent progress in computer applications has resulted in a number of selection procedures, which facilitate the selection of the proper dryer for each particular application.

Kemp (1999) and Kemp et al. (1997) have developed an expert system for dryer selection (DRYSEL), which has been tested in various industrial case studies. Dryer selection depends on (a) the equipment (mode of operation, heating, feeding), (b) the material (hard, sticky), and (c) the overall flow sheet (material flow rate, moisture content). The algorithm has a matrix structure with five steps:

1. Define the problem and supply the needed material and flow sheet data.
2. Make basic choices of feed/product form, operation/heating, or single stage or multistage.
3. Evaluate merit factors for individual dryers and perform approximate size estimation.
4. Study subtypes and refinements of the selected dryers.
5. Assess all remaining possible dryers and make final decision.

Batch dryers are used for solids throughputs (flows) below 50 kg/h, while continuous operation is preferred above 1000 kg/h.

The software program DRYSEL is a combination of a numerical calculation program and an advisory system. The merit factors are calculated and a rough sizing of the dryer is made. The reasons behind the possible choices are explained by the advisory system. The program may suggest several promising dryers, out of whom the final choice is made, based on the specific product. In a special case study of drying 2000 kg/h of corn cereal, a cascading rotary dryer was chosen.

A fuzzy expert system for selection of batch and continuous dryers was developed by Baker and Lababidi (1998, 2000). The combined fuzzy logic/expert system is rule based, i.e., linguistic variables are used (e.g., temperature: high, low, very low) as opposed to numerical values.

The iterative approach to dryer selection involves dryer specifications, preliminary dryer selection, bench-scale drying tests, comparison of economic alternatives, and final pilot-scale tests. Proposed food dryers are layer (contact, convective, and special) and dispersion (fluid bed) dryers.

A typical example of interest to food dehydration is the following: a solids feed of 120 kg/h with temperature constraint of 60 °C, for which a vacuum tray dryer is recommended. For this application, freeze- and microwave-drying were eliminated on cost grounds.

An information system (DRYING) and a database (BAND) were developed by Menshutina and Poutchkov (2000), Tsoukanov et al. (2000), and Matasov et al. (1998) to facilitate the selection of the appropriate dryer for a given material. The system consists of expert estimations of dryer types and a library of calculations and design procedures. The input data for preselection of a dryer include dryer capacity, particle size distribution, particle aggregation, adhesiveness/cohesiveness, moisture content, explosiveness, toxicity, and drying time. A list of 32 types of dryers is given.

A practical database (DRYERBASE), listing commercially available dryers and dryer manufacturers, was developed by Tsotsas (2000). The dryers are classified into 25 main types, which are sorted by dryer type and dryer manufacturer (supplier). The ten most important industrial dryers of the general list are tray, tunnel, belt, drum, rotary, bin, flash, fluid bed, spray, and tumbler dryers.

The mode of operation can be batch, continuous, or combined. Heating can be convective or contact and operating pressure atmospheric or vacuum. The feed can be liquids, pastes, powders (<0.5 mm), grains (0.5–5 mm), and pieces (>5 mm).

A directory of dryers and drying systems (in German and English) was published by VDMA (1999b). It lists, in a matrix form, 35 suppliers and 65 drying systems, which include field of application, classification of dryers, and dryer construction (convection, contact, radiation, electrical, combined energy, and vacuum).

8.3.5 Commercial Food Drying Equipment

Application of the diverse types of process dryers to food dehydration should take into serious consideration the unique requirements of processing of foods and biological products. The strict product requirements for food dryers (organoleptic, nutritional, and functional) should be met at the lowest possible cost. Practical aspects of food dehydration and food dryers are presented by Greensmith (1998). Design and performance of food dryers are discussed by Barbosa-Canovas and Vega-Mrcado (1996), Crapiste and Rotstein (1997), and Baker (1997). The technology of dehydration of various food products, with emphasis on fruits and vegetables, is discussed by Woodroof and Luh (1986), Luh and Woodroof (1988), and Salunkhe et al. (1991).

Table 8.3 Characteristics of food drying operations and equipment

Dryer type	Product form	Product temperature (°C)	Evap. capacity (kg/m^2 h)	Residence time
Sun drying	Pieces	Ambient	–	10–20 days
Bin or silo	Pieces, grains	30–50	–	1–3 days
Tray	Pieces	40–60	0.2–2	3–10 h
Tunnel	Pieces	50–80	5–15	0.5–3 h
Conveyor belt	Pieces	50–80	5–15	0.5–3 h
Rotary	Grains, granules	60–100	30–100	0.2–1 h
Drum	Sheet	80–110	5–30	10–30 s
Fluid bed	Grains, granules	60–100	30–90	2–20 min
Pneumatic flash	Grains, granules	60–120	10–100[a]	2–20 s
Spray	Powder	60–130	1–30[a]	10–60 s
Vacuum/freeze	Pieces	10–20	1–7	5–24 h

[a]kg/m^3 h, pieces >5 mm, grains and granules 0.5–5 mm, powders <0.5 mm

Preparation and pretreatment of raw food materials, especially fruits and vegetables, involving washing, peeling, slicing, blanching, and chemical treatment (e.g., sulfur dioxide, salts, sugar), is an integral part of the dehydration flow sheet (e.g., Fig. 8.6), and it is discussed by Greensmith (1998), Woodroof and Luh (1986), and Luh and Woodroof (1988).

The various types of drying operations and equipment, used in commercial food processing, are shown in Table 8.3. Selected operating characteristics were taken from the literature (Walas 1988; Green and Perry 1997; Crapiste and Rotstein 1997).

The description of the modern mechanical drying equipment is preceded by a brief overview of the ancient method of sun drying, which is still practiced today for drying certain fruits and other agricultural products and some fish.

The energy consumption depends on the type of dryer, varying from 3 to 6 MJ/kg water evaporated. Much higher energy consumption is required in vacuum and freeze dryers.

8.3.5.1 Sun Drying

Large quantities of grapes (raisins), apricots, figs, prunes, and dates are dried by direct exposure to sunlight in relatively hot and dry climates. Other sun-dried food materials include coffee beans, cereal grains, and fish. Sun-dried fruits contain about 15–20 % moisture, which is near the equilibrium moisture content at ambient air conditions, and they can be stored in bulk, without the danger of microbial spoilage. Typical operations for sun drying of grapes, figs, and apricots are as follows:

Seedless (sultana) grapes are usually pretreated by dipping in alkali solutions, containing vegetable oil or ethyl oleate, which increases the drying rate by increasing the moisture permeability of the grape skin. Corinth (currant) raisins are not pretreated, since they have thin skins. The grape bunches are spread in trays and dried by exposure to direct sunlight. Wooden or paper trays may be used, placed on the ground, between the vines. The grapes may also be dried by hanging the bunches from a string, while they are covered by a transparent plastic cloth, which protects the product from adverse weather conditions. Some currant raisins are dried in the shade, resulting in higher quality. The sun drying time varies from 10 to 20 days, depending on the solar radiation. The sun-dried raisins are separated from the stems by mechanical equipment and stored in bulk before further processing and packaging.

The ripe apricots are usually cut into halves before sun drying on trays, placed on the ground.

Figs may be sun dried on the trees, after ripening. The dried figs are left to fall to the ground, and they may need further sun drying to reach the desired moisture content (15–20 %). Some large figs are sliced into halves to reduce the sun drying time.

Dried fruits, especially figs and apricots, may require fumigation treatment with sulfur dioxide or other permitted insecticides during storage and before packaging.

8.3.5.2 Solar Dryers

Solar drying is actually a form of convective drying, in which the air is heated by solar energy in a solar collector. Usually, flat-plate collectors are used with either natural or forced circulation of the air. Solar energy and, in general, renewable energy sources are important and economical, particularly during energy crises, when the cost of fuel energy increases sharply.

Figure 8.8 shows a simple solar dryer with a flat-plate solar collector connected to a batch tray dryer. The air movement is by natural convection, but addition of an

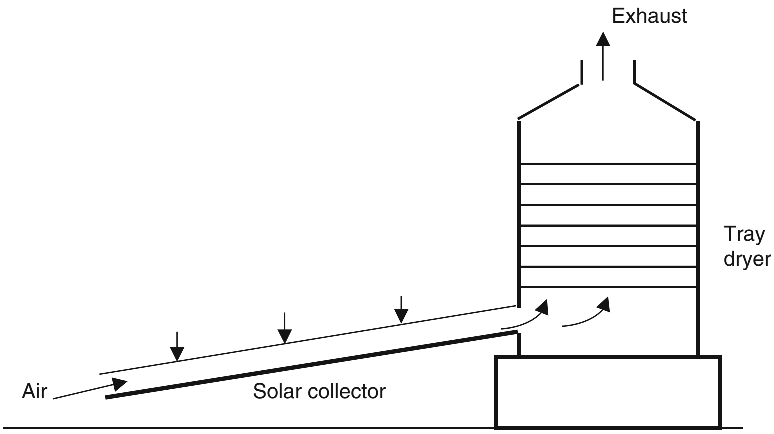


Fig. 8.8 Simple solar dryer

electrical fan will increase considerably the collector efficiency and the drying rate of the product.

Several types of solar collectors and drying systems have been proposed for drying various food and agricultural products, like fruits, vegetables, and grains. The common flat-plate collector consists of a black plate, which absorbs the incident solar radiation, a transparent cover, and insulation material.

The incident solar energy (insolation) varies with the geographical location and the season of the year. A typical insolation for a hot climate would be 0.6 kW/m^2 with an average sunshine time of 7 h/day. This energy corresponds to about $0.6 \times 3600 = 2.16$ MJ/h or 15 MJ/m^2 day (Imre 1995). The evaporation of water at 40 °C requires theoretically 2.4 MJ/kg and practically about 3 MJ/kg. Therefore, the mean evaporation rate of water will be about $2.16/3 = 0.72$ kg/m^2 h (intermittent operation 7 h/day).

The relatively low intensity of incident solar radiation is a serious problem for drying applications, where large amounts of thermal energy are required for the evaporation of water from the food material. Large surfaces of solar collectors are needed for drying significant amounts of food materials. For example, evaporation of 1000 kg/h of water (capacity of a typical mechanical convective dryer) would require about $100/0.72 = 1400$ m^2 of collector surface for a hot climate (intermittent operation 7 h/day). A larger surface would be required in a temperate zone.

Solar tunnel drying compares well with conventional convective drying, except for the lower capacity (kg water evaporated per hour) of the solar system (Fuller 1994). Solar drying is considered effective for relatively small drying operations of fruits, like grapes and apricots, under the climatic conditions of, for example, Southern Australia. Solar energy collected in this area for a continuous 30-h operation (including night) was estimated at 20 MJ/m^2, corresponding to about 186 W/m^2 (continuous operation) or 0.6 kW/m^2 (intermittent, 7 h/day operation).

The problem of intermittent solar radiation (day–night) is usually met with the use of some form of auxiliary energy, like fuel or electricity. Thermal storage of solar energy can be also applied, using rock beds or water to absorb extra solar energy for night or cloudy weather use (Raouzeos and Saravacos 1986).

Some other solar collectors, proposed for solar drying, are (a) a low-cost tunnel collector 1 m × 20 m connected to a tunnel dryer for drying a batch of 1000 kg of grapes (Lutz and Muhlbauer 1986); (b) a solar collector with V-grooves, attaining temperatures 50–70 °C at 0.7 kW/m^2 insolation, used for drying chili in Malaysia; and (c) an evacuated tubular solar collector (glass tubes 12.6 cm diameter and 2.13 m length), capable of heating the air to 90–110 °C (Yan and Hu 1994).

Solar collectors, integrated in the roof or the wall of a farm building, can provide heated air for drying grain in a bin or silo (Henrikson and Gustafson 1986). A conventional bin dryer is shown in Fig. 8.9.

Silo drying of grain usually reduces moisture content from about 20 to 18 %.

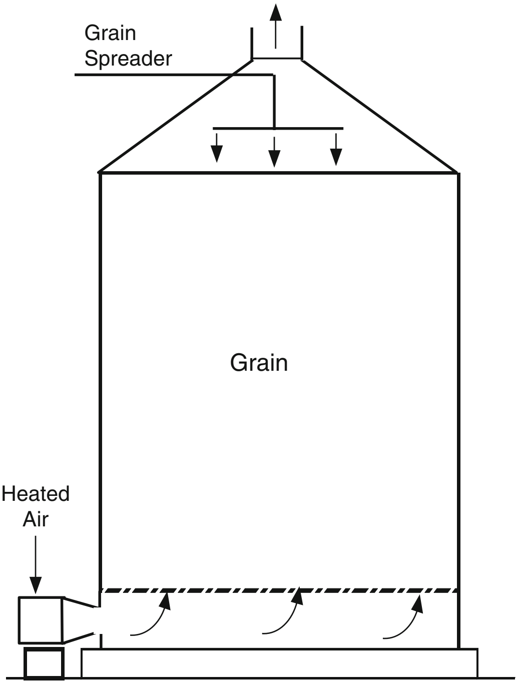


Fig. 8.9 Batch bin (silo) dryer

8.3.5.3 Bin, Silo, and Tower Dryers

Bin and silo dryers are used widely in the drying of agricultural products, notably grain (wheat, shelled corn, rice, soybeans, etc.), from an average harvest moisture of 25 % to a storage moisture of about 15 %. In addition to drying, mechanical aeration of the stored grain is needed to prevent local overheating and spoilage (Raghavan 1995). The aeration flow rate depends on the moisture content of the grain, varying usually from 45 to 90 m^3/h m^3 of grain. The moisture content of cereal grains in silos increases about 3 % during the winter. Silo fans require about 2 kW of power for 1000 tons of bulk grain.

Figure 8.9 shows the diagram of a batch bin or silo dryer, which consists basically of a fixed bed of product (e.g., grain), through the bottom of which heated air is forced by a mechanical fan. The maximum safe temperature of the air depends on the stored food material, ranging from 43 °C (rice) to 60 °C (wheat). Efficient grain dryers require high air flow rates, e.g., 450 m^3/h m^3 of grain.

In addition to the fixed batch dryers, recirculating batch, recirculating continuous, and portable grain dryers are also used (Raghavan 1995). The drying capacity of the grain dryers is about 2–4 tons/h for the batch, 3–9 tons/h for the portable, and above 15 tons/h for the continuous flow units.

Bin dryers are also used in finish drying of some vegetable materials, when the product is difficult to dry (low moisture diffusivity) in the primary dryer, without

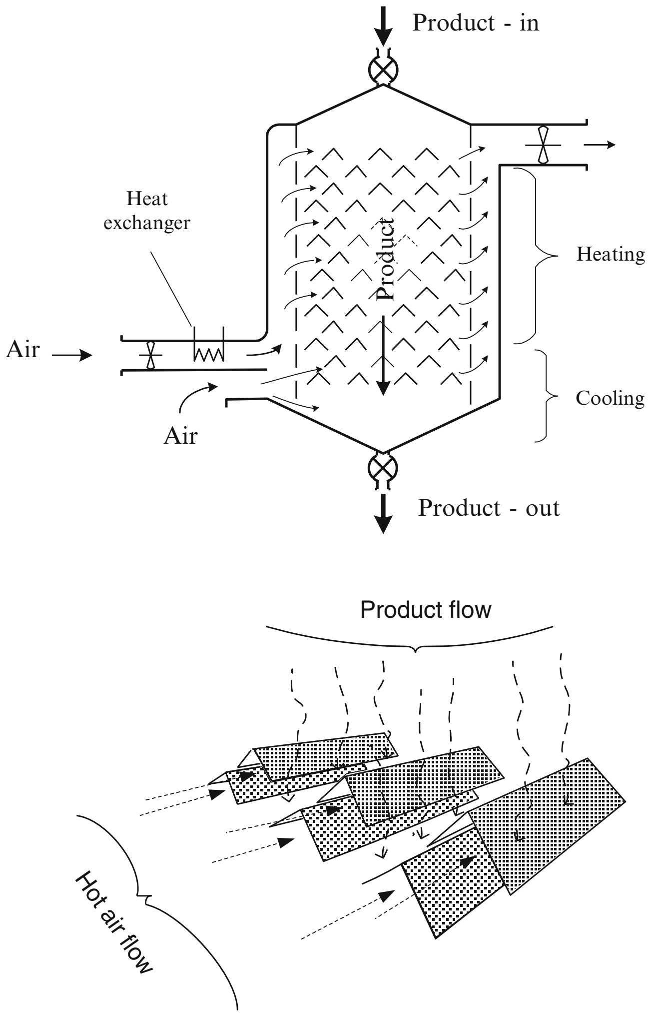


Fig. 8.10 Diagram of a continuous tower dryer

raising the temperature. Dehumidified air at near ambient temperature may be needed in finish drying of hygroscopic materials.

The tower dryer (Fig. 8.10) is a variation of the bin/silo dryer. Such dryers are used in reducing the moisture content of cereal grains after harvesting and before storage in silos. The tower dryers are usually metallic structures, composed of several similar units, each having dimensions 3.5 × 2.0 × 18.0 m. The product, after cleaning, is transported by bucket elevators to the top of the dryer, at a rate controlled by the emptying mechanism at the bottom of the unit (Chap. 3). Hot air, in cross flow, is drying the grain, which flows downward. The downstream movement, and thus the moisture of the grain, can be controlled by varying the cross section of the upper and lower parts of the dryer. At the lower part of the tower dryer, ambient air is blown for cooling the grain.

The capacity of the tower dryer may be from 5 to more than 100 tons/h of fresh grain. The initial moisture content of the grain depends on the product, the harvesting area, and the climatic conditions of the harvesting season. For long-term storage, the moisture content must be reduced to below 16 %.

The temperature of the heating air is usually 70–100 °C. In heating grain that is utilized in baking processes, the drying temperature must not exceed 80 °C to avoid heat damage of the useful enzymes. More than two large fans are used to blow the dying air, each requiring 5–11 kW of power and blowing 20,000–30,000 m^3/h. The specific energy consumption of tower dryers is about 5 MJ/kg water evaporated, and the total energy consumption of a tower dryer is 4–33 GJ/h.

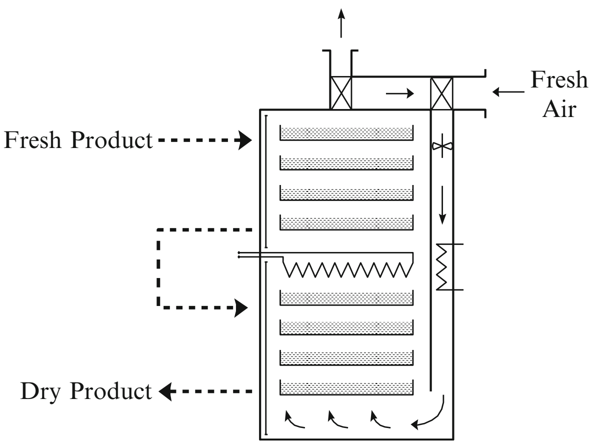
8.3.5.4 Tray/Cabinet Dryers

Tray or cabinet dryers are the simplest convective dryers, and they are used for drying relatively small batches of food materials in the form of pieces, such as sliced fruits and vegetables. They consist of a stack of trays, placed in a cabinet, and they are equipped with a heat exchanger and a mechanical fan for circulating the heated air through the trays (Fig. 8.11). The heat exchanger operates usually with steam, and part of the air is recirculated to recover part of the heat of the exhaust air or air/flue gases.

The trays may be placed on a mobile truck, moving on rails, for easy loading and unloading of the dryer. Large cabinet dryers can handle more than one truck of trays, making possible a semicontinuous operation.

A truck may contain about 30 trays with dimensions 80 cm × 80 cm × 5 cm. The amount of product loaded on a truck, containing 30 trays of dimensions 80 cm × 80 cm × 5 cm, each loaded with 5 kg, will be 30 × 5 = 150 kg (Greensmith 1998).

Fig. 8.11 Cabinet (tray) dryer. *HE* heat exchanger



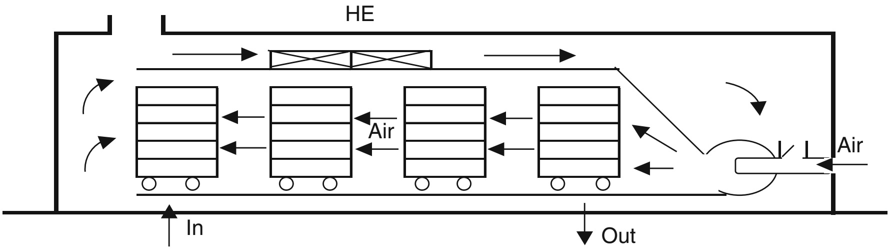


Fig. 8.12 Diagram of countercurrent tunnel (truck) dryer. *HE* heat exchanger

Typical data for the tray dryer of Fig. 8.11 are ten perforated aluminum trays 2.0 × 2.0 m of total area 40–60 m^2, heating with 600 kg/h of steam of 5-bar pressure, air temperature of about 100 °C, electrical energy (fan) of 6–8 kW, and drying capacity of 5–12 tons/h of fresh fruits or vegetables.

8.3.5.5 Tunnel Dryers

The tunnel (truck) dryers are essentially an extension of the tray/cabinet dryers, with several trucks moving slowly in a long tunnel, while coming in contact with hot air in parallel, counter, or combined flow (Fig. 8.12).

The drying air is moved by mechanical fans and heated by heat exchangers, operating with steam at a pressure of about 7 bar. Partial recirculation of the air is practiced (about 50 % of the total air), as in other convective dryers.

The dryer is loaded successively with new trucks, while an equal number of trucks of the dried product are removed from the other end. Each truck (trolley) is loaded with about 50 trays. A typical drying time for vegetables is about 6 h (Greensmith 1998).

Tunnel dryers can be constructed from low-cost materials, and they are simple to operate. They are suitable for economic dehydration of fruits and vegetables, near the production farms. Since the production of most fruits and vegetables is seasonal, the dryers should be used for various products to increase their operating time.

8.3.5.6 Conveyor Belt Dryers

Figure 8.13 shows the diagram of a typical single-belt dryer, used widely in the dehydration of food materials. The size of the belt (band) of a typical medium-scale operation is 30–40 m long and 2.5–3 m wide (Greensmith 1998). High air velocities are used (3–6 m/s) for fast drying. The capacity (product throughput) of commercial belt dryers varies with the product in the range of 1000–3000 kg/h.

Heat for drying is supplied either by direct combustion of "clean" fuels (natural gas or LPG) or by indirect heat exchange from steam or oil flue gases. The heated

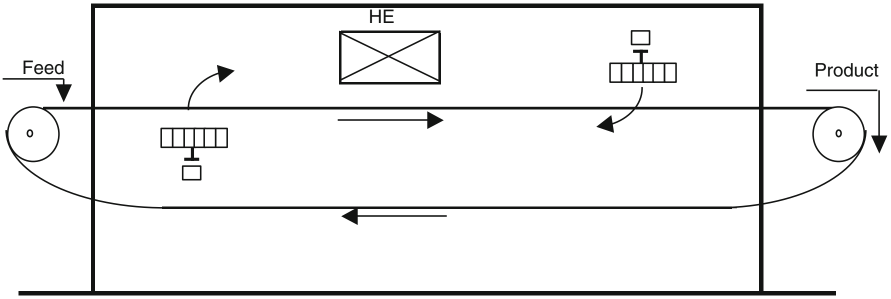


Fig. 8.13 Single-belt (band) conveyor dryer (up and down through flow). *HE* heat exchanger

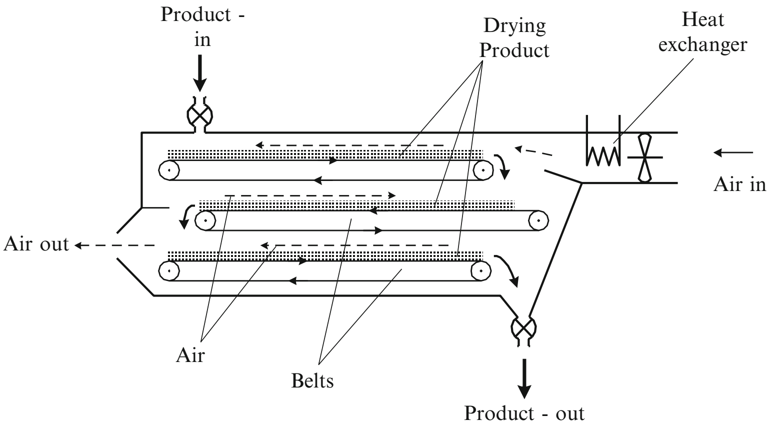


Fig. 8.14 Diagram of a 3-belt dryer

air passes through the product and the perforated belt upward or downward with properly installed fans.

The loading of the trays depends on the bulkiness or compactness of the material. Higher loading is used with porous than nonporous materials. Typical depth of belt loading for vegetable materials is 5–12 cm.

Two or more passes (stages) may be needed for some drying operations. Changing the operation from stage to stage exposes new surfaces of the product to the drying medium, resulting in faster and more uniform drying (Fig. 8.14).

For economical reasons, belt drying of some vegetables is stopped at about 12–15 % moisture, and the drying is completed to about 5 % in a bin dryer (Fig. 8.9). Small or mobile bin dryers may be used.

Figure 8.14 shows diagrammatically a 3-belt conveyor dryer, suitable for fruit and vegetable dehydration. Each belt is 1–3 m wide and 10–30 m long. The drying capacity is about 2–15 kg/m^2 h and the specific steam consumption 1.8–2.0 kg/kg water. Total electrical power was up to 100 kW. Temperature ranges from 70 to 100 °C and air velocities from 0.5 to 1.5 m/s.

8.3.5.7 Rotary Dryers

The rotary dryers consist of an inclined long drum (cylinder), rotating slowly, through which the material (particles or grains) flows with a tumbling (cascading) action (flights) in cocurrent or countercurrent flow with the heating air/gases (Fig. 8.15). The dryer shell is inclined about 5° to the horizontal, and it is rotating by a gear mechanism at a peripheral velocity of 0.2–0.5 m/s. A cyclone dust collector may be needed at the exit of the exhaust gases.

The rotary dryer is characterized by high air/gas temperatures, high evaporation rates, and relatively short residence time. The dimensions of normal rotary dryers range in 1.5–3 m in diameter and 6–20 m in length. The evaporating capacity is about 50 kg/m^2 h per heating surface or about 60 kg/m^3 h per dryer volume (Walas 1988). The air/gas velocity ranges between 0.5 and 2.5 m/s.

Heating of the rotary dryers is either by steam tubes, installed along the inside of the cylindrical shell, or by combustion gases from natural gas, LPG, or oil. Rotary dryers usually operate at high temperatures and, therefore, they have high evaporative capacity. They are used mostly in drying food by-products and wastes (peels and pomace), where high temperatures are permissible and economics is important.

Application of rotary dryers to food products is limited to particulate materials, such as granulated sugar and some grains. Large food particles cannot be handled in this type of dryer, due to the relatively short residence time, the danger of overheating, and the mechanical damage (abrasion) of the products. Such materials are dried more effectively in conveyor belt dryers. Direct and indirect (steam) heated rotary dryers are used economically for commercial drying of fish meal (Fresland et al. 2000) and solid food wastes, e.g., citrus peel and pulp.

Rotary dryers are used widely in the chemical process industries, and their mechanical and operational characteristics are discussed by Bhatia (1983), Walas (1988), and Green and Perry (1997). Automatic control of rotary dryers can improve significantly the economic operation (Ventzas 1998).

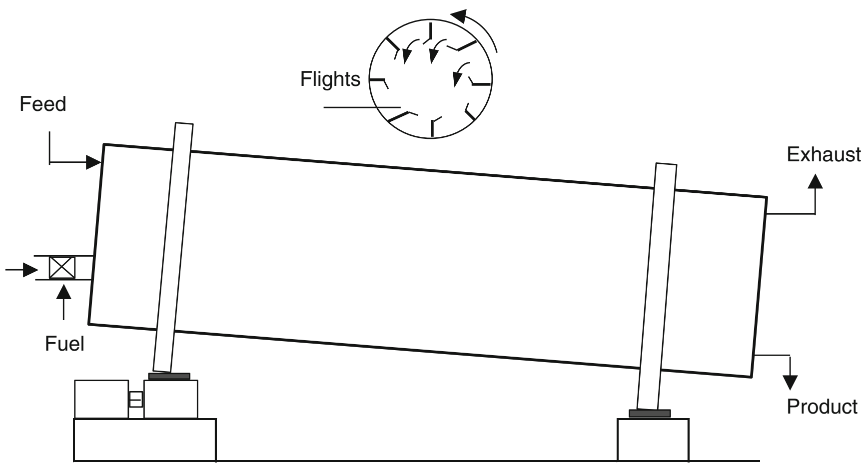


Fig. 8.15 Diagram of direct (fuel) heated rotary dryer

8.3.5.8 Fluid Bed Dryers

Fluid bed dryers are fast-drying equipment, which is based on the very high heat and mass transfer rate between the heating medium (hot air) and the fluidized granular material. They are efficient and economic units for drying food materials in granular form, like grains, peas, and other food particles. One of the basic elements of a fluid bed dryer is a bed of the material supported on a perforated plenum, through which hot air is passed, fluidizing and drying the material. A cyclone collector and other dust collecting equipments are installed before the centrifugal exhaust fan (Fig. 8.16). Basic requirement for this operation is the air fluidization of a bed of the particulate material (Hovmand 1995), which is affected by the size, shape, and density of the particles. Average particle size for efficient operation is 10–20 mm. A narrow particle size distribution is desirable, since it reduces entrainment of the smaller particles.

Rapid mixing of the solids leads to nearly isothermal operation throughout the bed and better process control. Residence time can be chosen in the order of minutes, in contrast to the pneumatic short-time operation (Vanecek et al. 1966).

Fluid bed dryers are used for the efficient primary and secondary drying of paddy rice in the moisture ranges of 22–45 % and 22–26 %, respectively (Soponronnarit et al. 1996).

The vibrated fluid bed (VFB) system is used widely in industrial applications, because of its important operating advantages. Typical applications of VFB include

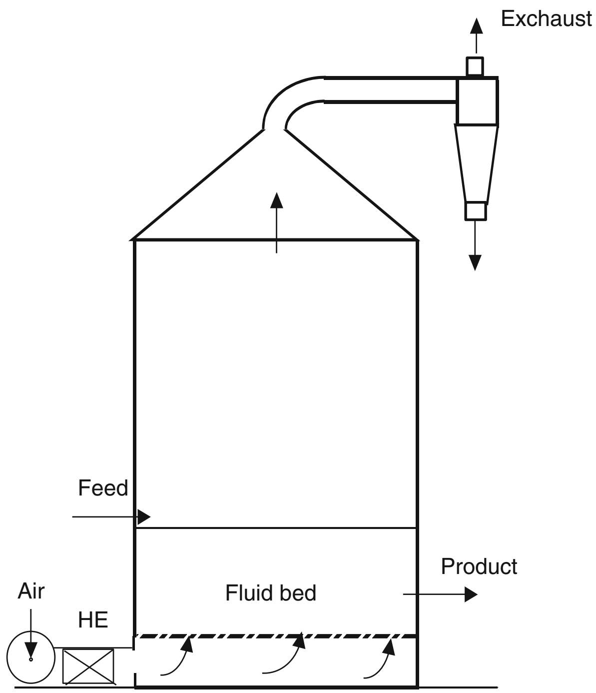


Fig. 8.16 Diagram of fluid bed dryer

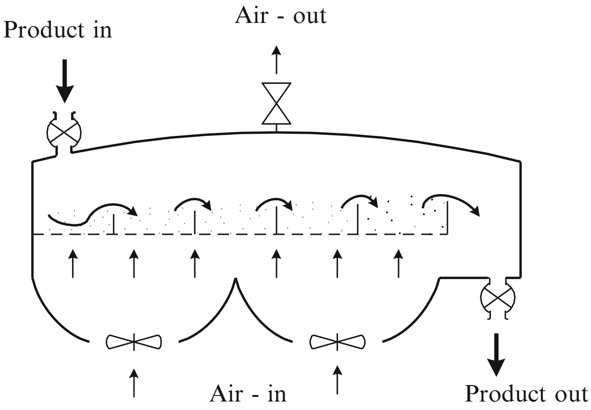


Fig. 8.17 Diagram of compartment fluidized bed dryer

post-drying in spray drying systems, and agglomeration of food powders to produce soluble food granules (Chap. 4).

Technical data on fluid bed dryers are presented by Walas (1988) and Green and Perry (1997).

Figure 8.17 shows diagrammatically a wide fluidized bed dryer with five compartments and two fans. The dimensions of a typical fluidized bed dryer are length 5–7 m, width 1.5–2.5 m, and height 6 m. The water evaporating capacity of this dryer is 600–800 kg/h, the heating capacity 850–1100 kW, and the electric motor power 6 kW.

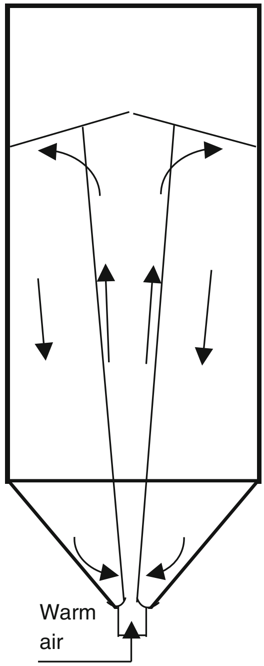
8.3.5.9 Spouted Bed Dryers

Spouted bed dryers are a special type of fluid bed equipment, in which the granular material is circulated vertically in a tall drying chamber. The heated gas enters as a jet at the center of the conical base of the vessel, carrying upward the granular material, which is dried partially and thrown to the annular space. The material in the bed moves slowly by gravity to the bottom, and the cycle is repeated continuously (Fig. 8.18). Spouted bed dryers are suitable for granular materials larger than 5 mm, such as wheat grain (Hovmand 1995).

8.3.5.10 Pneumatic/Flash Dryers

Pneumatic or flash dryers are used for efficient fast drying of particulate materials that can be transported pneumatically. Figure 8.19 shows diagrammatically a simple pneumatic dryer, which consists of a long drying tube (5–30 m), a particle collection system (cyclone), and heating/air moving equipment. Gas fuel is a convenient energy source.

Fig. 8.18 Spouted bed dryer



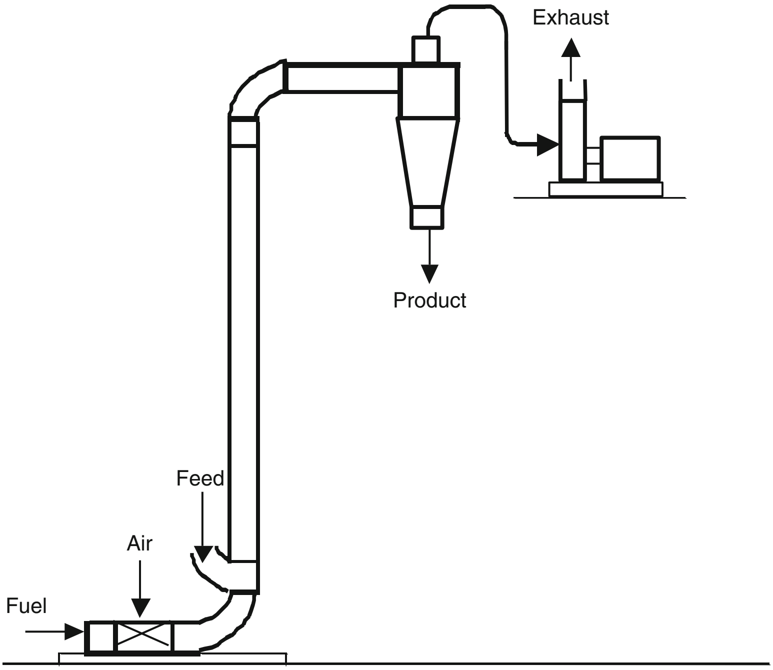


Fig. 8.19 Diagram of a simple pneumatic (flash) dryer

The terminal or entrainment velocity of the particles in the drying tube is estimated from the Stokes equation

$$u = d_p^2(r_s - r)/18h \tag{8.16}$$

where d_p is the mean particle diameter (m); r_s and r are the densities of solid particles and air (kg/m^3), respectively; and h is the viscosity of the air (Pa s).

The mixture of hot air/gases moves the wet material from the bottom through the drying tube at a high velocity (15–30 m/s) and temperatures up to 130 °C. The material is dried fast, due to the high heat and mass transfer rates. However, since the once-through residence time in the drying tube is very short (1–5 s), recirculation of the product is often required, reaching residence times up to 1 min. The residence time in pneumatic drying can be increased using a special cyclone with high residence time, which acts as an additional dryer (cyclone dryer), after the product is passed through the main drying tube (Korn and Nowak 2000).

The residence time in pneumatic dryers can be increased by forming the ducting into a continuous loop (pneumatic ring dryer), as shown in Fig. 8.20. Heating of the drying air can be direct (gas fuel) or indirect (steam heat exchanger).

Figure 8.21 shows a rectangular flash dryer of dimensions (5–6) × (4–4.5) × (6–6.5) m. The wet food particles are fluidized by a rotating table (50–500 RPM) and air, blown at the bottom of the dryer, at the rate of 11,000–30,000 m^3/h. The evaporative capacity of the dryer is 4.5–8.0 tons/h.

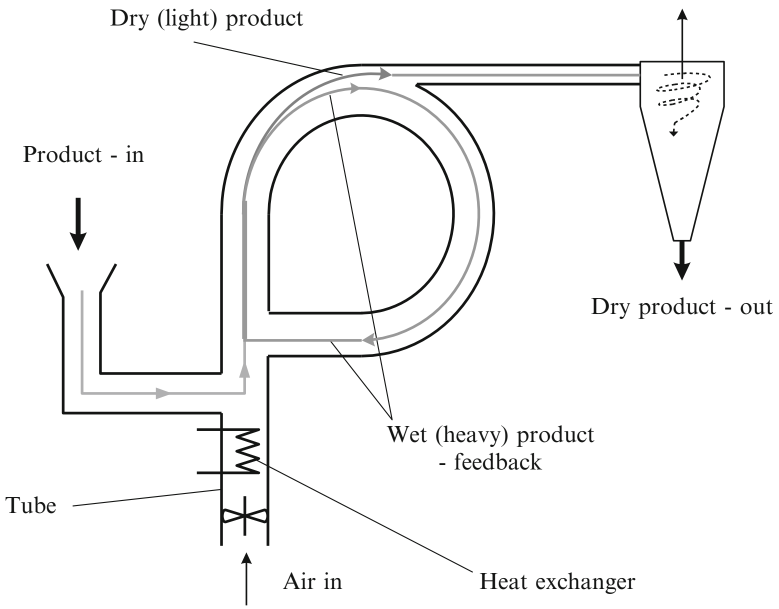


Fig. 8.20 Diagram of pneumatic ring dryer

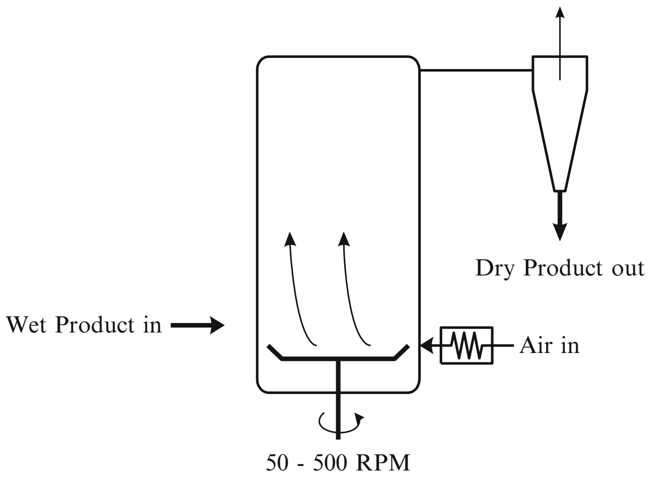


Fig. 8.21 Pneumatic (flash) dryer with centrifugal fluidizer

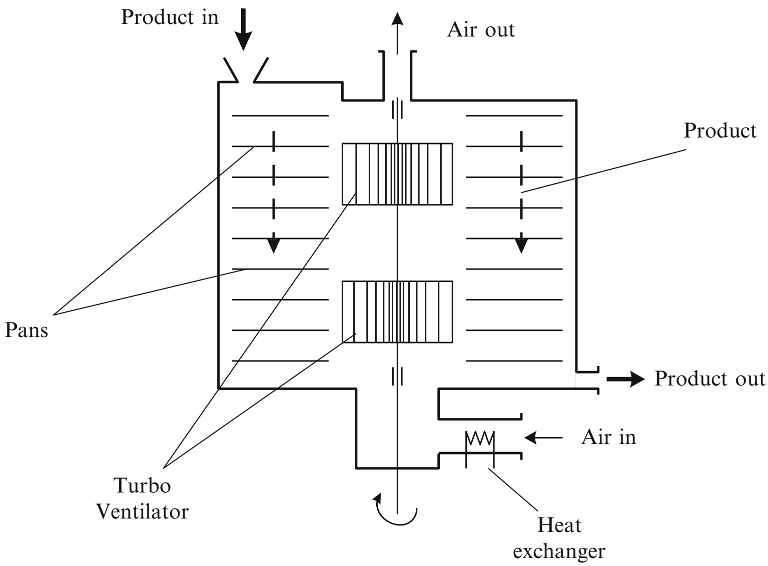


Fig. 8.22 Diagram of turbo dryer

8.3.5.11 Agitated Dryers

The drying rate of food pieces and particles can be increased by mechanical agitation, as indicated in the following examples of drying equipment:

The turbo dryer (Fig. 8.22) is a special tray dryer with the particulate product flowing slowly down, following a helical path, while it is agitated by air blown

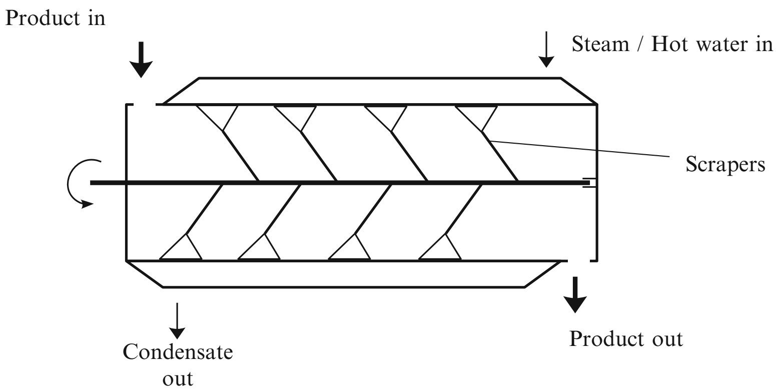


Fig. 8.23 Diagram of an agitated horizontal dryer

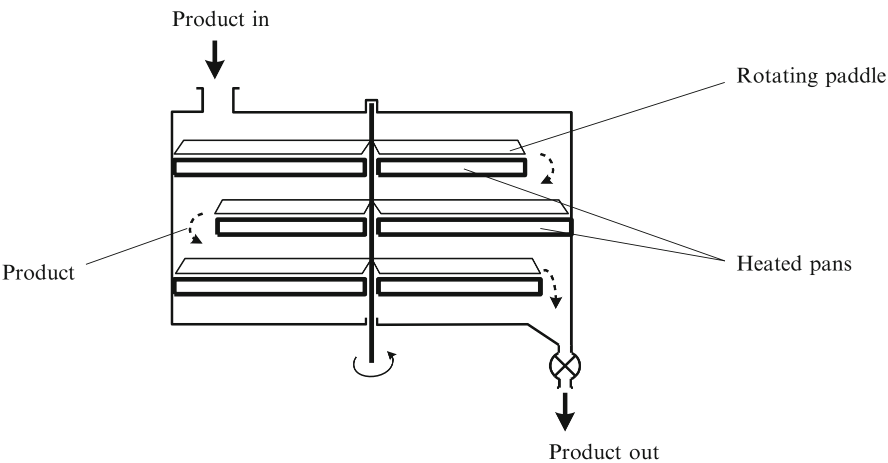


Fig. 8.24 Diagram of a pan dryer

countercurrently by two fans. The dimensions of such dryers are 6–8 m in diameter and 7–10 m in height. The product capacity is 2.5–8.0 tons/h and the water evaporation 2–4 tons/h. The specific heat consumption is 3.7 MJ/kg water evaporated. The electrical energy required for the fans is 16–20 kW.

Figure 8.23 shows an agitated horizontal dryer of small size (diameter 0.7–1.5 m) with mechanical scrapers (spatulas), suitable for paste products. The evaporative capacity is about 95 kg/h.

A pan dryer with rotating paddles (scrapers), suitable for paste products, is shown in Fig. 8.24. Such dryers have diameters of 2–3 m, the number of heated pans is up to 15, and the total pan surface is 5–100 m^2. The evaporative capacity can be up to 500 kg/h.

8.3.5.12 Spray Dryers

Spray dryers are used for drying liquid foods and food suspensions, which can be dispersed in the form of droplets in a stream of hot air. Figures 8.25 and 8.26 show the main components of cocurrent and countercurrent spray drying systems, which

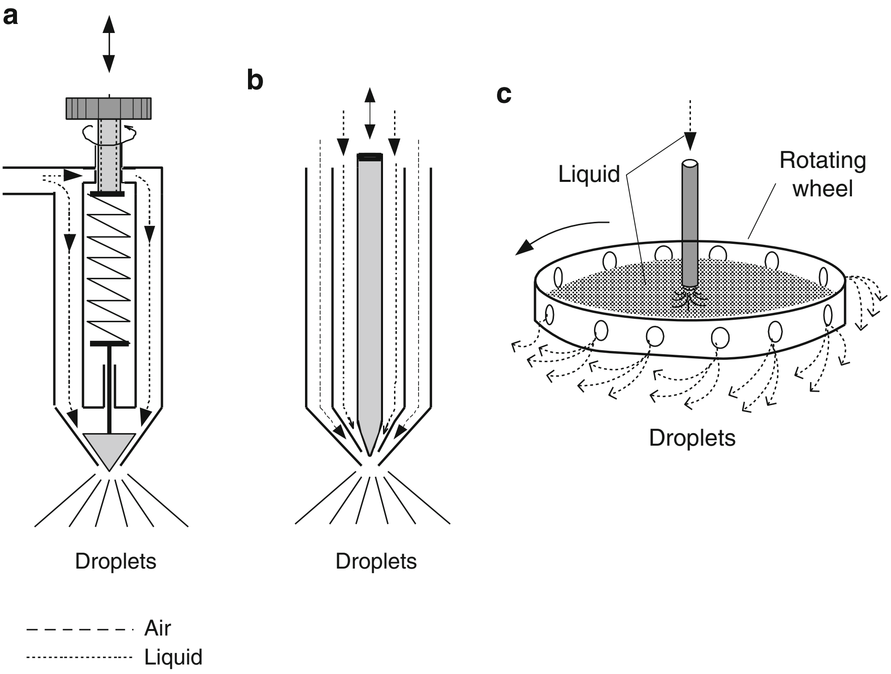


Fig. 8.25 Diagram of a cocurrent spray dryer

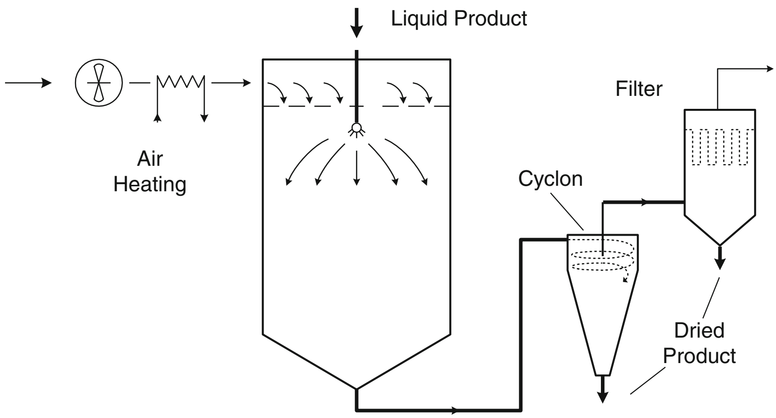


Fig. 8.26 Simplified diagram of a counter-current spray dryer

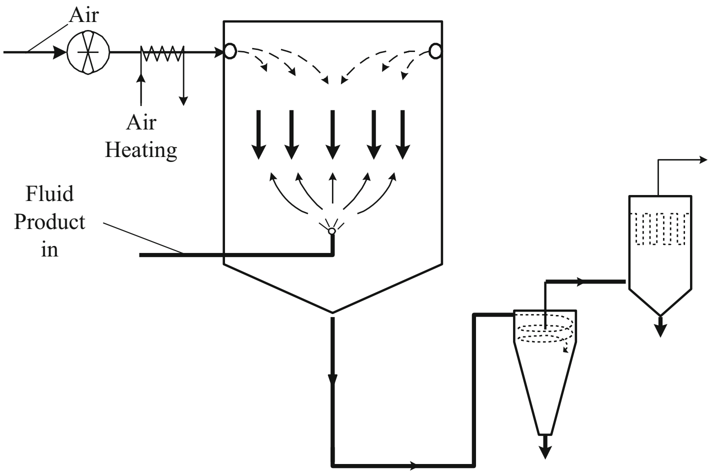


Fig. 8.27 Main types of atomization nozzles of spray dryers

consist of a spraying device, a large cylindrical drying chamber, a particle collection system (cyclone and bag filters) for the dried product, and the required heating and air moving equipment (Masters 1991; Filkova and Mujumdar 1995).

Concentrated food liquids, such as milk, coffee, and juices, are dispersed as droplets, using three types of atomizers, i.e., pressure nozzle, centrifugal (wheel), and two fluid (pneumatic) (Fig. 8.27). The high pressure of the liquid by using the nozzles (a) and (b) of Fig. 8.27 is achieved through piston pumps. Furthermore, the final control of the pressure in these nozzles is achieved through adjustment of needles in them (Kessler 1981).

The type of atomizer depends on the properties of the food liquid (concentration, viscosity) and the droplet size distribution desired (5–500 mm). Pressure nozzles, operating at 50–100 bar, produce nearly uniform size (narrow size distribution) of droplets; their capacity is limited to about 1000 kg/h liquid, and, therefore, multiple nozzles are needed in large spray dryers. The centrifugal wheel operates at very high speeds, 5000–25,000 RPM, with peripheral velocities of 100–200 m/s; it has a higher capacity than the pressure nozzle, and it gives a wider range of droplet sizes. The average droplet size, produced by the centrifugal wheel, is larger than the sizes produced by the pressure atomizers, an advantage in producing large, easily dissolved dried particles. The pneumatic nozzle operates at air pressure of 3 bar, requiring 0.5–0.6 m^3 air/kg liquid, and it is used mostly in small installations and pilot plants (Filkova and Mujumdar 1995).

The size and capacity of the spray dryers vary widely, with diameters up to 10 m and heights up to 30 m. In comparable capacities, dryers with pressure nozzles are higher than those using centrifugal atomizers, but the diameter of spray dryers with centrifugal atomizers is larger than that of dryers using pressure nozzles or pneumatic nozzles. Usually the diameter of dryers equipped with centrifugal atomizers is 5–7 m, while that of those equipped with pressure or pneumatic nozzles usually is up to 4 m.

Hot air, usually mixed with “clean” combustion gases at high temperature (150–300 °C), is used as the drying medium in cocurrent or countercurrent flow with the liquid droplets, which are sprayed from the top of the drying chamber. The droplets dry rapidly, due to high heat and mass transfer rates in the system, producing food particles, which are collected either at the bottom or the cyclone collector system, before the air is exhausted to the atmosphere. The temperature of the exit air is 70–100 °C. The product is kept at a relatively low temperature (50–70 °C), due to the evaporative cooling in the dryer.

The residence time in spray dryers is short, e.g., 5–30 s, (approximate speed of air in a drying tower: 0.3 m/s) during which the material must be dried to the desired moisture content, without under- or overdried particles. Some spray drying systems include a post-drying section, such as a fluid bed dryer, installed in the bottom of the drying chamber, in which the residence time is controlled to obtain the desired moisture content of the particles. The fluid bed can also act as an agglomeration unit for increasing the size of the particles and improving their solubility and other functional properties (see Chap. 4). The food agglomerates are finish-dried in a fluidized bed, adding also small quantities of liquid ingredients to the product during recirculation (*).

The heat consumption in spray dryers, due to high temperatures, is relatively high, about 6 MJ/kg water, and energy-saving systems are used (e.g., preheating of air) to improve the thermal efficiency.

Energy savings in spray drying can be achieved either by direct mixing of a part of the exhaust gases leaving the cyclones with fresh air or by indirect heating of the fresh air by the hot exhaust gases, using a heat exchanger. The method of partial mixing, for example, with 15–30 % exhausted warm air at 70 °C with fresh air, before heating both of them further up to about 155 °C, may save approximately 10 % of heat energy. The indirect heating of fresh air before its final heating by intervening a heat exchanger using exhausted air (e.g., 70 °C) may save about another 7–9 % heat energy in addition to that of the prementioned direct mixing of fresh air with exhausted air. However, this requires significant investment in an air/gas heat exchanger, which must have a relatively large exchange surface, due to the low gas/solid heat transfer coefficients.

Advances in spray drying of liquid foods are reviewed by Mermelstein (2001). Most of spray drying applications are related to the dairy industry (milk and whey products). Separation of small dried particles from the exhaust air/gases is achieved in cyclone separators, followed by bag filters. Bag filters of hygienic design are more effective than mechanical cyclone collectors in removing fine particles from the exhaust gases and preventing air pollution (Chap. 5).

An improved design of the spray drying chamber is based on the flow of the hot air from the top in the middle of the chamber, followed by the upward flow close to the walls, with exit at the top. In this system, the walls are kept at a relatively lower temperature, preventing the sticking and overheating of the drying droplets.

Safe operation of the drying chamber is required against spontaneous combustion and explosion, which may occur from overheated flammable and explosive powders, accumulating in the corners and crevices within the drying chamber. A fire suppression system, relief valves, and electrical insulation should be installed in the dryer.

8.3.5.13 Drum Dryers

Drum or roller dryers are used to dehydrate concentrated food liquids, purees, and pulp. The double-drum dryers (Fig. 8.28) consist of two counterrotating cylinders, heated internally with steam, which dehydrate quickly a layer of the material, spread on the outer surface. The dried product, in the form of flakes, is removed continuously from the drums, and a new layer is applied on the scraped surface. Single-drum dryers are also used in some applications (Figs. 8.29 and 8.30). The drums must be machined to very close tolerances, for both diameter and length, to allow close clearance operation (Moore 1987).

The drum dryers are usually operated at atmospheric pressure, but vacuum operation is possible, for heat-sensitive food products, by enclosing the drying system in a vacuum chamber. The size of the drum dryers varies in the range of diameter 0.4–1.2 m and length 1–3 m. Steam pressures of about 3–4 bar are used

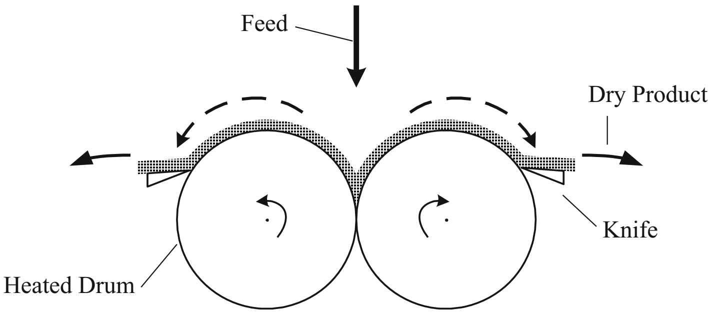
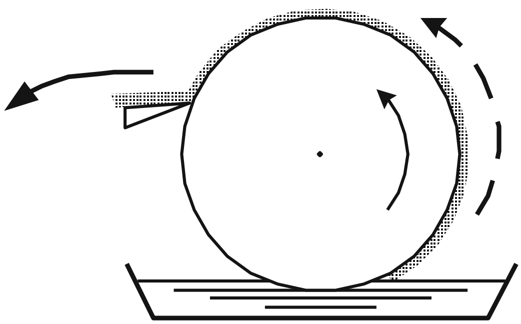


Fig. 8.28 Diagram of a double-drum dryer

Fig. 8.29 Diagram of a single-drum dryer



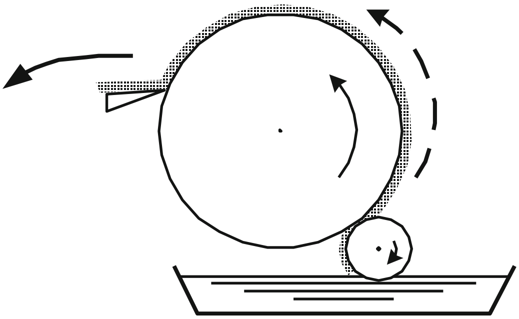


Fig. 8.30 Diagram of single-drum drier with auxiliary roller

and the evaporative capacity is in the range 20–40 kg/m^{2}h. The heat consumption of the drum dryers is relatively low (about 3 MJ/kg water evaporated), due to the direct heat transfer through the drum walls, without the interference of process heating air. Rotational speeds of the drums are 1–10 RPM (Walas 1988).

The drying rate is controlled mainly by heat transfer, since the material is dried as a thin film, in which mass transfer by diffusion is not controlling the process.

8.3.5.14 Vacuum and Freeze Dryers

Vacuum and freeze dryers are the most expensive drying equipment, and they are used to dehydrate sensitive, high-value food products, like coffee, fruit juices, vegetable extracts, mushrooms, dairy products, meat, and chicken. The improvement of quality, functional properties, and nutritive value of these products justifies the added cost, compared to the conventional (convective) drying methods.

Vacuum and freeze dryers are mostly batch operations of lower capacity than convective dryers. They consist basically of a vacuum cabinet (typical size, 50-m^2 tray area), where the product is dried and spread on trays, and a condensing/vacuum system for removing the water vapors and maintaining the vacuum (Figs. 8.31 and 8.32). The main difference between the two processes lies in the operating pressure of about 10 mbar (8 °C) in vacuum compared to lower than 1 mbar (−20 °C) in freeze-drying, which results in evaporation of liquid water in vacuum drying and in sublimation of ice in freeze drying. Freeze-dried products retain their shape, and they have a very high porosity and they rehydrate instantly. Freeze dryers are more expensive because they require lower-temperature condensers, e.g., −30 °C, and higher vacuum pumps.

Freeze dryers are used mostly in the pharmaceutical industry and in drying expensive biotechnological products, where the high cost of drying is justified (Liapis and Bruttini 1995; Oetjen 1999). Application to foods is confined to heat-sensitive, high-quality, and relatively expensive products, e.g., instant coffee.

The principles and applications of freeze-drying in foods received much attention in the past (King 1971; Mellor 1978), but cost considerations and alternative

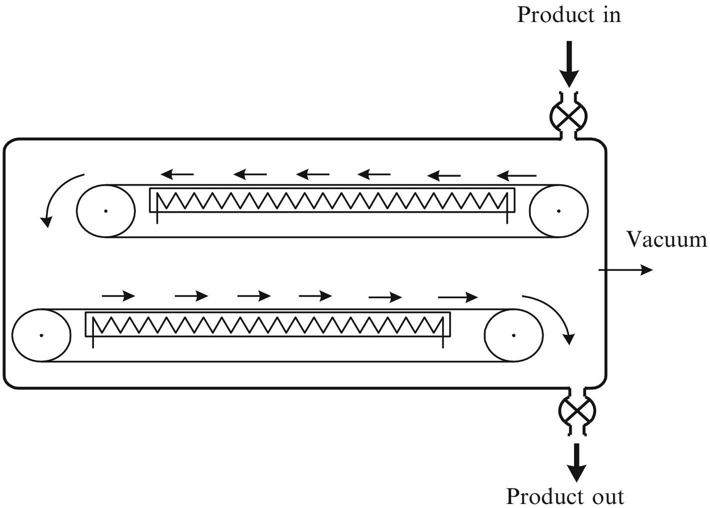


Fig. 8.31 Diagram of a continuous vacuum dryer

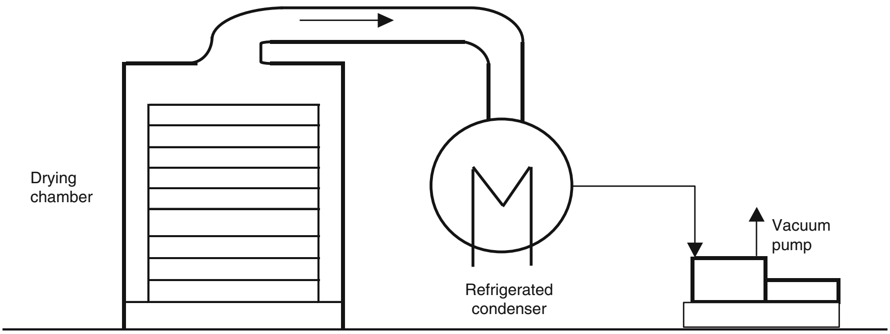


Fig. 8.32 Diagram of a batch freeze dryer

improved drying processes, like spray drying, have limited its application to only high-value food products.

Continuous vacuum dryers consist of a horizontal cylindrical vessel with a moving belt, on which a layer of food material (e.g., citrus juice) is dried with the aid of IR or MW heating. Typical capacity is about 50 kg/h dried product. Higher capacities can be obtained, using multiple-belt vacuum dryers.

Semicontinuous vacuum and freeze-drying systems have been developed for large industrial operations. In such a system, the drying chambers consists of a long cylindrical tunnel with one or two doors at the ends, equipped with special mechanisms to maintain the operating vacuum in the chamber. The tunnel is loaded with product-carrying trucks, and at the same time, dried product is removed from the other end.

The energy requirements for freeze-drying are much higher than in other dryers, e.g., 10 MJ/kg vs. 4 MJ/kg water evaporated, due to the extra needs for refrigeration and vacuum, and the higher heat of sublimation of ice (2.84 MJ/kg at −15 °C), compared to the heat of evaporation of water (2.26 MJ/kg at 100 °C).

8.3.6 Special Food Dryers

Special food dryers are used in small-scale food processing operations to dehydrate some sensitive food products, especially fruits and vegetables (Saravacos 1993). They are mostly batch operations and their cost is, in general, higher than the cost of conventional dryers. Some of the special dryers are still in the development stage, and their commercial application will depend on the process economics and the acceptance of the new products by the consumers.

8.3.6.1 Microwave and Dielectric Dryers

Microwave (MW) and dielectric or radio-frequency (RF) energy is used to remove water from food materials at atmospheric or in vacuum. The MW energy is usually applied at 915 or 2450 MHz (megacycles/s), while the frequency range of 1–100 MHz is used for the RF energy. Both types of electromagnetic energy can heat the materials by ionic or molecular motions or other mechanisms (Schiffmann 1995).

The basic advantage of MW and RF energy is that they heat the material internally, without the need of external convective or contact heat transfer (see Chap. 6). Water has a higher dielectric constant (about 8) than the other food components (about 2). Therefore, food materials of high moisture content absorb more MW or RF energy, facilitating the drying process. Free water can be removed more easily, because it absorbs more energy than adsorbed water.

The penetration depth of MW/RF energy (37 % decay of radiation intensity) is proportional to the free space wavelength and the square root of the dielectric constant and inversely proportional to the loss factor (6.40). Typical penetration depths are for RF at 40 MHz, 3 m; for MW at 915 MHz, 13 cm; and for MW at 2450 MHz, 4.9 cm. The wavelengths, corresponding to the above frequencies, are 7.5 m, 32.8 cm, and 12.3 cm, respectively. If the piece of the material is smaller than the wavelength, its center will be overheated, compared to the external surface, an important factor in drying applications.

Internal absorption of the MW/RF energy by a wet material will increase its temperature and vapor pressure, creating a puffing effect on the product and increasing the drying rate during convective or vacuum drying. MW/FR energy may be applied at the beginning, during, and at the final stages of drying.

Short MW pretreatment increases the moisture permeability of grape skins, facilitating subsequent sun drying or convective drying (Kostaropoulos and

Saravacos 1995). A similar effect is observed when food gels and other food materials are treated with MW energy before conventional drying (Drouzas et al. 1997).

MW energy improves the vacuum- and freeze-drying operations of food materials by better energy (heat) absorption within the product or by the development of a porous structure (puffing) in the material, which increases substantially the effective moisture diffusivity (Drouzas et al. 1999).

Conversion of the normal AC current of 50–60 Hz to the high frequency of the MW/RF systems requires special electrical equipment. RF circuits use simple self-excited oscillators or plate-tuned grid type. MW generators consist of a DC power supply and a tube, e.g., a magnetron or a klystron. The MW energy is applied through waveguides or cavity applicators.

RF drying is used in various post-baking systems, following the commercial fuel-heated oven, increasing the production rate of cookies, biscuits, etc., by 30–50 %.

MW drying can be applied to pasta drying operations, reducing substantially the drying time of conventional hot-air drying and improving the product quality. In a typical application, 1500 kg/h of pasta can be dried, using 60 kW of MW energy at 915 MHz. Post-drying of some vegetables (e.g., onions) with MW energy can remove the residual moisture from 10 to 5 % in a shorter time than convective drying.

Figure 8.33 shows diagrammatically a continuous MW-vacuum dryer, suitable for food products. Typical dimensions of such dryers are diameter 2–3.5 m and length 11–12 m. The MW energy supply is 35–50 kW at 2450 MHz, and the drying capacity is 60 L/h.

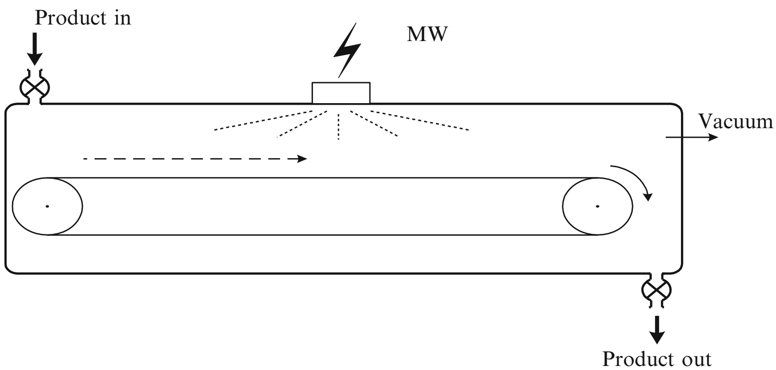


Fig. 8.33 Diagram of a continuous MW-vacuum dryer

8.3.6.2 Infrared Dryers

Infrared drying (IR) is used commercially in the drying of paints, coatings, and other films. IR in the wavelength range of 1–100 mm has a relatively small penetrating power, thus limiting the thickness of the treated materials. However, IR energy is less expensive than the MW/RF systems for drying applications (Ratti and Mujumdar 1885).

Industrial IR heat sources consist of electrically heated or gas-fired radiators. They are used in both convective (belt) or vacuum/freeze dryers for thin product layers.

8.3.6.3 Tumbling Dryers

The tumbling dryers consist of rotating cone or V-shaped vessels, which can be operated at atmospheric pressure or in vacuum. The vessels are jacketed to allow heating by steam or other medium. The sensitive food material slides inside the rotating vessels, drying at a fast rate and moderate temperature, which improves the quality of the product (Walas 1988).

8.3.6.4 Centrifugal Dryers

The centrifugal fluid bed (CFB) dryers consist of a cylindrical vessel with perforated walls, which rotates horizontally at high velocity and is heated by a cross flow air stream (Lazar and Farkas 1980; Jayaraman and Das Gupta 1995).

The piece-form food material moves through the rotating cylinder and is dried fast, due to the high heat and mass transfer rates in the centrifugal field. Centrifugal forces of 3–15 g's and air velocities up to 15 m/s are applied, which are much higher than in normal fluid bed drying.

CFB drying is suitable for pre-drying high-moisture food materials, like vegetables, followed by conventional drying (convective or vacuum). The capacity of the CFB dryers is relatively small (up to about 200 kg/h), limiting their economic commercial application.

8.3.6.5 Explosion Puffing

Explosion-puff drying is based on the development of a highly porous structure in fruit and vegetable materials, which increases greatly the drying rate of the product. The wet food material is dehydrated by conventional convective drying to about 25 % moisture and then heated in a rotating cylindrical vessel ("gun") until a high pressure is developed (2–4 bar). The pressure is released instantly, producing a puffed product, which is dried fast to the desired moisture content in a conventional dryer. The dehydrated porous product has improved rehydration properties, an important quality factor in many food products (Jayaraman and Das Gupta 1995).

8.3.6.6 Foam-Mat Drying

Foam-mat drying is used in small scale for the drying of sensitive food products, like concentrated fruit juices, fruit purees, and food slurries. The fluid food is foamed by incorporating a gas in a special mixer, using a foam stabilizer, if needed (Woodroof and Luh 1986; Salunkhe et al. 1991).

The foamed material is applied as a thin film (about 1.5 mm) on a perforated tray or belt and is dried at moderate temperatures and air velocities. Very fast drying is achieved, e.g., 15 min at 70 °C, and the product has a porous structure, which improves its rehydration properties. The operating cost of foam-mat drying is lower than vacuum drying, but, for commercial applications, large spray dryers are more efficient.

8.3.6.7 Acoustic Dryers

Acoustic or sonic dryers have been proposed to improve the drying rate of various food materials. Low-frequency sound waves increase considerably the heat and mass transfer rates at the particle/air interface (Mulet et al. 1999). The short drying times, achieved by sonic drying, improve the product quality, e.g., color, flavor, and retention of volatile aroma components. Food liquids of 5–75 % total solids have been dehydrated to low moistures, e.g., citrus juices, tomato paste, and corn syrups.

8.3.6.8 Osmotic Dehydration

Osmotic dehydration is used to remove part of the free water in food materials by the osmotic action of sugar or salt solutions. It is an ancient method of food preservation of fruits, vegetables, and fish, based on the reduction of water activity of the food material, which prevents or delays the growth of spoilage microorganisms in the product.

Osmotic dehydration is a nonthermal dehydration process, more efficient than conventional drying, operated at lower temperature, improving the product quality (color, volatile aroma, etc.). It is used to produce IMFs or as a pre-drying step, removing about 50 % of moisture, for conventional dehydration (convective or vacuum drying). IMF products (mainly fruits) contain 20–30 % moisture, and they need additional protection against spoilage, e.g., preservatives, low temperature, and freezing.

Mass transfer in osmotic dehydration involves the transport of water within the plant tissue, the transfer of water and natural solutes from the plant cells to the osmoactive solution, and the transfer of the osmoactive substance to the plant material (Lewicki and Lenart 1995). The transport mechanisms depend mainly on the physical structure of the food material. The diffusion (Fick) model is generally used for transport calculations, assuming that the driving force is a concentration gradient, using the effective diffusivity (D) as the principal transport property within the material (Saravacos and Maroulis 2001). Typical values of D in osmotic treatment for apples at 50 °C are 10×10^{-10} m^2/s (water) and 4×10^{-10} m^2/s (sucrose).

Osmoactive substances are sugars (sucrose, corn syrups) and dextrins at about 65 °Brix for fruits and sodium chloride (about 15 %) for vegetables and fish.

Equipment for osmotic dehydration is in the development stage before large-scale commercial application. It may be similar to extraction and leaching equipment used in chemical engineering. The food material should be cut into pieces, e.g., slices or cubes of 10 mm, to facilitate mass transfer. A typical process temperature is 50 °C. The diluted osmoactive solution should be concentrated in an efficient evaporator, before recycling in the osmotic process.

Energy requirements for the osmotic process include pumping and heating of the product and concentration of the diluted solution. They are estimated at 0.1–2.4 MJ/kg water removed, the highest values corresponding to the concentration of the diluted solution by evaporation (Lewicki and Lenart 1995). For comparison, convective drying requires about 3.5 MJ/kg water evaporated.

8.3.7 Hygienic and Safety Considerations

Dehydrated foods have a low water activity, which prevents or retards microbial growth and spoilage. Thus, food dryers have, in general, fewer hygienic (sanitation) problems than "wet" processing equipment.

High-temperature equipment, like drum dryers with surface temperatures above 120 °C, are practically sterile, but lower temperature units, like tray, conveyor, and fluid bed dryers, allow the growth of spoilage microorganisms. Contamination of some dryers may occur by adding back a dried product to the contents of the unit, a process used in some drying and agglomerating operations (Troller 1993).

Bacterial spores may survive the temperatures of convective dryers (up to 100 °C), and high microbial counts may be detected in some drying equipment. In such cases, wet cleaning of the equipment may be required, using the CIP sanitation system, if available. The equipment should be dried thoroughly with warm air before reuse.

The main hazards of drying equipment are fires and explosions. Fires may be caused by combustion of dried materials, volatiles, or fuels. Dust explosion may occur in the dryer, the ducts, or the cyclone collectors (Markowski and Mujumdar 1995).

Dust explosions are caused by overheated combustible materials (e.g., starch, flour, powders) or equipment contact surfaces in the drying system or by static electricity (Van't Land 1991).

The design, construction, and operation of drying equipment should comply with national and international fire protection laws and codes, like the National Fire Protection Association in the USA (NFPA 1992). The NFPA codes related to drying contain references on starch facilities, milling agricultural commodities, ovens and furnaces, exhaust systems for air-conveying materials, and pneumatic conveying systems for handling combustible materials (Crapiste and Rotstein 1997).

8.4 Energy and Cost Considerations of Drying

The cost of energy represents the major part of the operating cost of the industrial dryers. A typical cost breakdown for convective dryers is as follows (Bhatia): energy 62 %, capital cost 13 %, labor 10 %, overhead 10 %, and maintenance 5 %.

Industrial drying consumes about 12 % of the total energy used in manufacturing, e.g., 128×10^9 MJ/year in the UK and 166×10^9 MJ/year in France (Strumillo et al. 1995). The major part of this large energy is used for drying food and agricultural materials.

The energy consumption in drying is used mainly for the evaporation of free water, desorption of sorbed water, or sublimation of ice in freeze-drying. Theoretically, evaporation of free water requires 2.26 MJ/kg at 100 °C or 2.36 MJ/kg at 60 °C. The heat of sublimation of ice at 0 °C is 2.84 MJ/kg, and higher energies are required for desorption of water, bound on food biopolymers. In addition, energy is required for sensible heating of the food material, the dryer, and the exhaust air and for mechanical movement of the process air (operation of fans). Thus, the total energy consumption varies in the range of 3–4 MJ/kg water in continuous convective dryers. It is higher in batch dryers (3–6 MJ/kg water), and it may reach 10 MJ/kg water in vacuum and freeze dryers.

It is obvious that economy in drying is related to the efficient use of energy and the development of new systems and equipment, which will operate more efficiently and reduce the energy losses. In addition to the economic reasons, energy saving will reduce pollution (chemical and thermal) of the environment and preserve the fuel reserves. Utilization of renewable energy resources, like solar, wind, and geothermal energy, can reduce the excessive use of fossil energy for industrial drying.

8.4.1 Heat Sources for Drying

The heat required for drying is provided mostly by direct heating (firing) with fuels (gas or oil) and saturated steam. In some rather small-size applications, heat is supplied in the form of hot water, infrared radiation, or microwave energy. Combustion of fuel (natural gas, LPG or liquefied petroleum gas, or fuel oil) is the simplest and most economical energy source for drying applications. Saturated steam and hot water are more expensive than direct fuel combustion, because heat exchangers and condensers are needed, but they are preferred in some cases, when contamination of the food material with combustion gases may not be acceptable.

Natural gas, used for direct firing of the dryer, is suitable for agricultural and food drying (Kudra 1998).

High temperatures are obtained, which increase substantially the drying rate and shorten the drying time. The natural gas contains about 98 % methane and ethane, and its heating value is 37.2 MJ/m^3. The heating value of propane is 50.4 MJ/kg, and that of fuel oil is 41.7 MJ/kg.

The major limiting factor of using direct heating by natural gas and LPG fuels in drying is the presence of significant amounts of water vapor in the flue gases, produced by combustion of the hydrocarbons. Stoichiometric calculations indicate that flue (combustion) gases would contain 19 % by volume of water vapor, but in practice, lower concentrations are obtained, due to the use of excess air. As a result, the capacity of the heating air/gases to remove water in the dryer is reduced, and a low moisture content may not be reached easily for some food materials, which may require finish drying with low humidity air in, e.g., bin dryers.

8.4.2 Heat Recovery

Recirculation of the exhaust air/gases from the dryer is the simplest method of recovering part of the heat rejected to the environment. Almost all convective dryers use some form of recirculation, recovering only the sensible heat, since it is difficult to recover the latent heat of evaporation of water in the exhaust gases.

The thermal efficiency (N) of a convective dryer is related to the recirculation fraction w (ratio of recirculated air to total air flow) by the equation

$$N = (T_2 - T_3)/[(T_2 - T_3) + (1 - w)(T_3 - T)] \tag{8.17}$$

where, T, T_2, and T_3 are the ambient, inlet, and exit air temperatures.

The amount of recirculation is limited by the increase in humidity of the air stream, which reduces the drying rate of the material, particularly in the early stage of drying.

Part of the exhaust heat can be recovered by heating the inlet air to the dryer, using some type of heat exchanger, e.g., thermal wheel, pipe, or plate heat exchanger (Strumillo et al. 1995).

Part of the latent heat of evaporation of water can be recovered by a complex system of heat exchangers between the exhaust gases and the inlet air (Moraitis and Akritidis 1996).

8.4.3 Energy-Efficient Dryers

A number of efficient dryers have been developed, which can operate with less energy than conventional dryers. They operate mostly at high temperatures, and they have not found wide applications yet in the food processing industry.

8.4.3.1 Superheated Steam Dryers

The superheated steam dryer is an energy-saving unit, which is used commercially to dry materials that can tolerate high temperatures, such as coal, ceramics, sugar beet pulp, and wastewater sludge (Wimmerstedt 1994). The superheated steam or "airless" dryer operates with superheated steam, which is heated by a fuel gas and is recirculated in the dryer at about 100 °C, removing the moisture from the wet product. The water vapors are condensed in a heat exchanger, which heats cold water to about 95 °C (Stubbing 1994).

The dryer can operate at atmospheric pressure either batch or continuously. Stratification of the steam inside the dryer takes place with the steam at the upper layer, due to the difference in densities of air and steam, preventing their mixing in the dryer.

8.4.3.2 Heat Pump Dryers

The heat pump dryer uses electrical energy to generate heat by compression of a refrigerant (inverse of operation of the normal compression refrigeration cycle). It can recover the energy of condensation of water vapors in the closed system (Alves-Filho and Strommen 1996). The heat pump dryers can operate in a wide range of temperatures, from −20 °C (freeze-drying) to 30 °C. The system does not pollute the environment with exhaust gases, and it is suitable for areas where cheap electrical energy is available (e.g., Norway).

8.4.3.3 Impingement Dryers

Impingement jets of hot air are used in some industrial drying operations involving rapid drying of continuous sheets, such as paper and textiles (Mujumdar and Huang 1995). The high drying rates are obtained by the increased heat and mass transfer coefficients in the impingement systems.

Nozzle design and nozzle configuration are important factors in effective drying applications. Specific energy consumption in impingement dryers is about 3.1 MJ/kg water evaporated.

8.4.4 Cost Considerations

Reliable cost data for industrial dryers can be provided by manufacturers and suppliers of process equipment. To aid the price quotation, data for the particular application should be provided in an appropriate specification form (Chap. 2).

Preliminary cost estimation can be made on the basis of drying capacity (kg water/h), using empirical correlations, tables, and the Marshall and Stevens index (M&S index) of the *Chemical Engineering Journal* (Chap. 1). The exponent (n) of the cost/capacity equation (1.3) for convective dryers varies in the range of 0.50–0.70 (Sztabert and Kudra 1995).

For preliminary cost estimates, the following equation gives the capital cost of drying equipment (C_E in USD, 1995):

$$C_{\mathrm{E}} = (\mathrm{M\&SI})AQ^n \tag{8.18}$$

where, Q is the capacity, defined either by the transfer area (m^2) or the effective volume (m^3) of the dryer. The coefficient A and the exponent n are characteristic of each type of dryer. Typical values of these parameters for industrial dryers are (Sztabert and Kudra 1995) belt conveyor dryer (stainless steel), basis Q = belt surface area, $A = 21$, and $n = 0.59$ and direct (fuel gases) rotary dryer (carbon steel), basis Q = dryer volume, $A = 17$, and $n = 0.69$.

The total (installed) cost of drying plant (C_T), which includes the costs of dryer, piping, motors, fans, instrumentation, buildings, and engineering, can be estimated from the equipment cost (C_E), using the empirical relation (Van't Land 1991; Sztabert and Kudra 1995):

$$C_{\mathrm{T}} = aC_{\mathrm{E}} \tag{8.19}$$

The coefficient (a) is taken equal to 2.25 for carbon steel and 2.75 for stainless steel (Chap. 2).

Typical prices of drying equipment, converted to year 2000 by the M&S index, are (Van't Land 1991; Sztabert and Kudra 1995):

(a) Rotary dryer, carbon steel, steam tube heating, 1.83 m diameter and 18.30 m length, 290 m^2 transfer area, and 14.9 kW power motor: USD 450,000
(b) Spray dryer, cocurrent open cycle, 5 m diameter, operating at 370 °C (air inlet)/105 °C (air outlet) temperatures, 1090 kg/h water evaporative capacity: USD 380,000

Costs of new, used, and salvage drying equipment are listed by Bhatia (1983). The cost of used dryers is roughly 50 % of the cost of the new equipment, depending on the condition and the age of the various units. The salvage value of dryers is about 5 % of the initial cost.

Comparative cost data for concentration and drying food processes were presented by Sapakie and Renshaw (1984). The relative cost of dryers is convective

1, drum 1, spray 1, vacuum 3, and freeze 6. It should be noted that the basis of cost comparisons should be the total evaporative capacity of the unit (kg/h) and not the specific cost per transfer surface (m^2) or transfer volume (m^3). For example, the specific cost of drum dryers per m^2 is very high, compared to the specific cost of tray dryers, but their specific evaporative capacity (kg/m^2h) is much higher, and the two dryers are approximately equivalent in cost, in terms of overall capacity (kg/h).

The cost of energy for drying applications is usually expressed as cost/GJ or cost/kg water evaporated, assuming the appropriate energy requirement in MJ/kg water evaporated, e.g., 3–5 MJ/kg (1 GJ = 1000 MJ). The cost of natural gas, LPG, and fuel oil depends on the location, and it may increase significantly during international oil (petroleum) crises.

Example 8.1 Design a rotary convective dryer to dry the by-products peels and pulp, produced in the orange processing plant of Example 1.1.

The plant processes 20,000 kg/h of oranges, producing $49.7 \times 20{,}000/100 = 9940$ kg/h of peels/pulp of 15 % TS (total solids). The dried product (animal feed) will contain 10 % moisture. The total dry solids are $9940 \times 0.15 = 1491$ kg/h, and the dried product (10 % moisture) will be $1491/0.9 = 1656$ kg/h. The amount of water to be evaporated in the dryer will be $m_w = 9940 - 1656 = 8284$ kg/h.

Because of the high evaporation duty, an efficient rotary dryer is selected. The product to be dried (animal feed) can tolerate relatively high temperatures and "clean" combustion gases. Therefore, an economical cocurrent dryer is proposed, heated directly with LPG. A simplified diagram of the dryer, useful for preliminary calculations, is shown in Fig. 8.34.

For approximate design estimation, the standard psychrometric chart is used to calculate the air and fuel requirements of the dryer. For more accurate estimation, analytical calculations, based on material and energy balances, can be performed, or a computer version of psychrometric and drying calculations, like the DryPACK software (Pakowski 1998), can be used.

The use of direct heating with combustion gases from the fuel introduces significant quantities of combustion water in the dryer, which should be taken under consideration in the calculations. Assuming that atmospheric air at 20 °C and 50 % RH (relative humidity) is used, its moisture content (Y_o) and enthalpy (H_o), taken from the psychrometric chart (Fig. 8.1), will be $Y_o = 0.0075$ kg/kg db (dry air basis) and $H_o = 67$ kJ/kg db. The air is heated by mixing with the

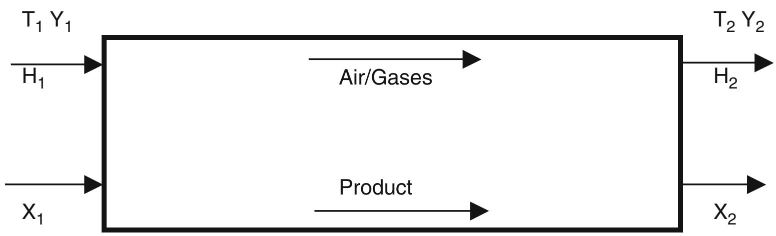


Fig. 8.34 Diagram of a cocurrent rotary dryer of Example 8.1

combustion gases to $T_1 = 300$ °C and, neglecting the combustion water, the moisture content will remain constant at $Y_1 = Y_o = 0.0075$ kg/kg db, and the enthalpy will be $H_1 = 340$ kJ/kg db (using a high-temperature psychrometric chart; Walas 1988).

The hot air/flue gases are passed adiabatically (constant H) through the dryer, leaving at 80 % RH, a reasonable assumption for practical application. From the chart, the exit air/gases will have a (dry bulb) temperature $T_1 = 57$ °C, a moisture content of $Y_2 = 0.110$ kg/kg db, and the same enthalpy $H_2 = H_1 = 340$ kJ/kg db.

The moisture pickup of the air/gases in the dryer will be $DY = Y_2 - Y_1 = 0.110 - 0.0075 = 0.1025$ kg/kg db. The needed dry air to remove 8284 kg/h water in the dryer will be 8284/0.1025 = 80,820 kg db/h. Since the specific volume of the initial air (30 °C and 50 %) is 0.840 m^3/kg (psychrometric chart), the volumetric air flow in the dryer will be 80,820 × 0.840 = 67,889 m^3/h. The mean air/gas velocity in the dryer will be $u = 67{,}889/(3.14 \times 3600) = 6.0$ m/s.

The required enthalpy to heat the process air will be $DH = H_2 - H_o = 340 - 67 = 273$ kJ/kg db. The total energy required for heating will be 80,820 × 0.273 = 22,064 MJ/h = 22,064/3600 = 6.13 MW. If the heating value of the LPG is 50 MJ/kg, the amount of fuel gas needed will be 22,064/50 = 441 kg/h LPG.

The presence of combustion water in the air/gas mixture will increase significantly the requirements for process air and fuel. Stoichiometric calculations indicate that the flue (combustion) gases of fuel gas will contain 19 % by volume combustion water. However, since excess air is used, the amount of water in the combustion gases can be assumed to be about 10 %, with approximately similar increases in the air and fuel requirements in the dryer. Thus, the air flow requirement for this example will be 67,889 × 1.1 = 74,678 m^3/h and the fuel requirement 441 × 1.1 = 485 kg/h LPG.

The size of the rotary dryer for this application can be selected from performance data of direct heated rotary dryers (Walas 1988). A rotary dryer of 2.0 m diameter and 15 m length, similar to the one used for drying sugar beet pulp, appears to be a good approximation. The dryer will have a volume of 47 m^3 and 94.2-m^2 wall surface, with a specific evaporative capacity of 8284/94.2 = 88 kg/m^2 h, which falls within the range of capacities (30–100 kg/m^2 h), found in the literature (Table 8.3).

The air flow capacity of the above literature dryer is 75,960 m^3/h, close to the air requirement of our example. The fan power is 52 kW and the motive power for the dryer is 11 kW.

Carbon steel is an economic and acceptable material of construction for this particular application.

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