34) CLASSIFICATION OF DRYERS

Drying methods and processes can be classified in several different ways. It can be classified as batch, where the material is inserted into the drying equipment and drying proceeds for a given period of time, or as continuous, where the material is continuously added to the dryer and dried material continuously removed.

Drying processes can also be categorised according to the physical conditions used to add heat and remove water vapour: (1) in the first category, heat is added by direct contact with heated air at atmospheric pressure, and the water vapour formed is removed by the air; (2) in vacuum drying, the evaporation of water proceeds more rapidly at low pressures, and the heat is added indirectly by contact with a metal wall or by radiation (low temperatures can also be used under vacuum for certain materials that may discoulour or decompose at higher temperatures); and (3) in freeze drying, water is sublimed from the frozen material. Dryers expose the solids to a hot surface with which the solid is in contact. Dryers, which expose the solids to a hot gas, are called adiabatic or direct dryers; those in which heat is transferred from an external medium are known as non-adiabatic or indirect dryers. Dryers heated by dielectric, radiant, or microwave energy is also non-adiabatic. Some units combine adiabatic and non-adiabatic drying; they are known as direct-indirect dryers.

Most commercial dryers are insulated to reduce heat losses, and they recirculate hot air to save energy. Many designs have energy-saving devices, which recover heat from the exhaust air or automatically control the air humidity. Computer control of dryers is increasingly sophisticated and also results in important savings in energy.

1. HOT-AIR DRIERS

Bin Dryers

Bin dryers are cylindrical or rectangular containers fitted with a mesh base. Hot air passes up through a bed of food at relatively low speeds (for example 0.5 m$^3$ s$^{-1}$ per square metre of bin area). These dryers have a high capacity and low capital and running costs. Bin dryers are used, particularly for piece-form vegetable products, to complete the drying operation after most of the moisture has been removed in a tunnel dryer or the equivalent. Typically, they reduce the moisture content of a partially dried, 10 to 15% moisture cut vegetables to 3 to 6% or even lower in the case of onion slices and possibly cabbage shreds. Bin dryers improve the operating capacity of initial dryers by taking the food when it is in the falling rate period, when moisture removal is most time consuming. Because they can do the job of removing a small amount of tightly bound moisture from the pieces, the long time is required, ranging up to as much as 36 hr in some cases. Bin drying also serves several other purposes. The product discharged from the main drying tunnel or conveyor may range widely in moisture content, containing decided “wet spots” and “dry spots”. The redistribution of pieces of the material as the bin is loaded, and the long holding of the entire batch in warm flowing air, assists in bringing about substantial equalisation of the moisture. The bins themselves also serve as storage reservoirs to smooth the flow of product between the drying units and the finishing and packing units of a plant. However the dryers may be several metres high, and it is therefore important that foods are sufficiently strong to withstand compression at the base and to retain an open structure to permit the passage of hot air through the bed. Bin dryers can be stationary, portable and continuous. In stationary bins, product is usually moved into and out of fixed bins by conveyor. The bottom of the fixed bin discharges the product onto a conveyor.
beneath it. In a potable bin system, the comparatively small bins are mounted on wheels, and after loading, are pushed up to and connected to a stationary air supply duct. A single fan and heater supply warm drying air for the entire system. Disconnecting the bin from the air source unloads the product and a forklift is used to discharge the product into a hopper. Continuous bins are used routinely for large-scale grain drying. Drying conditions required for bins is recommended that incoming air temperature should fall within the range of 40-45 °C and the partial pressure of water vapour in the incoming air must be well below the equilibrium vapour pressure of the finally dried vegetable at the chosen temperature.

**Cabinet Dryers (Tray dryers)**

These consist of an insulated cabinet fitted with shallow mesh or perforated trays, each of which contains a thin (2-6 cm deep) layer of food. Hot air circulated through the cabinet at 0.5-5 ms⁻¹ per square metre tray area. Fresh air enters the cabinet, is drawn by the fan through the heater coils, and is then blown across the food trays to exhaust (Figure 1). In this case the air is being heated by the indirect method. Screens filter out any dust that may be in the air. If the designs have perforated trays, the air is directed up through these; otherwise it passes across and between the trays. The air is exhausted to the atmosphere after one pass rather than being recirculated within the system. However, in recirculating designs, the moisture laden air, after evaporating water from food, would have to be dried before being recirculated, or else it would soon become saturated and further drying of the food would stop. In such a case passing it through a desiccant such as a bed of silica gel, or condensing moisture out by passing the moist air over cold plates or coils could dry the air. Note also that if we are not going to dry the exhaust air for recirculation, then the exhaust vent should not be close to the fresh air intake area, otherwise the moist exhaust air will be drawn back through the drier and drying efficiency will be lost. Thermometers are installed with the sensitive elements directly in the main air current approaching the drying trays, and often also in the air current leaving trays. One of the most important problems encountered is not to supply the same drying rate at all position within the tray dryers. The other is the fast drying of food in the position where the air first enters to the system and the slow drying of food in the other position. So additional heaters and the fans may be placed above or alongside the trays to increase the rate of drying. Tray dryers are used for small-scale production (1-20 t/day⁻¹) or for pilot-scale work. They commonly are used to dry fruit and vegetable pieces, and depending upon the food and the desired final moisture, drying time may be of the order of 10 or even 20 hr. They have low capital and maintenance costs but has relatively poor control and produces more variable product quality.
Continuous–Conveyor Dryers (Belt Drier)

Continuous conveyor dryers are up to 20 m long and 3 m wide. Food is dried on a mesh belt in beds 5-15 cm deep. Wet material supplied to the spreader device at the left-hand end is loaded evenly and in a relatively deep layer on the surface of a slowly moving conveyor belt (Figures 2 and 3). The air is initially directed upwards through the bed of food and then downwards the last 1 or 2 sections so as to prevent light-weight, nearly dry pieces from blowing out of the bed, although sometimes the drier is designed to produce up-through and down-through flow in alternate sections in order to improve the uniformity of drying of a thick layer of wet material. Sectionalising the drier makes it possible to control air temperature, humidity, and velocity independently in several stages to give optimum output and quality.

The first section can be supplied with air at high temperature and moderate humidity because rapid evaporation from the wet material keeps its temperature down. The final stage can be operated with very dry air at a low enough temperature to avoid damage during the long, slow approach to the desired final level of moisture content. Foods are dried to 10-15 % moisture content and then transferred to bin dryers for finishing. Construction of the dryer as two separate conveyors in series makes it possible to discharge the partly dry material at the end of the first stage. This is an important feature. Not only does the mixing aid in making a uniform product, but also the repiling makes possible a great saving in the flour space required. For example, potato strips originally piled on the conveyor in a layer 4 in. deep will shrink by the time they reach the end of the first stage to a layer 4 in. deep; some 90% of the original moisture will have been evaporated, but more than ½ of the total required drying time is still to go. If, at this point, the material is stacked to a depth of 10-12 in., the conveyor area needed for the second stage will be only 1/5 or less of that which would have been necessary without the restacking. Centrifugal fan wheels are ordinarily used. A large proportion of the air passing through the layer of moist material recirculates into the fan; dampers into the next section, to lattes into fan, may divert part of it; dampers into the next section, to be replaced by heated fresh air, may divert part of it. The fact that air temperature is uniform makes it necessary to control this temperature at a level which is safe to apply to the moist material.
leaving the first section and already partly dry. This equipment has good control over drying conditions and high production rates. It is used for large scale drying of foods (e.g. fruits and vegetables are dried in 23.5 h at up to 5.5 t h\(^{-1}\)). Some soft, starchy or sugary materials may benefit by being subjected first to very rapid surface drying in such equipment as the belt-through drier so that the working surfaces of the conveyor drier will remain clear and free of sticky build-up. It has independently controlled drying zones and is automatically loaded and unloaded, which reduces labour costs. As a result it has largely replaced the tunnel drier.

**Figure 2.** Continuous conveyor dryer

**Figure 3.** Continuous conveyor dryer

**Pneumatic Dryers**

Pneumatic conveying dryers are those in which powders or granular materials are dried while suspended in a stream of heated air. In such dryers, powders or particulate foods are continuously dried in vertical or horizontal metal ducts. A cyclone separator is used to remove the dried product. Since the material entering this kind of dryer must be conveyable in an air stream, the incoming material must have been dried in other ways to a moisture level below 35-40%. The moist food (usually less than 40% moisture) is metered into the ducting and suspended hot air. In vertical dryers the air flow is adjusted to classify the particles; lighter and smaller particles, which dry more rapidly, are carried to a cyclone more rapidly than are...
heavier and wetter particles which remain suspended to receive the additional drying required. For longer residence times the ducting is formed into a continuous loop (pneumatic ring dryers) and the product is recirculated until it is adequately dried. High temperature short time ring dryers expand enchaining subsequent conventional drying and rehydration rate.

A pneumatic conveying dryer is often integrated with a spray dryer to provide a second stage of drying, for example to produce sufficiently dry egg or milk powder. The product obtained directly from the spray dryer is normally low enough in moisture content for the commercial market, but special specifications may call for spray-dried milk or egg solids at lower moisture contents than are readily obtained directly by spray drying. In such cases, the powder may be collected from the spray dryer and metered into a duct into which a fresh supply of heated air is introduced. The duct leads to a cyclone collector and the powder dries while being conveyed by the air stream, both in the duct and in the cyclone. This type of installation is used to reduce the moisture content of the product by only a few percentage points. Pneumatic dryers have relatively low capital costs, high drying rates and thermal efficiencies, and close control over drying conditions. They are often used after spray drying to produce foods, which have lower moisture content than normal (e.g. special milk or egg powders and potato granule). In some applications the simultaneous transportation and drying of the food may be a useful method of materials handling.

**Fluidised Bed Dryer:**

Fluid bed dryer is an entirely different kind of pneumatic conveying dryer. Fluid-bed drying permits continuous, large-scale drying of foods without over drying. The high heat transfer rates make it an economical process, and the lack of mechanical parts ensures low maintenance costs. The rapid mixing in the bed provides nearly isothermal drying conditions. In batch operation products are mixed by fluidisation and this leads to uniform drying. In continuous dryers, there is a greater range of moisture contents in the dried product, and bin dryers are therefore used for finishing. Fluidised-bed dryers are limited to small particulate foods that are capable of being fluidised without excessive mechanical damage (e.g. peas, diced or sliced vegetables, grains powders or extruded foods). These considerations also apply to fluidised-bed freeze dryers and freezers.

A typical fluidised-bed design consists of metal trays with mesh or perforated bases, which contain a bed of particulate foods up to 15 cm deep (Figure 4). The grid must be fine enough to prevent the product from falling through it when the dryer is not in operation. Beneath the grid lies a gas distributor and air heater. The column is made tall enough to allow for expansion of the bed due to fluidising and to prevent particles from being carried into the air exhaust system. The air exhaust system is connected to a dust recovery system and an exhaust fan. Hot air is blown through the bed, causing the food to become suspended and vigorously agitation (fluidised). The air thus acts as both the drying and the fluidising medium, and the maximum surface area of food is made available for drying. The air is heated by steam, electricity, or a combustion chamber. Control of the air temperature is based on the bed temperature or exit air temperature. Bed heights typically range from 1 to 50 ft. The free board height is the distance between the top of the fluid bed and the air exit nozzle. The bed height is determined by the space available and flow rate required, the product residence time, and the space required for internal heat exchanges. It permits entrained particles to fall back to the bed. There is a solid feed mechanisms, which is usually a standard weighing and conveying device, such as a screw conveyor or dip pipe. An overflow weir or a flapper valve discharges the solids. Solids may be collected from the exit air in cyclones.
When the pressure of the air equals the weight of the particles per area of bed, the layer of particles is incipiently fluidised. At this pressure the layer undergoes moderate particle mixing. Velocities lower than this results in no particle mixing. Increasing the air velocity over that caused by incipient fluidising results in rapid mixing of the particles. The additional fluidising gas passes through the particle layer in bubbles. At higher gas velocities, the particles entrained in the fluidising gas may be pneumatically conveyed out of the drying chamber. The lists below are the characteristics that generally describe the materials suitable for fluid-bed drying:

1. The average particle size must be between 20 µm and 10 mm to avoid channelling and slugging. Particles smaller than 20 µm tend to lump together because of their large surface area.

2. The particle size distribution must be narrow to ensure that the majority of the particles are fluidised and few are lost by entrainment in the air.

3. For proper fluidisation, especially of larger particles, the particles should be spherical.

4. If any lumps are present in the fluid material, they must break up readily once in the dryer, to retain fluidity in the bed.

5. The particles must be strong enough to withstand vigorous mixing in the bed.

6. The final product must not be sticky at the fluid-bed exit temperature.

Dryers may be batch or continuous in operation; the latter are often fitted with a vibrating base to help to move the product. Continuous ‘cascade’ systems, in which food is discharged under gravity from one tray to the next, employ up to six dryers for high production rates.

There are various fluid bed designs:

1. Vibrated fluid bed: If the product to bed dried does not fluidise in a standard fluid-bed dryer because the particle distribution is too wide or the particles break up due to their low strength, or if they are sticky, thermoplastics, or pasty, vibrated fluid-bed dryer may be applicable. A long, rectangular, narrow drying chamber is vibrated at 5 to 25 Hz. The air velocity within the dryer can be as low as 20 % of the minimum fluidisation velocity. The large particles are transported through the dryer by the vibration of the dryer. The vibration provides a gentler means of transportation than vigorous of agitation in stationary fluid-bed dryers. Vibrated fluid-bed dryers typically dry such products as milk, whey, cocoa, and coffee.

2. Fluid-bed granulation: A second variation of fluid-bed drying is fluid-bed granulation. A binding liquid is sprayed into the fluidised bed of granules, causing the particles to agglomerate. The process is advantageous because it is not dust producing. The average particle size produced ranges from .5 to 2 mm. The process has widespread use in the pharmaceutical industry.

3. Spouted bed dryer: When the particles to be dried are larger than 5 mm and are not readily fluidised in a conventional fluid-bed dryer, a spouted bed dryer is employed. The drying air enters the drying chamber at the centre of the conical bottom. The particles move in a cyclic fashion through the dryer. As they travel upward in the centre, they are carried by the incoming air stream and fall downward at the periphery of the chamber. The advantages of
spouted bed dryers are the excellent solids mixing and heat transfer rates. Spouted bed dryers have successfully dried-heat sensitive goods such as wheat and peas.

4. **Mechanically agitated fluid-bed dryer**: A combination fluid-bed and flash dryer used to wet cakes was developed to conserve energy costs. The wet cake is fed directly via a screw conveyor. Once in the drying chamber, a mechanical agitator breaks up the particles while air is introduced to fluidise the small particles. Dry particles are carried to the exhaust system by the fluidising system. Pastes of pigments and dyes are dried industrially using this method.

5. **Centrifugal fluid-bed dryers**: Rapid pre-drying of sticky foods with high moisture content has been done in centrifugal fluid-bed dryers. Diced, sliced, and shredded vegetables that are difficult to fluidise and too heat sensitive to dry in conveyor dryers are also dried in centrifugal fluid-bed dryers. The cylindrical dryers rotate horizontally while air flows into the chamber through the perforated wall. The solids alternate between fluid-bed and fixed bed configuration as the dryer rotates.

6. **Fluidized spray dryer**: Another alternative for hygroscopic and thermoplastic foods is the fluidised spray dryer. A fluid-bed chamber is installed directly in the spray-drying chamber. The fluidising air is led to the bottom of the drying chamber. The combination of partially dried and dried products and allows agglomeration to take place. Small particles entrapped in the air are recycled from the exhaust system to the drying chamber. The combination of spray and fluid drying provides very efficient use of the drying chamber and produces agglomerated products with low bulk density and good instantizing characteristics.

![Fluidised-bed dryer](image)

**Figure 4.** Fluidised-bed dryer

**Kiln Dryers**

These are two-storey buildings in which a drying room with a slatted floor is located above a furnace (Figure 5). Hot air and the products of combustion from the furnace pass through beds of food up to 20 cm deep. The fruit is dried as a batch, but operates periodically enter the kiln and use hand scoops to turn and mix the partly dry product. The traditional kiln relies upon natural draft to provide sufficient circulation of air up through the moist material, but more modern units are provided with a mechanical exhaust fan in the space above the drying floor. If fuel oil is used for heating, the furnace is provided with an extensive array of sheet-iron flues to transfer heat to the drying air. These dryers have been used traditionally for
drying apple rings or slices in the USA, and hops or malt in Europe. There is limited control over drying conditions and drying times are relatively long. High labour costs are incurred by the need to turn the product regularly, and by manual loading and unloading. However, the dryers have large capacity and are easily constructed and maintained at low cost.

Figure 5. Kiln dryer

Rotary Dryers

A slightly inclined rotating metal cylinder is fitted internally with flights to cause the food to cascade through a stream of hot air as it moves through the dryer (Figure 6). Airflow may be parallel or counter-current. The agitation of the food and the large area of food exposed to the air produce high drying rates and a uniformity dried product. The method is especially suitable for foods that tend to mat or stick together in belt or tray dryers. However, the damage caused by impact and abrasions in the drier restrict this method to relatively few foods (e.g., sugar crystals and cocoa beans).

Figure 6. Rotary Dryer

Spray Dryers

In a spray dryer, foods are transformed from slurry into a dry powder. A fine dispersion of pre-concentrated food is first ‘atomised’ to form droplets (10-200 μm diameter) and sprayed into a current of heated air at 150-300°C in a large drying chamber. The feed rate is controlled to produce an outlet air temperature of 90-100°C, which corresponds to a wet-bulb temperature (and product temperature) of 40-50°C. The spray-drying operation is easily divided into three distinct processes; atomisation, drying through the contact between the
droplets and the heated air, and collection of the product by separating it from the drying air. A typical spray dryer configuration is shown in figure. The dryer configuration and the properties of the feed material determine the operating conditions necessary to provide a high-quality finished product (Figure 7).

The type of atomizer is important because it determines the energy required to form the spray, size and distribution of the droplets, available heat transfer area, drying rate, droplet speed and trajectory, and final product size. Following types of atomiser is used.

1. Centrifugal atomiser (wheel atomiser): A wheel atomizer is shown in figure. Liquid is fed to the centre or a rotating bowl (with a peripheral velocity of 90-200 ms⁻¹). The droplets are guided and shaped by vanes in the wheel (Figures 8 and 9). The droplets are projected horizontally away at 100 to 200 m/s with angular velocities of 10 000 to 30 000 rpm. Disk diameters typically range from 2 to 18 in. Since wheel atomizers are not susceptible to clogging, they are often used for slurries or pastes. Wheel atomizers produce a homogeneous spray, and varying rotational speed can control the mean particle diameter. Wheel atomizers are widely used in the food industry because they can handle a wide range of liquid viscosities and physical properties.

Figure 7. Spray dryer
2. **Pressure nozzle atomiser**: Liquid is forced at a high pressure (700-2000 kPa) through a small orifice. Nozzles have a maximum flow rate of 1 L/h. In situations that warrant higher flow rates; several nozzles are installed in the drying chamber. Typical pressures range from 300 to 4000 psig. Dryers with pressure nozzles typically contain drying chambers that are narrow in diameter and tall in height (Figures 10 and 11). The small orifice facilitates clogging, so pressure nozzles are seldom used when the feed is highly concentrated. Droplet sizes are 180-250 μm. Grooves on the inside of the nozzle cause the spray to form into a cone shape and therefore to use the full volume of the drying chamber.
3. Two-fluid nozzle atomiser: Compressed air creates turbulence, which atomises the liquid. The operating pressure is lower than the pressure nozzle, but a wider range of droplet sizes is produced.

Both types of nozzle atomiser are susceptible to blockage by particulate foods, and abrasive foods gradually widen the apertures and increase the average droplet size.

There are a large number of designs of atomiser, drying chamber, air heating and powder collecting systems. The variations in design arise from the different requirements of the very large variety of food materials that are spray dried (e.g. milk, egg, coffee, cocoa, tea, potato, ground chicken, ice cream mix, butter, cream, yoghurt and cheese powder, coffee whitener, fruit juices, meat and yeast extracts, encapsulated flavours and wheat and corn starch products).

The chamber design depends on the type of atomizer selected, the airflow pattern, the production rate, and when drying a heat-sensitive product, the temperature profile of the air in the chamber. Pilot-scale tests determine the optimum size of the dryer chamber. The shape of the drying chamber is a function of the trajectory angle of the droplets as they leave the atomizer. The chamber must be sized so that the largest droplet is dry before it contacts a wall.
The auxiliary equipment will vary with spray dryer design, but the most commonly employed pieces are air heaters and fans. The heater may be direct or indirect and fuelled by steam, fuel oil, gas, electrically, or thermal fluids. The most common heater in the food industry is the steam heater. Saturated steam at 150 to 200 °C is used to heat the air up to 10 °C below the steam temperature. Because they are able to produce high flow rates, centrifugal fans are used to control the airflow in most spray dryers. A two-fan system, with one fan positioned behind the powder recovery cyclones and the other at the drying chamber inlet, provides chamber pressure control. The pressure produced is a function of blade design.

There are three airflow patterns that are commonly used in spray drying: concurrent, countercurrent, and mixed flow. The air pattern used most often with heat-sensitive materials is countercurrent because the product temperature is lower than the inlet air temperature. If high-density dried products of heat-sensitive materials are required, concurrent flow is utilized. The drying air flows in the opposite direction to the falling particles. If the size of the dryer is limited, mixed flow patterns are used. The most economical spray-drying systems have typically been mixed flow, but that flow pattern is not suitable for heat-sensitive materials.

The dry powder is collected at the base of the drier and removed by a screw conveyor or a pneumatic system with a cyclone separator.

Spray dryers vary in size from small pilot scale models for low-volume high value products (e.g. enzymes and flavours) to large commercial models capable of producing 80,000 kg of dried milk per day. Spray drying is especially advantageous for heat-sensitive products because the particles are never subjected to a temperature higher than the wet-bulb temperature of the drying air, and their residence time is short, usually between 3 and 30 because of the very large surface area of the droplets. The temperature of the product remains at the wet-bulb temperature of the drying air and there is minimum heat damage to the food. The other advantages are large-scale continuous production, low labour cost and simple operation and maintenance. The major limitations are high capital costs and the requirement for a relatively high-feed moisture content to ensure that the food can be pumped to the atomiser. This results in higher energy costs (to remove the moisture) and higher volatile losses.

The bulk density of powders depends on the size of the dried particles and on whether they are hollow or solid. This is determined by the nature of the food and the drying conditions (e.g. the uniformity of droplet size, temperature, solids content, and degree of aeration of the feed liquid). Instant powders are produced by either agglomeration or non-agglomeration methods. Remoistening particles in low-pressure steam in an agglomerator, and then redrying achieve agglomeration. Alternatively, ‘straight-through’ agglomeration is achieved directly during spray drying. A relatively moist powder is agglomerated and dried in an attached fluidised bed drier. Non-agglomeration methods employ a binding agent (e.g. lecithin) to bind particles together. This method was previously used for foods with a relatively high fat content (e.g. whole milk powder) but agglomeration procedures have now largely replaced this method. Agglomeration is an example of a size enlargement operation.

**Trough dryer (Belt-trough dryer)**

Small, uniform pieces of food (e.g. peas or diced vegetables) are dried in a mesh conveyor belt, which hangs freely between rollers, to form the shape of a trough. Hot air is blown
through the bed of food, and the movement of the conveyor mixes and turns it to bring new surfaces continually into contact with the drying air.

Figure 12. Belt-trough dryer

The moist material supplied to the dryer forms a flat bed several inches deep in the bottom of this trough. When the mesh belt is driven slowly by means of its supporting rolls, the bed of material slowly turns over, continuously exposing new surfaces within the bed to the blast of hot, dry air coming through the grate at the bottom of the trough. Because of dynamic considerations, the trough bottom is slanted at an angle of about 15°-20° so that the material at the bottom of the bed moves up a gentle slope, works to the top of the bed, and slowly works across and down again on the opposite side. The entire belt assembly is also tilted slightly toward one end. The result is that the material in the bed feeds slowly in a generally helical path toward the downside; operation is made continuous by feeding fresh material to the arised end and removing the dried material at an adjustable weir positioned at the low end. The drying air is delivered at a volume high enough to support, but not fluidise, the material in the bed. The mixing action moves food away from the drying air, and this allows time for moisture to move from the interior of the pieces to the dry surface. The moisture is then rapidly evaporated when the food again contacts the hot air. The dryer operates in two stages, to 50-60 % moisture and then to 15-20 % moisture. Foods are finished in bin dryers.

Products from conventionally operated tunnels or conveyor dryers are not uniform in moisture content, and equalisation of moisture content and drying of the wettest pieces occupy much of the time spent by the material in bin finishing dryers. When the uniformly-dried material from the belt-trough is put into the finishing bin, drying time for finishing drying and heat damage therein are minimised. These dryers have high drying rates (e.g. 55 min for diced vegetables, compared with 5 h in a tunnel dryer), high-energy efficiencies, good control and minimal heat damage to the product. The belt-trough dryer has limitations in regard to piece shape and piece size distribution. The material in the bed of the dryer is slightly supported, but not fluidised, by the drying air. This characteristic permits the drying of reasonably soft materials without mashing of pieces or significant rounding of cut edges. The dryer is not suitable for fruits that become very sticky on the surface as drying proceeds. In this case, the bed of material will not move properly and the surfaces of the pieces are marred. Red and green peppers, onions and pimentos cut by a dicer can be dried satisfactorily. In contrast, the dryer
is not suitable for apple rings or onion slices. Apple rings break, onion slices separate into onion rings that become entangled to the extent that drying becomes impossible.

2.9 Tunnel dryers

A tunnel dryer is basically a group of truck-and-tray batch dryers, operated in a programmed series so as to be quasi-continuous. Truckloads of freshly prepared material are moved at intervals into one end of the long, closely fitting enclosure, the whole string of trucks is periodically advanced a step, and the dried truckloads are removed at the other end of the tunnel. The hot drying of air is supplied to the tunnel in any of several different ways, known as the counter flow, concurrent or parallel flow, centre exhaust, multistage, and compartment arrangements. In operation, thin layers of food dried on trays, which are stacked on trucks programmed to move semi-continuously through an insulated tunnel. The trays are fabricated of wood or light metal, with thin slat or open-mesh bottoms, and are designed so that when they are properly stacked a clear air passage is left between trays. The loaded trucks are pushed either manually or mechanically, one at a time, into the “wet end” of the drier. The passageway, which constitutes the tunnel, is just large enough to accommodate the loaded trucks; clearances are kept small so that hot air will not circulate uselessly around the stacks of trays but will be forced to flow mainly between trays. Typically a 20 m tunnel contains 12-15 trucks with a total capacity of 5000 kg of food. This ability to dry large quantities of food in a relatively short time (5-6 h) made tunnel drying widely used. However, the method has now been largely superseded by conveyor drying and fluidised-bed drying, as a result of their higher energy efficiency, reduced labour costs and better product quality.

The drying characteristics of a tunnel are strongly influenced by its general design and arrangement, especially the direction of progression of the trucks relative to the direction of the main airflow. In the far more common types of tunnel design, the main airflow is parallel to the direction of truck movement (Table 1). It may be same direction (concurrent, or parallel flow), or the opposite direction (counter flow), or it may be partly the other, as in various types of multistage dryer. Figure13 illustrates a simple concurrent tunnel and counter flow tunnel. Figure14 shows a more complex counter flow tunnel, designed to allow a portion of the drying air to be re-circulated. The essential differences between the effects of the two arrangements is that in the counter current tunnel very rapid initial drying of the material takes place, causing a high moisture gradient within each piece, rapid setting of the outer layers after only a little shrinkage, and formation of internal splits or porosity as the internal flesh finally dries and shrinks; final stages of drying are very slow because not only is the material approaches dryness. Unless the evaporative load is very light, initial stages of drying take place in much cooler and more humid air, internal moisture gradients are not so steep, and more nearly unhindered and complete volume shrinkage can take place. For many years, counter flow drying was standard practice for dehydration of fruits such as prunes, which amount to about 90 % of the fruit so processed. However, more than half of the current prune crop is dried in parallel-flow tunnels. Air recirculation is common to reduce heat costs.
Several other tunnel arrangements have been used to take advantage both of the high wet-end evaporate capacity characteristics of the concurrent arrangement and the good final drying capability of the concurrent arrangement and the good final drying capability of the counter flow tunnel. The combination generally preferred consists of a concurrent wet end a counter flow dry end.

Many other tunnel arrangements have been proposed. One is a closed-cycle system—that is, there is no exhaust to the atmosphere; instead, the exhaust air from the drying section is partially dehumidified and returned to the fresh-air intake. The system has been proposed for onion and garlic dehydration, in order to diminish the nuisance aspect of the highly odorous exhaust from an ordinary tunnel drier. Closed-cycle drying has also been investigated as part of a system for dehydration foods in an atmosphere of inert, oxygen-free gas, the closed cycle being necessary to diminish the cost of supplying fresh inert gas. The major advantage of such an arrangement probably is its flexibility with respect to the drying a wide variety of different products under nearly optimum conditions for each.
Table 1: Advantages and limitations of parallel flow, counter-current flow, centre-exhaust and cross-flow drying

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

2. HEATED-SURFACE DRYERS

Dryers in which heat is supplied to the food by conduction have two main advantages over hot air drying.

1. It is not necessary to heat volumes of air before drying commences, and the thermal efficiency is therefore high.

2. Drying may be carried out in the absence of oxygen to protect components of foods that are easily oxidised.

Typically heat consumption is 2000-3000 kJ per kilogram of water evaporated compared with 4000-10 000 kJ per kilogram of water evaporated for hot air dryers. However, foods have low thermal conductivities which become lower is the food dryers. There should therefore be a thin layer of food to conduct heat rapidly, without causing heat damage. Foods may shrink during drying, lift off the hot surface and therefore introduce an additional barrier to heat transfer. Careful control is necessary over the rheological properties of the feed slurry to minimise shrinkage and to determine the thickness of the feed layer.
Drum Dryers (Roller Dryers)

Slowly rotating hollow steel drums are heated internally by pressurised steam to 120-170 °C. A thin layer of food is spread uniformly over the outer surface by dipping, by spraying, by spreading or by auxiliary feed rollers. Before the drum has completed 1 rev (within 20 s-3 min), the dried food is scraped off by a ‘doctor’ blade, which contacts the drum surface uniformly along its length. The capacity of a drum dryer is a function of the drying rate of the thin layer of material and the amount of product that adheres to the drum surface. The drying rate depends on the type of feed device, steam pressure within the drum, and the drum speed. Preheating and preconcentration of the feed can reduce the drying load. Properties that affect drum adherence are viscosity, surface tension, and wetting power. The four variables that govern the operation of drum dryers are steam pressure, rotational speed, film thickness, and feed material characteristics. The steam pressure, or heating medium temperature, will regulate the drum’s temperature. The rotational speed of the drum determines contact time. The wet material is applied to the drum from below by splash feeders that splash the product onto the drums by rotary blades, by dip feeders where the drum dips into a tank and the concentrated material adheres to the drum, or from below by a pendulum feed pipe.

Dryers may have a single drum, or double drums or twin drums. With the double-drum dryer, the distance between the drums determines the thickness of the food product (Figure 14). The product dries as the drums rotate and is then scraped off by the knives. This type of drum dryer is advantageous because it can handle a wide range of products, it has high production rates, and it has low labour requirements. Materials ranging from dilute solutions to heavy pastes can be effectively dried in double-drum dryers. Food products dried by this method include heat-sensitive liquids and pastes, which can be quickly rehydrated from the resulting flakes or powders. Applesauce, fruit purees, bananas, pre-cooked breakfast cereals, and dry soup materials are manufactured in double-drum dryers. In a twin double dryer the drums rotate away from one another, and splash feeders at the bottom of the drum apply the wet feed (Figure 15). The dry material is removed by knives located 270 ° away from the rotary feed devices. This type of drum dryer is used for materials with solids that are dusty when dry, such as salt solutions or clay slips. The twin drum dryer can be used as a pre-dryer when a top feed is installed. The material is removed from the dryer at high moisture content and drying is completed with a rotary dryer. This drying method is economical only when increased capacity is obtained by avoiding difficulties that would be encountered by using either dryer alone.

The application of wet material onto a single-drum dryer (Figure 17) is done with applicator rolls. The rolls heavy product sheets resulting in a thick final product. The number of applicator rolls used determines the characteristics of the dry product sheet. Applicator rolls are advantageous when the wet material does not uniformly coat the drum surface. It is used for drying pastes and for food products high in starch, such as potato flakes.

The layer of material on the heated drum is thin and presents no restriction to the vaporizing water. Three stages of heat transfer occur in this thin layer: the first stage consist of heating the thin layer up to its boiling point, the second stage when the water is vaporized and the material gradually changes from a liquid to a solid state, and a final stage where the temperature of the product approaches that of the drum.

Drum drying involves heat transfer from condensing steam through the metal drum to the product layer. The rate of heat transfer depends on the resistance to the removal of water at lower moisture contents and product characteristics. When the time to remove the lass few
percent moisture becomes too great to be practical, the drum dryers often increase dramatically in these instances.

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

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

Figure 14. Double drum dryer

Figure 15. Twin drum dryer
Figure 16. Single-drum dryer

Vacuum band and vacuum shelf dryers

Food slurry is spread or sprayed onto a steel belt (or band), which passes over two hollow drums, within a vacuum chamber at 1-70 Torr. The food is dried by the first steam-heated drum, and then by steam-heated coils or radiant heaters located over the band. The dried food is cooled by the second water-cooled drum and removed by a doctor blade. Vacuum shelf dryers consist of hollow shelves in a vacuum chamber. Food is placed in thin layers on flat metal trays, which are carefully made to ensure good contact with the shelves. A partial vacuum of 1-70 Torr is drawn in the chamber and steam or hot water is passed through the shelves to dry the food.

Rapid drying and limited heat damage to the food make both methods suitable for heat-sensitive foods. However, care is necessary to prevent the dried food from burning onto trays in vacuum shelf dryers, and shrinkage reduces the contact between the food and heated surfaces of both types of equipment. Both have relatively high capital and operating costs and low production rates.

Vacuum band and vacuum shelf dryers are used to produce puff-dried foods. Explosion puff drying involves partially drying food to moderate moisture content and then sealing it into a pressure chamber. The pressure and temperature in the chamber are increased and then instantly released. The rapid loss of pressure causes the food to expand and develop a fine porous structure. This permits faster final drying and rapid rehydration. Sensory and nutritional qualities are well retained. The technique was first applied commercially to breakfast cereals and now includes a range of fruit and vegetable products.

3. FREEZE-DRYING

Food products that are too sensitive to withstand any heat are often freeze-dried. Freeze dehydration is an operation in which water is removed from foods by transfer from the solid state (ice) to the gaseous state (water vapour). This operation (sublimation) can only be accomplished when the vapour pressure and temperature of the ice surface at which the sublimation takes place below those at the triple point. Food structure is affected differently by sublimation than by other methods of dehydration because of a liquid phase during freeze
dehydration. The sublimated ice is pulled from the vacuum chamber by vacuum pumps or steam jet injectors. The heat of sublimation is supplied by conduction or radiation. It is well known that freeze-drying produces the highest-quality food product. This is largely because the structure of the food is not severely damaged as in other drying processes. When water is removed from a material by sublimation, a porous, nonshrunken structure remains. Freeze-dried foods are easily rehydrated. Little or no loss of flavour and aroma occur during freeze-drying. Product quality remains high because the low drying temperature is not conductive to most degrading processes, such as nonenzymatic browning, protein deterioration, and enzymatic reactions. The greatest disadvantage of freeze-drying is the cost. The drying rate is slow and the use of a vacuum adds to the cost. The final product has low moisture content, so alleviating the refrigeration and storage costs saves cost.

Freeze drying process is subdivided into different steps, and usually three main steps are considered: the prefreezing, the sublimation drying and the secondary drying.

1. Prefreezing Step: The freezing of clean water normally takes place at a constant temperature of 273 K, ice crystals forming and growing from the liquid water gradually as heat is removed. In freeze drying clean water is not considered food. This water is normally present as a part of aqueous solutions and suspensions, and the freezing of those is connected with phenomena such as freezing point depression, eutectic solutions, subcooling, ice crystal growth and glassy structure.

In the prefreezing step of a liquid food, an international structure is created in the food material, which may be stabilised during a later sublimation drying and secondary drying. This structure is formed by a network of ice crystals incorporated in a matrix of concentrated food material. In latter steps of the freeze drying process the ice crystals are sublimed away leaving a network of channels for the water vapour to escape to the product surfaces. The water content of the matrix reaches these channels by diffusion and also escapes to the surfaces. At the end of the freeze-drying process the former liquid material is transformed to a porous solid with the concentrated solid matrix as a structural network. In the prefreezing of solid foods, the structural influence is also of importance. Slow freezing favours the formation of large ice crystals, which can penetrate and damage cell membranes. Also ultra quick cryogenic freezing may result in drastic structure break down caused by temperature stresses. These structural changes are normally undesired in quick frozen foods.

2. Sublimation Drying: In the sublimation-drying step the two main transport processes are heat transfer and water vapour transfer. In the normal vacuum freeze dryer heat is transferred to the product surface and on through the product layers to the sublimation front. The driving force of this heat transfer is the temperature difference from the heater surface to the sublimation front. The highest product temperature will be found on the product surface where heat is transferred from the heater surface. To avoid serious quality losses it is important to keep this product temperature below a certain limit. At a moderate freeze drying vacuum of 1 torr each gramme of ice when sublimated produces approximately 1 m$^3$ of water vapour and at 0.5 torr even 2m$^3$ may be formed. Being produced at the sublimation front all this water vapour has to be transported first to the product surface and then away from the product surface, otherwise the vapour pressure will rise and the temperature at the sublimation front will also rise so that melting of the frozen product will occur. This vapour transport must take place under limited pressure differential, or likewise melting may occur, which may first be recognised as collapse of the regular, porous structure of the freeze dried product.
3. Secondary Drying: The sublimation drying of the ice crystals leaves a system of pores in a matrix of product. The rest of the water content of the product has not been frozen out as ice crystals and is still distributed during the secondary drying step. This moisture may partly exist in the vitreous state, partly hydroscopically bound water. The secondary drying step is very similar to the latter steps of any drying process, when water is no longer mobile in the product in the liquid form and a temperature rise is necessary to release the hygroscopically bound water. Foods normally in the secondary drying can tolerate the sufficient rise in temperature over the sublimation temperature to achieve this.

4. NOVEL DRYING TECHNOLOGIES

Saving in energy consumption will result in considerable overall improvement in energy efficiency. In addition, the final quality of the product is greatly influenced by the drying technique and strategy.

To investigate alternative novel drying technologies in order to arrive at more energy-efficient processes with improved quality, a brief overview of some novel drying techniques is given below:

1. Microwave Drying: High-frequency radio waves up to 30 000 MHz are utilized in microwave drying. A high-frequency generator guides the waves and channels them into an oven designed to prevent the waves from leaving the chamber. Proper wavelength selection is necessary to ensure thorough penetration into the food. The depth of the material and type of material being exposed also affects penetration. It is important that each product be evaluated individually to ensure proper wavelengths and dehydration. As the energy enters the foods, the molecules try to align in the electric field orientation. They oscillate around their axis, generating heat within the food, resulting in dehydration. The waves bounce from wall to wall, until the product absorbs eventually all of the energy. In this manner, the drying rate is increased greatly. There is a problem with uniformity of drying because of the penetration of the microwaves through the product. This type of heating is highly efficient; and power utilization efficiencies are generally greater than 70%. Important commercial aspects include the ability to maintain colour and quality of the natural food. This has been found prevalent in potato chips. Cabbage and potato blocks were reduced in moisture content from 15% to 9% and 7% to 5%, respectively, and the time required was about one-fifth of that in a cross-air blow dryer.

2. Ethyl Oleate: In the drying process, certain compounds can be used to enhance the drying specific products. One such compound is ethyl oleate. This acts as a wetting agent, increasing the evaporation rate of water in the initial stages of drying. Ethyl oleate acts as a surfactant by increasing the spreading of free water within the sample. This, in turn, increases the drying rate. On the skin of grapes, ethyl oleate causes a dissolving action on the waxy components of the skin. It is these components that offer high resistance to moisture transfer. By dissolving these, the moisture transfer is much easier.

3. Acoustic Drying: Products are dried at relatively low temperatures, 140 to 200 °F, with intense low-frequency sound waves. These strong sonic waves increase heat and mass transfer coefficients across the boundary layer of the product. This tends to promote liquid-solid separation. The drying rates of these dryers are 3 to 19 times faster than those of conventional dryers. Its efficiency rate is around 1500 Btu/lb H₂O removed. The product enters the dryer at the top in a gravity-fall situation. The product is atomised in order to enter the chamber. As the product hits the air and sound waves, it is dried in seconds. A cyclone bag house helps
collect the dried products. This dryer requires sound-diminishing devices because of the loud produced during drying. Foods that have been commonly classified as difficult to dry have been dried successfully in acoustic dryers. Liquids containing between 5 and 78 % moisture have been dried to 0.5 % moisture content. Products with high fat contents, up to 30 %, have also been dried in these dryers. Other products that dry well are high-fructose corn syrups, tomato pastes, lemon juice, and orange juice. Because this process is relatively quick and cool, the degradation of natural colour, flavour, and nutrition is reduced.

4. Infrared Radiation Drying: This technique is often used in conjunction with freeze-drying (to accelerate the sublimation process), batch drying, and continuous band drying. Heating the product to a high temperature, resulting in direct penetration of the surface by the radiation, generates the infrared radiation. The ideal products for this system are referred as black bodies. This heat is usually generated by gas flames, electrical methods including reflector incandescent lamps (100 to 5000 W), quartz tubes, and resistance elements. The heat radiation is projected from planes arranged above the trays of product. Band systems are common because of the need for the product layers to be no thicker than 3 mm. Slurries and gels work best in this system, providing optimal penetration. This drying technique produces a high drying rate without burning.

5. Electric and Magnetic Field Dewatering: The method of using electric and magnetic fields is used primarily as a separation technique with solid-liquid combinations. Once the product has been dewatered through this method, it is sent on to another conventional dryer to complete the dehydration process. The backbone of the process is the flow of a dc electric field applied to enhance dewatering. This influences the surface characteristics of the solid-liquid, such as zeta potential, dipole interactions, and hydrophobicity. This method works with two processes: electroosmosis and electrofiltration. Electroosmosis is the movement of water through the porous membranes of the product with the application of a dc electric potential. This is a surface diffusion processes. Electrofiltration is the movement of charged particles toward electrodes in the presence of a dc electric field. The processes are carried out in a separation chamber before the product is sent on to another dryer. These processes are not used on a commercial scale yet because of the economics of the system, but they are becoming more prominent because of the growing environmental concern with supernatant discard.

6. Superheated Steam: This method of drying is normally incorporated with a two-belt dryer system. The product is put onto an upper belt in a uniform noncompact layer. As it passes through the dryer, steam is passed up through the belt and product. At the end of the first belt, a gravity-fall system loads the production to a second lower belt. The product is passed through the chamber once again. The steam is blown over the product in a parallel fashion. No air is introduced into this type of system. For this reason it is important to minimize any leaks within the dryer. Superheated steam at atmospheric pressure is the only drying medium involved. This occurs because steam increases the efficiency of the system over air. This in turn reduces drying time and dryer surface area. The evaporation rate is controlled by the rate of heat exchange between the drying fluid and the product. At the end of the drying process, the steam is diffused from inside the product to the outside more easily than air would be. The steam leaves the dryer completely saturated, and upon exit, is compressed to condense out some of the water present in the steam. This steam is then expanded and recycled through the dryer.

Despite its initial high expense, this system has many advantages. There is no material loss and no burning of the product. No pollution, a higher quality dry product, uniform drying, a
sterile atmosphere, and a 50% energy savings in primary consumption are all benefits of the procedure.

7. Desiccant: Desiccants have been used primarily in the air-conditioning industry for many years, but several people believe that this particular technique has some aspects applicable to the dehydration of food. The process is basically a dehumidification of the air followed by an adiabatic evaporative cooling period. The idea is that the water in the product would condense out through the pores of the desiccant and the latent heat of vaporization would be converted into sensible heat. The product is normally dried in a rotary type or batch dryer. The high speed or revolution of the drying drum plus a low airflow rate causes a great potential for mass transfer from air to desiccant. Cooling water is circulated continuously to maintain a constant desiccant temperature. A solid gel or liquid desiccant can be used. The solid gel requires very high pressures to evaporate the water out. Higher temperatures are required for reactivating the used desiccant. There are significant operating costs involving here. The liquid desiccant has a lower vapour pressure that the water, which results in a dilution of the desiccant. This means that the desiccant is absorbing the moisture from the product.

8. Osmotic Dehydration: The principal type is sugar syrup treatment. This causes removal of moisture by placing the food in contact with the sugar solution. The product slices are immersed in the concentrated sugar solutions for a range of 4 to 24 h, depending on the food being dried. This will reduce the moisture content about 50% and then the product can be dried further by another conventional method. The other agents involved are sugars, sugar-starch mixtures, and sugar syrups. This "candling" leaves a product with a porous, crisp texture while retaining most of its original flavour. Reverse osmosis is also used as a dewatering technique. This process is useful for fruit juice concentrations and is much faster than conventional methods. The optimum temperature range is 20 to 40°C, the drying time is inversely proportional to the temperature. Studies have shown that raising the temperature range to 40 to 80°C shortens the dehydration time but lowers the quality of the product. It also causes the cell membranes to plasmolyze. The plant material, osmotic substance used, and the parameters of the dehydration process affect this drying rate. Also, at higher temperatures, the viscosity of the solution decreases as the water diffusion process. Also, at higher temperatures, the viscosity of the solution decreases as the water diffusion coefficient in osmotic solution increases.

9. Explosion Puffing: This technique produces many of the desired qualities of freeze-dried product but with significantly less expense and in a much shorter time with better reconstitution. The product is partially dehydrated in a preliminary stage and then loaded into a closed rotating cylinder called a “gun”. The product is heated inside until the internal pressure reaches a predetermined value. The food is instantly discharged to atmospheric pressure. As this occurs, some of the water is vaporised. The important fact is that the explosion produces a porous network within the particle. This porosity enables the final dehydration to be completed rapidly, approximately two times faster than conventional methods. The gun was redesigned some years ago by introduced superheated steam at 500°F and 55 psig into it. This prevents condensation and guarantees that the particles are exposed on all sides. This process issued mainly for fruits, vegetables, and grains.

10. Foam-Mat Drying: The conversion of liquid foods to foam has been found to be a less costly means of improving product quality. Foams dry more rapidly than liquids, allowing the use of lower temperatures and shorter residence times. The increased rate of drying is due to an increase in surface area and the relative ease of moisture transport through the porous dried foam structure as compared to the less porous structure of the dried liquid. Heat transfer is
less efficient in foam but is adequate since the drying of food materials is predominately controlled by internal mass transfer. In addition to the reduction in thermal exposure to heat-sensitive foods, dried foams retain a porous structure, allowing rapid rehydration characteristics. Several applications of foam drying have been developed, including vacuum puff drying, foam spray drying, and foam-mat drying. “Vacuum puff drying” refers to processes that use a vacuum to induce product foaming. When gases are dissolved in the liquid feed under considerable pressure prior to spray drying, the process is called foam spray drying. Half typically reduces the density of the foam-spray-dried products, and “whereas spray-dried particles are hollow spheres surrounded by thick walls of dried material, the foam process produces particles having many internal spaces and relatively thin walls”. In foam-mat drying, the foaming of a liquid is due to surfactants that are either naturally occurring or added. Stable foam is spread out in a thin mat and dried with heated air. The dried product, examples of which include milk, mashed potatoes, and fruits can be scraped off moving trays or belts and crumbled. The cost of foam-mat drying is higher than spray or drum drying but less than freeze-drying. This is due to the large drying surface required to dry a thin film layer. Thicker films are unsuitable because the drying time exceeds the time of stability for most foam.

11. Supercritical Fluid Extraction and Its Application to Drying: Supercritical fluids possess unique properties that enable them to extract components selectively from a mixture. This ability has been investigated recently as an alternative to currently used extraction processes such as distillation or liquid extractions. SCF extraction exploits the properties that occur at or above the supercritical pressure and temperature. The supercritical region is that point beyond the critical point. The properties exhibited by fluids in this region are intermediate between those of liquids and gases. The property of greatest interest for SCF extraction is that of density. With increasing pressure, a gas will become increasingly dense. Above the critical point, this increased density produces enhanced solvency, approaching that of that of a liquid. It is this solvency that makes SCF extraction a feasible alternative. Mass transfer properties resembling that of gases are also a significant factor in SCF extraction. An application of SCF extraction that has seemingly gone unexplored is to the drying of food products. Since moisture content influences texture, chemical reactions, and susceptibility to microbial spoilage, drying is a way to retain quality and prolong shelf life. A complication associated with drying of food products is that they may undergo changes that alter the physical or chemical structure, thus changing the integrity of the product. SCF extraction avoids this problem because it allows the food product to be dehydrated without undergoing a phase from liquid water-to-water vapour. Also, if a solvent such as supercritical carbon dioxide is used, it will not be necessary to heat the product above ambient temperatures.

5. SELECTION OF DRYING EQUIPMENT

The first consideration in selecting a dryer is its operability; above all else, the equipment must produce the desired product in the form at the desired rate. The quality required in a finished product, and its necessary physical characteristics, are determined by its end use. A tomato powder, for example, would be made to have different characteristics if it were intended for beverages use that if it were to be used as tomato paste in spiced cookery. Despite the variety of commercial dryers on the market, the various types are largely complementary, not competitive, and the nature of the drying problem dictates the type of dryer that must be used, or at least limits the choice to perhaps two or three possibilities. The final choice is then made on the basis of capital and operating costs. Attention must be paid, however, to the costs of the entire isolation system, not just the drying unit alone.
There are some general guidelines for selecting a dryer, but it should be recognised that the rules are far from rigid and exceptions not uncommon. Batch dryers, for example, are most often used when the production rate of dried solid is less than 150 to 200 kg/h; continuous dryers are nearly always chosen for production rates greater than 1 or 2 tons/h. At intermediate production rates other factors must be considered. Thermally sensitive materials must be dried at low temperature under vacuum, with a low-temperature heating medium, or very rapidly as in a flash or spray dryer. Fragile crystals must be handled gently as in a tray dryer, a screen-conveyor dryer, or two dryer.

The dryer must also operate reliably, safely, and economically. Operation and maintenance costs must be excessive; pollution must be controlled; energy consumption must be minimised. As with other equipment these considerations may conflict with one another and a compromise reached in finding the optimum dryer for a given service.

As far as the drying operation itself is concerned, adiabatic dryers are generally less expensive than non-adiabatic dryers, in spite of the lower thermal efficiency of adiabatic units. Unfortunately there is usually a lot of dust carry over from adiabatic dryers, and these entrained particles must be removed almost quantitatively from the drying gas. Elaborate particle-removal equipment may be needed, equipment which may cost as much as the dryer itself. This often makes adiabatic dryers less commercial than a “buttoned-up” non-adiabatic system in which little or no gas is used.
### Table 2. Characteristics of driers (Fellow, 1988).

<table>
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<th>Type of drier</th>
<th>Characteristics of the food</th>
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<th>Size of pieces</th>
<th>Drying rate required</th>
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