Current Dehydration Techniques

11.7 DRYING EQUIPMENT

11.7.1 Sun Drying

Large quantities of fruits, particularly grapes (raisins), apricots, figs, prunes, and dates are dried by direct exposure to sunlight in hot and dry climates. Coffee beans, cereal grains, and fish are also sun-dried prior to storage and preservation. Sun-dried fruits contain about 15%–20% moisture (wet basis), which is near the equilibrium moisture content at ambient air conditions, and they can be stored in bulk, without the danger of microbial spoilage.

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. The grape bunches are spread in trays and dried by exposure to direct sunlight. 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. The sun drying time varies from 10 to 20 days, depending on the insolation (solar radiation). The ripe apricots are usually cut into halves before sun drying on trays, placed on the ground.

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

11.7.2 Solar Dryers

Solar drying is a form of convective drying, in which the air is heated by solar energy in a solar collector. Flat-plate collectors are used with either natural or forced circulation of the air. Figure 11.8 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 electrical fan will increase considerably the collector efficiency and the drying rate of the product (Saravacos and Kostaropoulos, 2001).

Several types of solar collectors and drying systems have been proposed for drying various food and agricultural products, such as 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. 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).

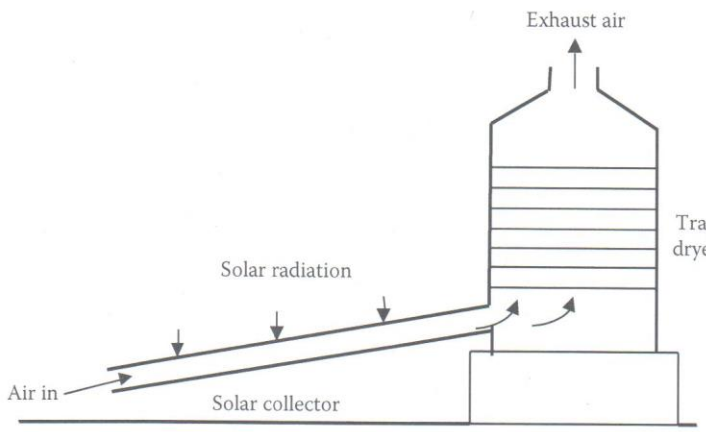

FIGURE 11.8 Simple solar dryer.

The relatively low intensity of incident solar radiation is a serious limitation for food drying applications, where large amounts of thermal energy are required for the evaporation of water.

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 1000/0.72 = 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 drying is considered effective for relatively small drying operations for fruits, such as grapes and apricots, in high insolation regions.

Intermittent solar radiation (day–night) can be supplemented by the use of auxiliary energy, such as fuel or electricity. Thermal storage of solar energy can also be applied, using rock beds or water to absorb extra solar energy during the day, which can be used during the night or during cloudy weather.

Some other solar collectors, proposed for solar drying are (a) a low-cost tunnel collector 1 × 20 m connected to a tunnel dryer for drying a batch of 1000 kg of grapes; (b) a solar collector with V-grooves, attaining temperatures 50°C–70°C at 0.7 kW/m^2 insolation; 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°C–110°C.

Solar collectors, integrated on the roof or the walls of a farm building can provide heated air for drying grain in a bin or silo.

11.7.3 Silo and Bin Dryers

Silo dryers are used for partial drying of large quantities of grains (wheat, corn, etc.) from moisture contents (wet basis) of about 25% (harvest) to 18% (storage). Hot air at 40°C–60°C is blown from the bottom of the fixed bed through the grains for several hours (Figure 11.9). Continuous tower dryers are more effective, using higher air temperatures (e.g., 80°C), while the grain slowly moves down.

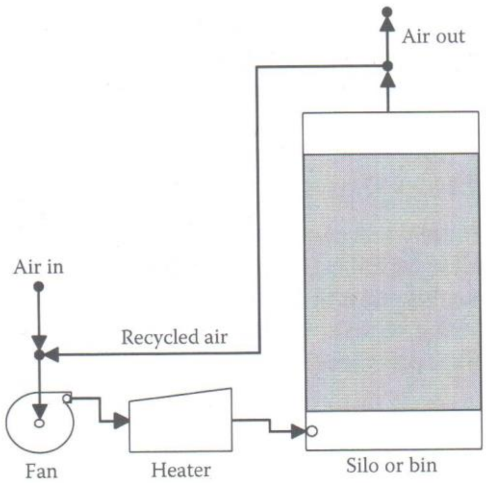

FIGURE 11.9 Batch silo or bin dryer. (Modified from Maroulis, Z.B. and Saravacos, G.D., *Food Process Design*, CRC Press, Boca Raton, FL, May 9, 2003, fig. 7.3.)

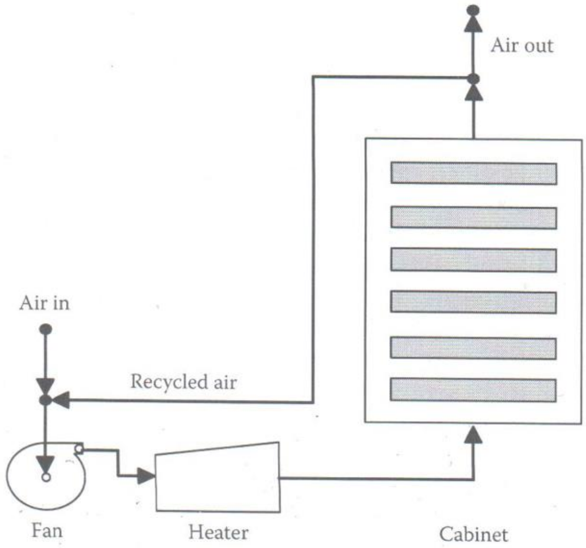

FIGURE 11.10 Diagram of a cabinet (tray) dryer. (Modified from Maroulis, Z.B. and Saravacos, G.D., *Food Process Design*, CRC Press, Boca Raton, FL, May 9, 2003, fig. 7.4.)

Bin dryers are similar but generally smaller than silo dryers and they are used as finish dryers of partially dried vegetables. Normal convective drying of vegetables reduces their moisture content to about 10%, and bin drying can bring it down to 2%–4%, which is necessary for preservation and storage. Bin dryers operate at relatively low temperatures with dry dehumidified air, blown upward.

11.7.4 Tray Dryers

Tray dryers are relatively small batch units for drying small quantities of food products (Figure 11.10). The air is heated in a heat exchanger outside the dryer, and it is usually recirculated to increase the thermal efficiency. The product in the form of pieces, particles, or pastes is placed in metallic trays, which are reused after the drying operation.

11.7.5 Tunnel or Truck Dryers

Tunnel dryers are relatively low cost constructions, with the product trays (pieces or pastes) loaded on trucks, which move slowly co-current or countercurrent to the hot air (Figure 11.11). The thermal efficiency of the dryer is improved by recirculation. The system runs semicontinuously, and the trays are loaded and unloaded manually. Tunnel or truck dryers are used mainly in the drying of fruits and vegetables.

11.7.6 Belt Dryers

Belt or conveyor dryers are used extensively in food processing for continuous drying of food pieces (Figure 11.12). The product, in the form of pieces, such as fruits and vegetables, is dried on a long perforated conveyor belt, which moves slowly

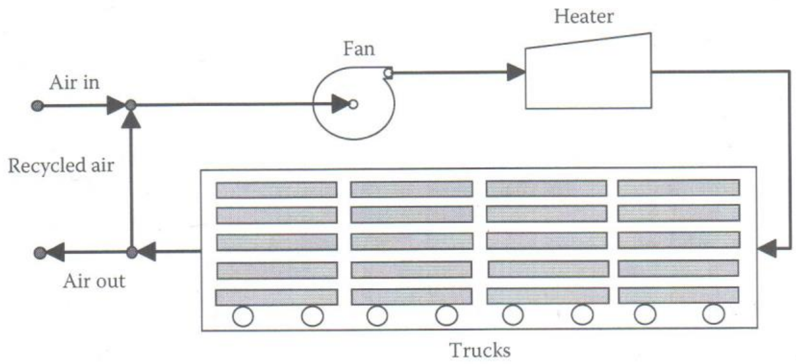

FIGURE 11.11 Diagram of a tunnel or truck dryer. (Modified from Maroulis, Z.B. and Saravacos, G.D., *Food Process Design*, CRC Press, Boca Raton, FL, May 9, 2003, fig. 7.5.)

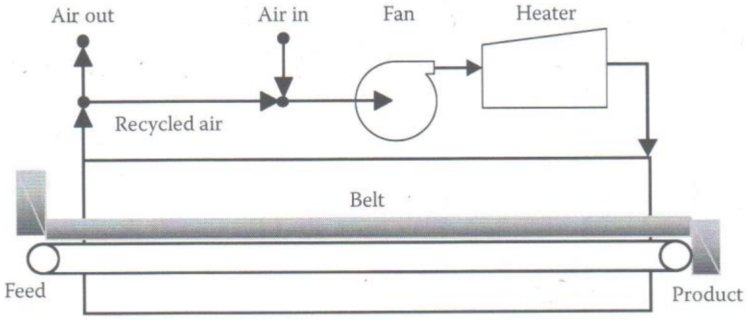

FIGURE 11.12 Diagram of a single-belt conveyor dryer. (Modified from Maroulis, Z.B. and Saravacos, G.D., *Food Process Design*, CRC Press, Boca Raton, FL, May 9, 2003, fig. 7.6.)

for the required drying time. The air is heated to the desired temperature in a heat exchanger or is mixed with the combustion gases of suitable fuels, and it is directed against the product in up- or down-flow. Long residence times are obtained using multibelt dryers (e.g., three belts), which run in opposite directions.

11.7.7 Rotary Dryers

The rotary dryers consist of an inclined long cylinder rotating slowly, while the material (grains, granules, powders) flows with the tumbling (cascading) action of the internal flights (Figure 11.13). The air is heated either in heat exchangers or by mixing with combustion gases of suitable fuel, e.g., natural gas. Rotary dryers are less expensive than belt dryers, but they cannot handle large food pieces, which may be damaged by mechanical abrasion during tumbling (Perry and Green, 1997).

11.7.8 Fluidized Bed Dryers

Fluidized bed dryers are used for fast drying of food pieces and particles that can be suspended in a stream of hot air (Figure 11.14). High drying rates are obtained due to high heat and mass transfer.

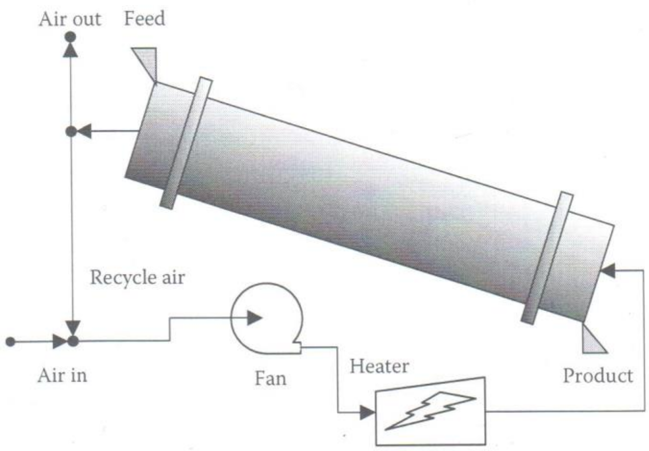

FIGURE 11.13 Diagram of a rotary dryer. (Modified from Maroulis, Z.B. and Saravacos, G.D., *Food Process Design*, CRC Press, Boca Raton, FL, May 9, 2003, fig. 7.7.)

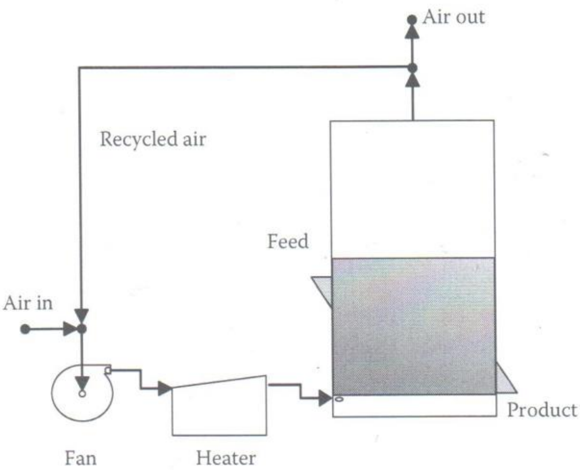

FIGURE 11.14 Diagram of a fluidized bed dryer. (Modified from Maroulis, Z.B. and Saravacos, G.D., *Food Process Design*, CRC Press, Boca Raton, FL, May 9, 2003, fig. 7.8.)

11.7.9 Spouted Bed Dryers

Spouted bed dryers are a special type of fluidized-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 the granular material upward, 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 (Figure 11.15). Spouted bed dryers are suitable for granular materials larger than 5 mm, such as wheat grain.

11.7.10 Pneumatic or Flash Dryers

Pneumatic or flash dryers are used for fast and efficient drying of food particles that can be suspended and transported in the stream of heating air (Figure 11.16). The residence time in pneumatic dryers is much shorter than in fluidized-bed units.

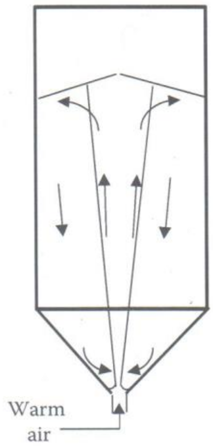

FIGURE 11.15 Diagram of a spouted bed dryer.

11.7.11 Spray Dryers

Spray dryers are used to dehydrate liquid foods or food suspensions into dry powders or agglomerates. The liquid feed is atomized in special valves (Chapter 7) and the droplets are dried by hot air as they fall in a large chamber (Figure 11.17). The flow of hot air can be co-current or countercurrent to the flow (fall) of the droplets and dried particles. The dryers are equipped with cyclone collectors and bag filters to collect the small particles from the exhaust air/gases, and prevent air pollution. Spray dryers are usually combined with agglomeration equipment, which produces food agglomerates of desirable quality (Masters, 1991).

The engineering of particles (liquid and solid) and agglomerates is discussed in the section of Mechanical Processing (Chapter 7). Pressure atomizers are preferred in spray drying because they produce droplets of approximately uniform size. The other two atomizers (centrifugal and pneumatic) produce a wider dispersion of droplet sizes, which dehydrate unevenly.

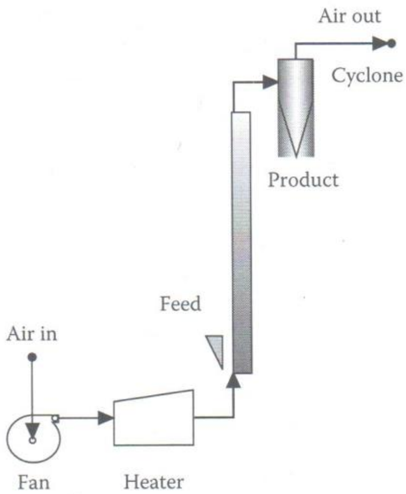

FIGURE 11.16 Diagram of a pneumatic dryer. (Modified from Maroulis, Z.B. and Saravacos, G.D., *Food Process Design*, CRC Press, Boca Raton, FL, May 9, 2003, fig. 7.9.)

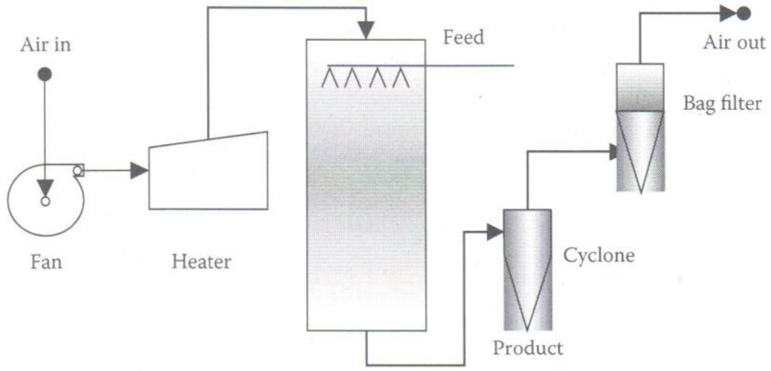

FIGURE 11.17 Diagram of a co-current flow spray dryer. (Modified from Maroulis, Z.B. and Saravacos, G.D., *Food Process Design*, CRC Press, Boca Raton, FL, May 9, 2003, fig. 7.10.)

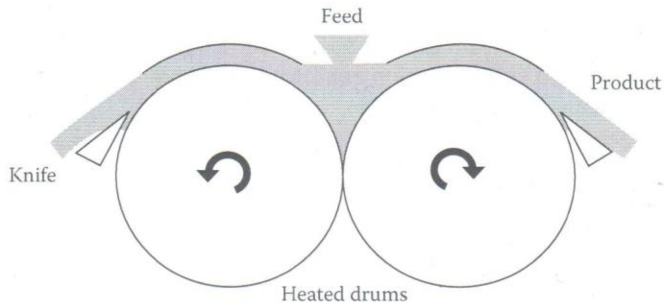

FIGURE 11.18 Diagram of a double drum dryer. (Modified from Maroulis, Z.B. and Saravacos, G.D., *Food Process Design*, CRC Press, Boca Raton, FL, May 9, 2003, fig. 7.11.)

11.7.12 Drum Dryers

Drum dryers are used to dehydrate concentrated liquid foods or suspensions and food pastes. They consist of one or two slowly rotating drums, heated internally by steam, with the product dried on the cylindrical surface (Figure 11.18). They are more efficient thermally than convective (air) dryers and they are operated either at atmospheric pressure or in vacuum.

11.7.13 Vacuum Dryers

Vacuum dryers are used for the dehydration of heat-sensitive food products, such as fruit juices. They operate at pressures of about 10 mbar and temperatures around 10°C (drying from the liquid state). They require vacuum pumping and low-temperature condensing equipment. Heat transfer is by contact to a heated shelf, infrared radiation, or microwaves. The product is dried either in trays or in a belt (Figure 11.19). Both batch and continuous operating systems are used.

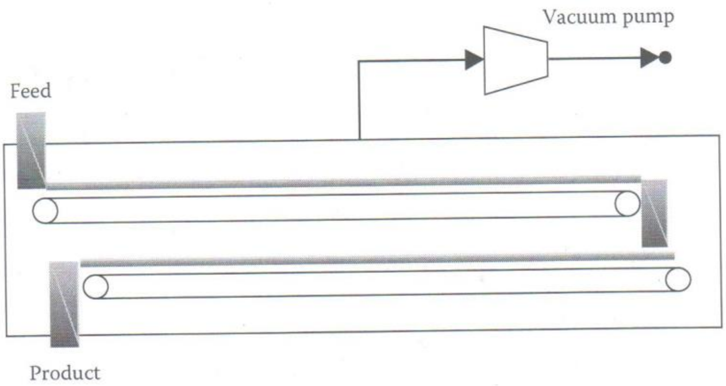

FIGURE 11.19 Diagram of a continuous belt-vacuum dryer. (Modified from Maroulis, Z.B. and Saravacos, G.D., *Food Process Design*, CRC Press, Boca Raton, FL, May 9, 2003, fig. 7.12.)

11.7.14 Freeze Dryers

Freeze dryers are the most expensive drying equipment, and they are justified economically only for drying certain expensive food products of unique quality, such as instant coffee. They are used mainly in the freeze drying of pharmaceutical products, which can afford the high cost (Liapis and Bruttini, 1995; Oetjen, 1999).

Freeze-dryers operate at pressures below 1 mbar and temperatures below −10°C (drying from the frozen state). The prefrozen product is placed in trays (Figure 11.20) and heated by contact, infrared radiation, or microwaves. Freeze-drying rate is limited by heat transfer to the drying surface. Batch freeze dryers are normally used, but there are some semicontinuous systems for large operations.

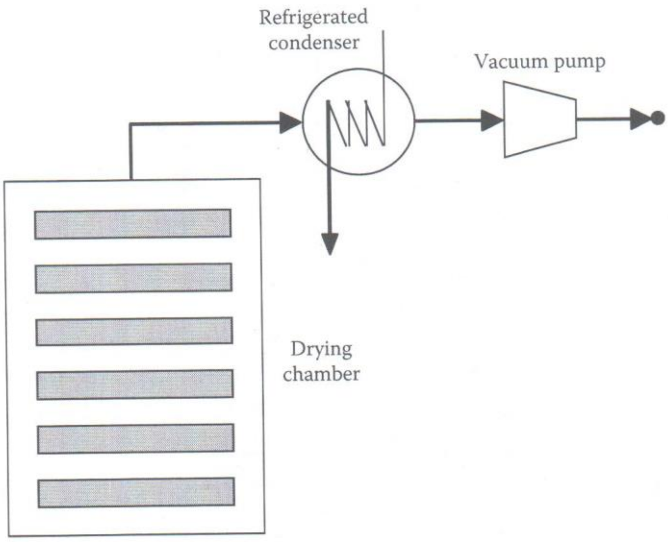

FIGURE 11.20 Diagram of a batch freeze-dryer. (Modified from Maroulis, Z.B. and Saravacos, G.D., *Food Process Design*, CRC Press, Boca Raton, FL, May 9, 2003, fig. 7.13.)

11.7.15 Agitated Dryers

Various types of agitated dryers are used for the drying of food pieces and particles, improving the heat and mass transfer rates and reducing the drying time. Among them, the agitated horizontal dryers have a rather small size and employ mechanical scrapers, suitable for paste products. Pan dryers use rotating paddles (scrapers) and they are suitable for pulps and pastes.

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.

The turbo dryer (Figure 11.21) is a special tray dryer with the particulate product flowing slowly down, following a helical path, while it is agitated by air blown countercurrently by two fans.

11.7.16 Microwave Dryers

Microwave (MW) and dielectric or radio frequency (RF) energy at 915 or 2450 MHz (Megacycles/s) are used to remove water from food materials at atmospheric or in vacuum. MW and RF energy heat the material internally, without the need of external convective or contact heat transfer. 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 (Chapter 8).

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.

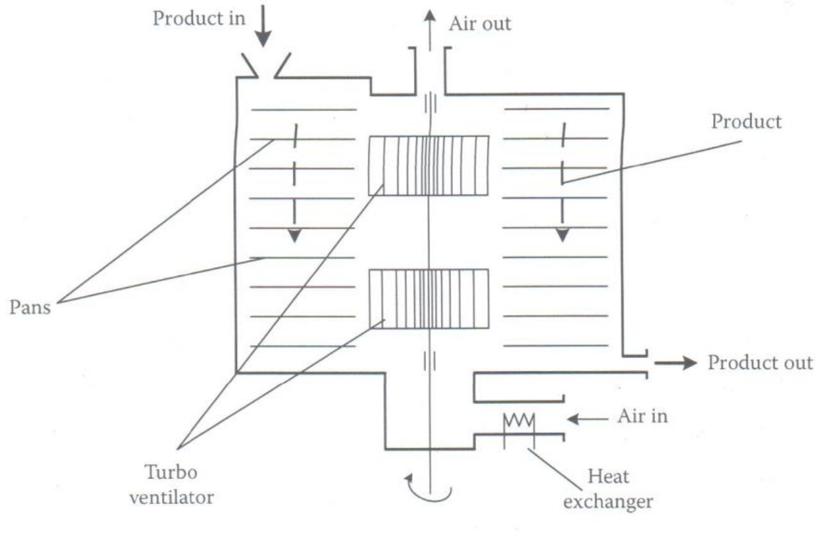

FIGURE 11.21 Diagram of a turbo dryer.

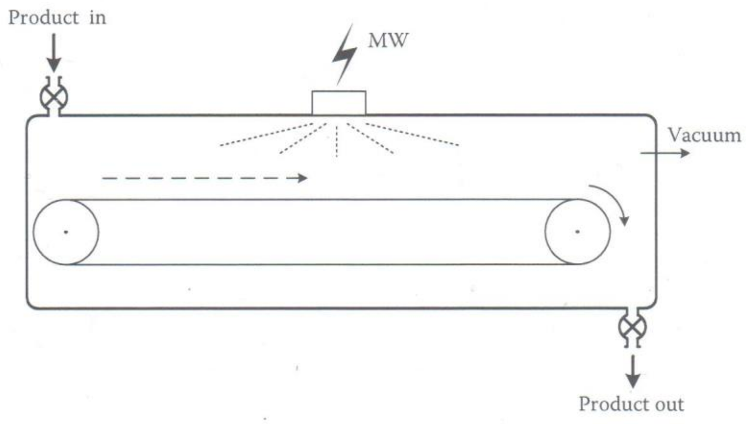

FIGURE 11.22 Diagram of a continuous MW-vacuum dryer.

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.

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.

Figure 11.22 shows a continuous MW-vacuum dryer, suitable for food products.

11.7.17 Impingement Dryers

Impingement jets of hot air (high speed) can be used in drying operations to increase the dying rate of food materials, due to the resulting higher heat and mass transfer coefficients. Nozzle design and geometry of the dryer-food material system are important factors in effective drying application. Specific energy consumption in impingement dryers is about 3.1 MJ/kg water evaporated.

11.7.18 Special Dryers

Several dryers have been tested and some of them have been applied in the food process industry. They are mostly batch food processing operations used to dry some sensitive food products, such as fruits and vegetables. 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.

11.7.18.1 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. Food material pieces move through the rotating cylinder and are dried fast, due to the high heat and mass transfer rates in the centrifugal field. Centrifugal forces of 3–15 *g*, and air velocities up to 15 m/s are applied, higher than in fluidized-bed drying.

CFB drying is suitable for predrying high moisture food materials, such as 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.

11.7.18.2 Explosion-Puff Drying

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.

11.7.18.3 Foam-Mat Drying

Foam-mat drying is used in small scale for the drying of sensitive food products, such as 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. The foamed material is applied as a thin film of 1.5 mm on a perforated tray or belt, and it 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 cost effective.

11.7.18.4 Acoustic Dryers

Acoustic or sonic dryers can 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. The short drying times, achieved by sonic drying, improve the product quality, such as color, flavor, and retention of volatile aroma components. Food liquids of 5%–75% total solids have been dried to low moistures, e.g., citrus juices and tomato paste.