

## Advances in dehydration of foods

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### Abstract

Food dehydration is still one of the most relevant and challenging unit operations in food processing, although the art of food preservation through the partial removal of water content dates back several centuries. This article provides essential information on the fundamental, including psychrometry, and applied engineering aspects of food dehydration with up-to-date available commercial applications. The evolution of drying technology, divided into four generations, is thoroughly reviewed, from tray drying to the combination of some drying technologies (the hurdle technology approach in drying) in order to optimize the process in terms of final food quality and energy consumption. The study of each generation covered numerous examples of different dryers, including their principles of operation, basic configurations and most common applications, as well as their main advantages and disadvantages. © 2001 Elsevier Science Ltd. All rights reserved.

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### 1. Introduction

The first known record of drying involved vegetables and appeared in the 18th century (Van Arsdel & Copley, 1963). Thereafter, development of the drying industry was closely related to war scenarios around the world. British troops in the Crimea (1854–1856) received dried vegetables from their homeland, Canadian dried vegetables were shipped to South Africa during the Boer War (1899–1902), and around 4500 tons of dehydrated vegetables were shipped from the US during World War I. By 1919, among the products processed in the US were green beans, cabbage, carrots, celery, potatoes, spinach, sweet corn, turnips, and soup mixtures.

Drying is a process in which water is removed to halt or slow down the growth of spoilage microorganisms, as well as the occurrence of chemical reactions. The terms *dried* and *dehydrated* are not synonymous. The US Department of Agriculture lists dehydrated foods as those with no more than 2.5% water (dry basis), while

dried foods apply to any food product with more than 2.5% water (dry basis).

The selection of a dryer should be based on the entire manufacturing process. Raw materials, intermediate product, and final product specifications and characteristics (i.e., final moisture content) need to be clearly defined. Preprocessing steps may be considered to partially remove water prior to the final drying step (i.e., osmotic dehydration prior to freeze drying). The final assessment for selecting a dryer should include, but not be limited to, the production capacity, initial moisture content of the product, particle size distribution, drying characteristics of the product, maximum allowable product temperature, explosion characteristics (i.e., spray or fluid bed dryings), moisture isotherms, and physical data of the material. Fig. 1 summarizes a possible procedure for the selection of either a batch or a continuous dryer.

Food dehydration is not limited to the selection of a dryer. The physicochemical concepts associated with food dehydration need to be understood for an appropriate assessment of the drying phenomena in any food product. Water activity, glass transition temperature, dehydration mechanisms and theories, and chemical and physical changes should be recognized as key elements for any food dehydration operation.

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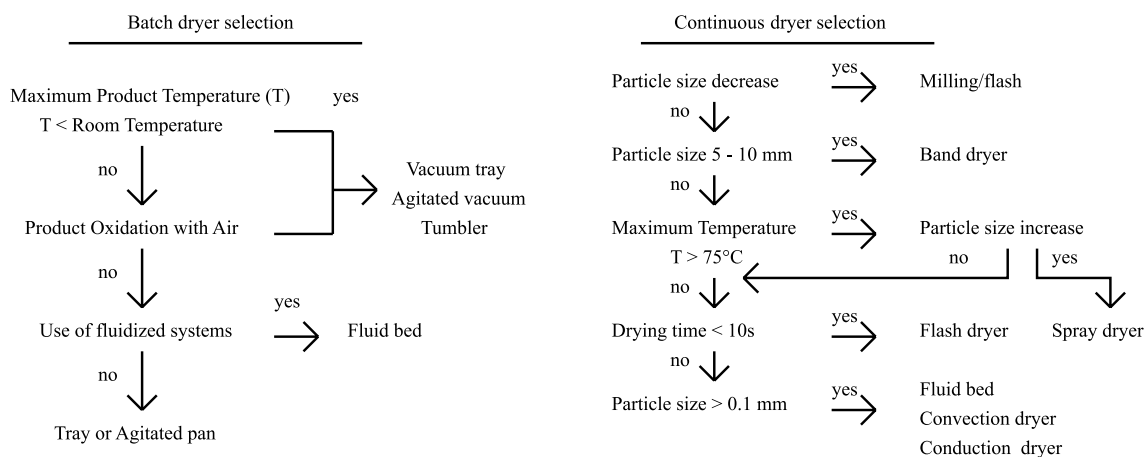


Fig. 1. Flowchart for selection of dryers (Barbosa-Cánovas & Vega-Mercado, 1996).

## 2. Fundamentals of air–water mixtures

The term *humidification* has been used in engineering to describe the interface transfer of mass and energy between a gas and a pure liquid when they are brought into contact. The term covers not only humidification but also dehumidification of the gases, measurement of vapor content, and cooling of both gases and liquids.

For air–water mixtures the term *vapor* is related to water whereas the term *gas* is related to air. Air is considered for all purposes a single substance, although it is really a mixture of gases such as nitrogen, oxygen, argon, carbon dioxide, neon, helium, and other minor components. Its physical and chemical properties are reported elsewhere (Geankoplis, 1983).

## 3. Air–water relationships

The ideal gas law is used to predict the behavior of air–water mixtures, because the air temperature is high enough and the water vapor pressure low enough in relation to their respective saturation points. Thus, their pressure–volume–temperature (PVT) relationship can be expressed as (Himmelblau, 1982):

$$P_{\text{air}}V = n_{\text{air}}RT, \quad (1)$$

$$P_{\text{water}}V = n_{\text{water}}RT, \quad (2)$$

where  $P_{\text{air}}$  is the partial pressure of air in the mixture,  $P_{\text{water}}$  the partial pressure of water vapor,  $V$  the total volume,  $R$  the gas constant,  $T$  the absolute temperature,  $n_{\text{air}}$  the number of moles of air, and  $n_{\text{water}}$  the number of moles of water. The total pressure of the air–water vapor mixture can be expressed as:

$$P_{\text{total}} = P_{\text{air}} + P_{\text{water}}, \quad (3)$$

which is known as Dalton's Law. Dalton postulated that the sum of the partial pressures exerted by each com-

ponent is equal to the total pressure of the system. A similar relationship may be used for volumes when the system is at a constant temperature and pressure.

### 3.1. Moisture content of air

In drying operations, the properties of moist air change as a function of time. The main change is in the amount of water removed from the product as air passes through the system. It is convenient to express the change in moist air properties in terms of dry air. Eqs. (1) and (2) can be combined to express the amount of water in terms of the amount of dry air, which results in the following expression for the molal absolute humidity:

$$W' = \frac{n_{\text{water}}}{n_{\text{air}}} = \frac{P_{\text{water}}}{P_{\text{air}}}, \quad (4)$$

where  $W'$  is expressed in moles of water per mole of dry air. The humidity ratio or absolute humidity is obtained when  $W'$  is expressed as the water/air mass ratio rather than moles:

$$W = W' \left( \frac{M_{\text{water}}}{M_{\text{air}}} \right), \quad (5)$$

where  $M_{\text{water}}$  is the molecular weight of water and  $M_{\text{air}}$  the molecular weight of air. Eq. (4) is preferred over Eq. (5) because the moles and volumes can be interrelated easily through the ideal gas law.

The mole fraction of the water in an air–water mixture is defined as:

$$y_{\text{water}} = \frac{n_{\text{water}}}{(n_{\text{air}} + n_{\text{water}})} \quad (6)$$

or

$$y_{\text{water}} = \frac{P_{\text{water}}}{(P_{\text{air}} + P_{\text{water}})}. \quad (7)$$

Notice the numerators of Eqs. (6) and (7) can be obtained by adding Eqs. (1) and (2) or by Dalton's Law:

$$(P_{\text{air}} + P_{\text{water}})V = (n_{\text{air}} + n_{\text{water}})RT \quad (8)$$

and Eq. (8) can be summarized as:

$$P_{\text{total}}V = n_{\text{total}}RT. \quad (9)$$

If the mole fraction of water and the total pressure are known, it is possible to evaluate the partial pressure of water:

$$P_{\text{water}} = y_{\text{water}}P_{\text{total}}, \quad (10)$$

and a similar expression can be written for the air:

$$P_{\text{air}} = y_{\text{air}}P_{\text{total}}. \quad (11)$$

#### 4. Psychrometric chart

The psychrometric chart (Fig. 2) for an air–water mixture is widely used because it relates basic properties such as humid volume, enthalpy, and humidity. It is necessary to understand the following terms in order to interpret the chart:

##### 4.1. Dry bulb temperature

This is the temperature of the mixture measured by the immersion of a thermometer in the mixture without any modification on the thermometer.

##### 4.2. Relative saturation or relative humidity

The relative humidity is defined as the ratio between the partial pressure of water vapor ( $P_{\text{water}}$ ) in the system and the partial pressure of water vapor ( $P_{\text{water-sat}}$ ) in a saturated condition at the same temperature of the system. It can be expressed as:

$$\Phi = 100 \frac{P_{\text{water}}}{P_{\text{water-sat}}} = 100 \frac{X_{\text{water}}}{X_{\text{water-sat}}}, \quad (12)$$

where  $X_{\text{water}}$  is the mole fraction of water in the mixture and  $X_{\text{water-sat}}$  the mole fraction of water in a

saturated mixture at the same temperature. The saturation line for  $P_{\text{water-sat}}$  in the psychrometric chart is identified as 100% relative humidity, while other humidity levels are identified with their respective percentages.

##### 4.3. Percentage saturation or percentage absolute humidity

The percentage saturation is expressed as:

$$\mu = 100 \frac{W'}{W'_{\text{sat}}}, \quad (13)$$

where  $W'_{\text{sat}}$  is the molal absolute humidity, as defined by Eq. (4) for saturated conditions at the dry bulb temperature of the mixture.

##### 4.4. Humid volume or specific volume ( $v$ )

Humid volume or specific volume is defined as the volume of unit mass of dry gas and the accompanying vapor at the mixture temperature and pressure, in  $\text{m}^3/\text{kg}$  of dry air. It is expressed for an air–water mixture as (Treybal, 1980):

$$v_h = T(2.83 \times 10^{-3} + 4.56 \times 10^{-3}W), \quad (14)$$

where  $T$  is the absolute temperature of the mixture (K) and  $W$  the absolute humidity.

##### 4.5. Humid heat

The term *humid heat* represents the amount of heat required to raise the temperature by  $1^\circ\text{C}$  of 1 kg of dry air plus the water vapor present (Geankoplis, 1983). An air–water vapor mixture is defined as:

$$C_S = C_{\text{air}} + WC_{\text{water}} \quad (15)$$

or

$$C_S = 1.005 + W1.884 \quad (16)$$

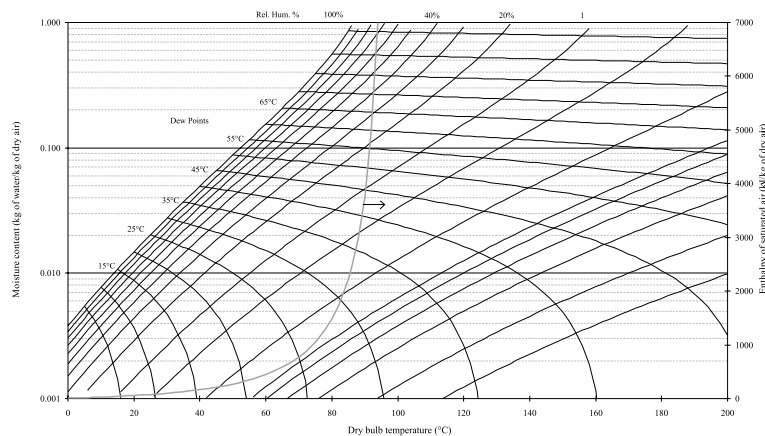


Fig. 2. Psychrometric chart for air–water mixture (Barbosa-Cánovas & Vega-Mercado, 1996).

where  $W$  is the absolute humidity,  $C_{\text{air}}$  the heat capacity of air (kJ/kg of dry air K) and  $C_{\text{water}}$  the heat capacity of water (kJ/kg of water K).

4.6. Enthalpy of a vapor–gas mixture

The enthalpy of a vapor–gas mixture is defined as the sum of the enthalpies of the gas and vapor content. This relationship can be expressed for air–water mixtures as:

$$H' = C_S(T - T_0) + \lambda_0 W, \tag{17}$$

where  $T_0$  is a reference temperature and  $\lambda_0$  the latent heat of water at  $T_0$ . The value of  $\lambda_0$  is 2501.4 kJ/kg of water, using air and saturated water vapor at 0°C as the reference point.

4.7. Dew point

The dew point of an air–water mixture is the temperature at which the mixture becomes saturated when cooled at constant total pressure. If the mixture is cooled to a temperature below the dew point, the mixture will condense water. The dew point temperature can be determined from the psychrometric chart by drawing a straight line from a given point until reaching the saturation line, and the corresponding dry bulb temperature is the dew point.

4.8. Saturated condition

When a gas holds the maximum amount of vapor it is said to be in a saturated state. The partial pressure of the water vapor at saturated conditions can be found in a standard steam table or by using mathematical models such as (Treybal, 1980):

$$\begin{aligned} \ln(P_{\text{water-sat}}) = & (-5674.53359/T) + 6.3925 \\ & - 0.9678 \times 10^{-2}T + 0.6222 \\ & \times 10^{-6}T^2 + 0.2075 \times 10^{-8}T^3 \\ & + 0.9484 \times 10^{-12}T^4 + 4.1635\ln(T) \end{aligned} \tag{18}$$

for a temperature range of –100 to 0°C, with  $T$  in K, and  $P_{\text{water-sat}}$  in Pascals (Pa):

$$\begin{aligned} \ln(P_{\text{water-sat}}) = & (-5800.2206/T) + 1.3915 \\ & - 0.0486T + 0.4176 \times 10^{-4}T^2 \\ & - 0.1445 \times 10^{-7}T^3 + 6.546\ln(T) \end{aligned} \tag{19}$$

for a temperature range of 0–200°C.

The moisture content at saturation,  $W_{\text{sat}}$ , can be described by (Treybal, 1980):

$$W_{\text{sat}} = 0.621 \frac{P_{\text{water-sat}}}{(1.0133E5 - P_{\text{water-sat}})} \tag{20}$$

Notice that Eq. (20) also applies to non-saturated conditions ranging from zero to saturation. For the non-saturated state, the term  $P_{\text{water-sat}}$  is replaced by the partial pressure of water ( $P_{\text{water}}$ ). Eq. (20) can be expressed as a function of the mole fraction of water and air (Treybal, 1980):

$$W_{\text{sat}} = 0.621 \frac{X_{\text{water}}}{X_{\text{air}}} \tag{21}$$

4.9. Adiabatic saturation temperature

Liquid water at temperature  $T_{\text{sat}}$  recirculated through an adiabatic chamber is said to be at adiabatic saturation temperature when an entering gas at temperature  $T$  and humidity  $W$  is saturated at temperature  $T_{\text{sat}}$  and humidity  $W_{\text{sat}}$ . The enthalpy balance over the chamber (Fig. 3) can be expressed as follows:

$$C_S(T - T_0) + W\lambda_0 = C_S(T_{\text{sat}} - T_0) + W_{\text{sat}}\lambda_0, \tag{22}$$

where  $C_S$  is the humid heat,  $T_0$  the reference temperature of 0°C, and  $\lambda_0$  the latent heat of water (2501.4 kJ/kg of water). Eq. (22) can be rearranged by using Eq. (16) as follows:

$$\frac{(W - W_{\text{sat}})}{(T_{\text{sat}} - T)} = \frac{(1.005 + 1.884W)}{2501.4} \tag{23}$$

4.10. Wet bulb temperature

The adiabatic saturation temperature is attained when large amounts of water come in contact with the entering gas. When a small amount of water is exposed to a continuous stream of gas under an adiabatic condition, it reaches a steady-state non-equilibrium temperature known as the wet bulb temperature.

The thermodynamic wet bulb temperature can be formally defined as the temperature  $T_{\text{wb}}$  at which, water, by evaporating into moist air at a given dry bulb tem-

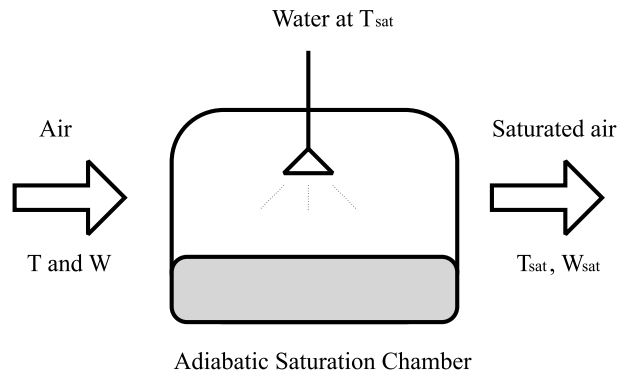


Fig. 3. Adiabatic saturation chamber (adapted from Geankoplis, 1983).

perature  $T$  and moisture content  $W$ , can bring the air to saturation adiabatically, while constant pressure is maintained. The latent heat required for evaporation will be supplied at the expense of the liquids sensible heat, as the temperature of the liquid decreases. The heat and mass balance can be used to describe the wet bulb temperature as follows:

$$q_t = q_s + N_{\text{water}}\lambda_{\text{water}} + N_{\text{air}}\lambda_{\text{air}}, \quad (24)$$

where  $q_t$  is the total heat transfer,  $N_{\text{air}}$  the air mass flux,  $q_s$  the sensible heat transfer flux, and  $N_{\text{water}}$  the water vapor mass flux. The quantities  $q_s$  and  $N_{\text{water}}$  can be expressed as:

$$q_s = h_{\text{air}}(T_{\text{air}} - T_{\text{wb}}), \quad (25)$$

$$N_{\text{water}} = k_{\text{air}}(P_{\text{water-T}} - P_{\text{water-wb}}), \quad (26)$$

while  $q_t$  and  $N_{\text{air}}$  are zero. Incorporating Eqs. (25) and (26) into Eq. (24) yields:

$$T_{\text{wb}} = T_{\text{air}} - \frac{\lambda_{\text{water}}(W_{\text{wb}} - W_T)(M_{\text{air}}P_{\text{air}}k_{\text{air}})}{h_{\text{air}}}, \quad (27)$$

where  $h_{\text{air}}$  and  $k_{\text{air}}$  are the convective heat transfer and gas-phase mass transfer coefficients of the air, respectively. The ratio

$$\frac{h_{\text{air}}}{M_{\text{air}}P_{\text{air}}k_{\text{air}}}$$

is reported to be 950 N m/kg K for the air–water vapor system (Treybal, 1980).

The wet bulb temperature is similar to the adiabatic saturation temperature, but with the replacement of  $C_s$  by the ratio

$$\frac{h_{\text{air}}}{M_{\text{air}}P_{\text{air}}k_{\text{air}}}.$$

For many practical purposes, the adiabatic saturation curves of the psychrometric chart can be used instead of Eq. (27).

Wet bulb temperature is determined with a thermometer on which the bulb has been covered with a wet cloth. The thermometer is immersed in a rapidly moving stream of air, and the temperature will reach a value lower than the dry bulb temperature if the latter is unsaturated.

The state of a given air–water mixture is commonly specified by the wet bulb temperature and dry bulb temperature. Properties such as dew point, humidity ratio, relative humidity, and enthalpy can be evaluated using the dry bulb and wet bulb temperatures from the psychrometric chart.

The heat transfer to or from the air may result in a change in the dry bulb temperature of the mixture. A change in the humidity conditions may also occur as a result of latent heat added or removed from the mixture. The quantity of heat added or removed may be obtained by the difference in enthalpy between the initial and final

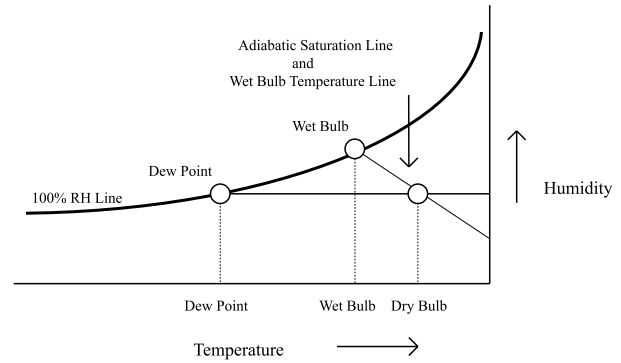


Fig. 4. Representation of moist air properties in the psychrometric chart (Barbosa-Cánovas & Vega-Mercado, 1996).

conditions, while the amount of water added or removed may be calculated by differences between the humidity ratios before and after the process. Note that when the saturation line is reached the air is not able to retain or absorb more water and the process moves along the saturation line. The case of cooling air below its dew point is an example of water leaving the mixture as a condensate while the saturation condition is reached. The concepts, dew point, dry bulb temperature, wet bulb temperature, and adiabatic saturation line, are summarized in Fig. 4.

It is also possible to use interactive spreadsheets to calculate air–water properties consistent with ASHRAE psychrometric information. Linric Company (1999), a software developer and engineering services company for the Heating, Ventilation and Air Conditioning (HVAC) industry, developed a psychrometric calculation and psychrometric property software tool, that is available for free to universities and colleges.

Software such as “PsyCalc 98” contains climatic design data for 1456 locations all over the world and is great for making comparisons to test given designs. By plugging in two psychrometric properties it is capable to calculate eight more including: dry bulb temperature, wet bulb temperature, percent relative humidity, dew point, humidity ratio, enthalpy, vapor pressure, specific volume, PPM by weight, PPM by volume, and absolute humidity (Fig. 5). One can choose between English (I-P) or metric (SI) units or convert to/from either one. In addition it can perform mixing calculations using standard or actual airflow (Fig. 6), thus shows promise as an excellent tool for food dehydration in this new century.

## 5. Dehydration methods

Drying technology has evolved from the simple use of solar energy to current technology that includes, among others, kiln drying, tray drying, tunnel drying, spray

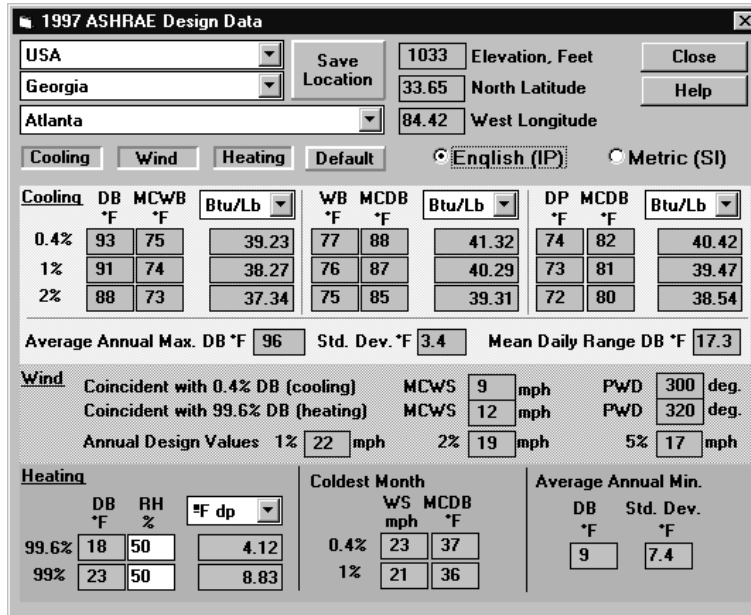


Fig. 5. Psychrometric calculations using PsiCal 98 (courtesy of Linric Company, 1999).

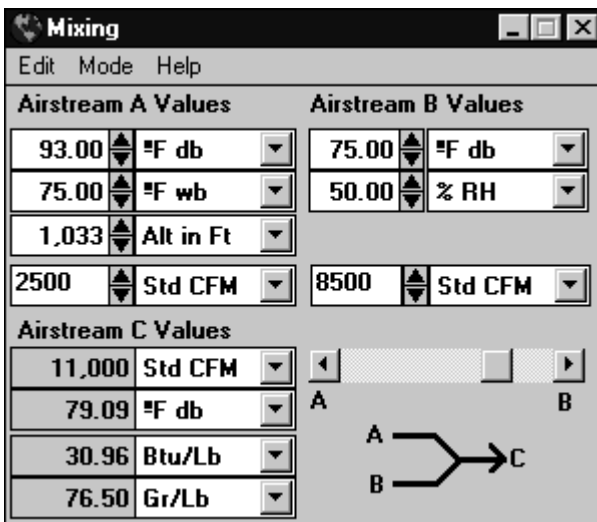


Fig. 6. Air stream properties using PsiCal 98 (courtesy of Linric Company, 1999).

drying, drum drying, freeze dehydration, osmotic dehydration, extrusion, fluidization, and the use of microwaves, radio frequency (RF), refractance window®, and hurdle technology. The development of dehydration technology can be divided in four groups or generations.

5.1. First generation

Cabinet and bed type dryers (i.e., kiln, tray, truck tray, rotary flow conveyor, tunnel) fall into this generation. This type of dryer involves hot air flowing over an extensive area of the product to remove water from the surface. Dryers in this category are mostly suitable for

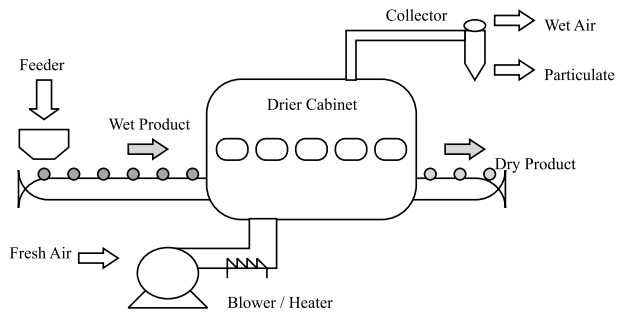


Fig. 7. Configuration of a cabinet air dryer (Barbosa-Cánovas & Vega-Mercado, 1996).

solid materials such as grains, sliced fruits and vegetables, or chunked products. The food industry uses this type of dryer in a variety of processes of which several commercial alternatives are available.

The basic configuration of a dryer comprises a feeder, a heater, and a collector, and the final arrangement of these components is characteristic for each dryer type. Fig. 7 presents a basic scheme for a dryer.

Fig. 8 shows three process plants developed by Sandvik Process Systems (1996) for dried apples, dried parsley, and dried raisins. Meanwhile, Fig. 9 shows a picture of existing pre-dryer and dryer modular designs from Sandvik Process Systems.

Fig. 10 shows one example of a dryer from Wenger Mfg. The system is designed and sized for customer-specific product applications and capacity requirements.

Recently, Wenger Mfg. introduced the Wenger TrueTemp dryer which takes advantage of isolated temperature and air flow conditions on each pass inside the dryer. The Wenger Series VII design allows floors to

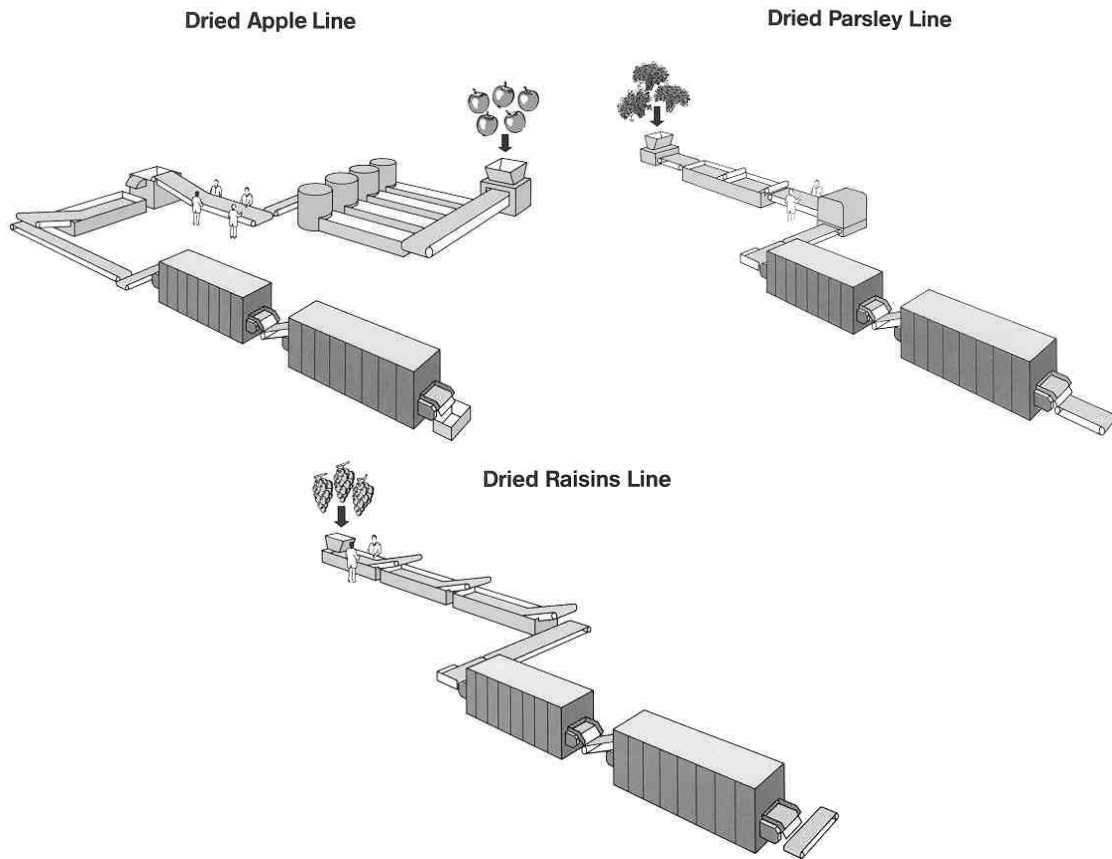


Fig. 8. Example of process plants for dried apples, dried parsley, and dried raisins (courtesy of Sandvik Process Systems, 1996).



Fig. 9. Pre-dryer and dryer modular design (courtesy of Sandvik Process Systems, 1996).

be added between the conveyor passes. The concept has been used in drying snack pellets and was recently introduced in the drying of fruits and vegetables (Clark & Butler, 1999). The Wenger Series VII is available with up to four passes, which results in a very controlled

drying process as stated by Clark and Butler (1999). Fig. 11 shows several schematics (courtesy of Wenger Online, 2000), describing the *Wenger Series VII Dryer*.

The manufacturer uses a modular design to optimize drying efficiency, provide precise temperature control,

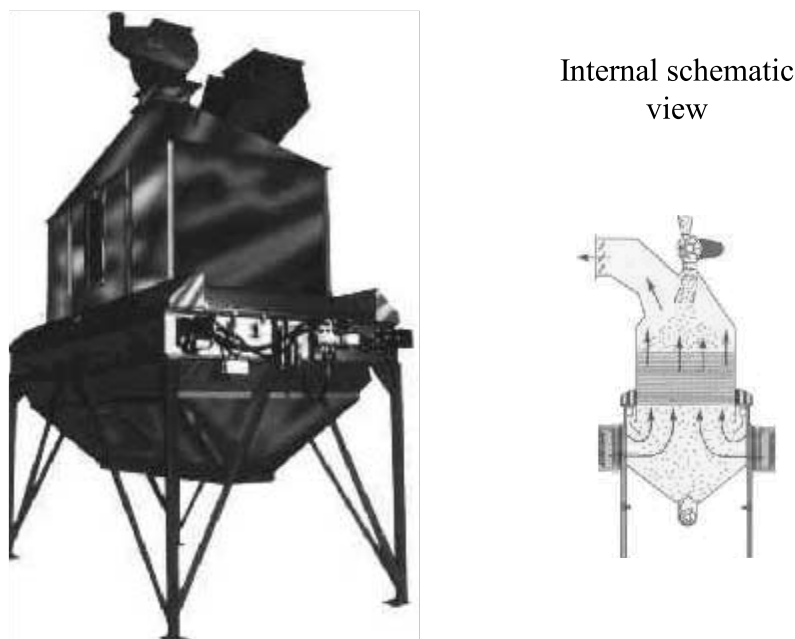


Fig. 10. Wenger true temp dryer (courtesy of Wenger Mfg., Inc, Sabetha, KS., 2000).

reduce installation time, and facilitate future expansions. An example of a commercially available conveyor band dryer for breakfast cereal is shown in Fig. 12.

Wyssmont Co. Online (2000) has developed a dryer that consists of a stack of slowly rotating circular trays known as the Turbo Dryer<sup>®</sup>. The unit feeds the product onto the top tray, which is then swept onto the next lower tray every revolution. The trays are contained in an enclosure in which heated air or gas is circulated by internal fans. Fig. 13 shows the Turbo-Dryer<sup>®</sup> unit developed by Wyssmont.

### 5.2. Second generation

Second-generation dryers are more dedicated to the dehydration of slurries and purees. Among these are the spray dryers and drum dryers intended for dehydrated powders and flakes.

Spray drying involves both particle formation and drying, which makes it a special type of drying process. The feed is transformed from a fluid state into droplets and then into dried particles by spraying it continuously into a hot drying medium. Similar to fluid bed drying, flash drying, spray granulation, spray agglomeration, spray reaction, spray cooling, and spray absorption, spray drying is a suspended particle processing operation (Masters, 1991). The main differences between spray drying, fluidized bed drying and flash drying are in the feed characteristics (fluid in spray drying versus solids): residence time (5–100 s for spray drying versus 1–300 min for fluidized bed) and particle size (10–500  $\mu\text{m}$  for spray drying versus 10–3000  $\mu\text{m}$  for fluidized bed).

The most common spray dryer is the open cycle, co-current unit illustrated in Fig. 14 (Dittman & Cook, 1977; Masters, 1991; Shaw, 1994). Open cycle systems have an intake of atmospheric air on a continuous basis. The air is heated, used as a drying medium, cleaned by means of cyclones and scrubbers, and then released again into the environment. This type of operation results in the wasting of heat contained in the exhaust air. A second type is the closed loop in which the heating medium (air,  $\text{CO}_2$ , etc.) is heated, used in the drying process, then cleaned, dried, and reused again on a continuous basis. The energy efficiency of this type is higher than in the open loop systems. Closed loop systems are more environmentally sound because the only output is the dried product, whereas open loop systems release hot air and sometimes microparticulates.

Spray drying involves the atomization of the feed into a drying medium, resulting in moisture evaporation. The drying proceeds until the desired moisture level in the product is reached. The drying is controlled by means of the product and air input conditions (flow and temperature). Finally, the product is recovered from the air.

The advantages of spray drying include the following (Masters, 1991):

- Powder specifications remain constant throughout the dryer when drying conditions are held constant.
- It is a continuous and easy drying operation and adaptable to full automatic control.
- A wide range of dryer designs are available that are applicable to heat-sensitive materials, heat-resistant materials, corrosives, and abrasives.



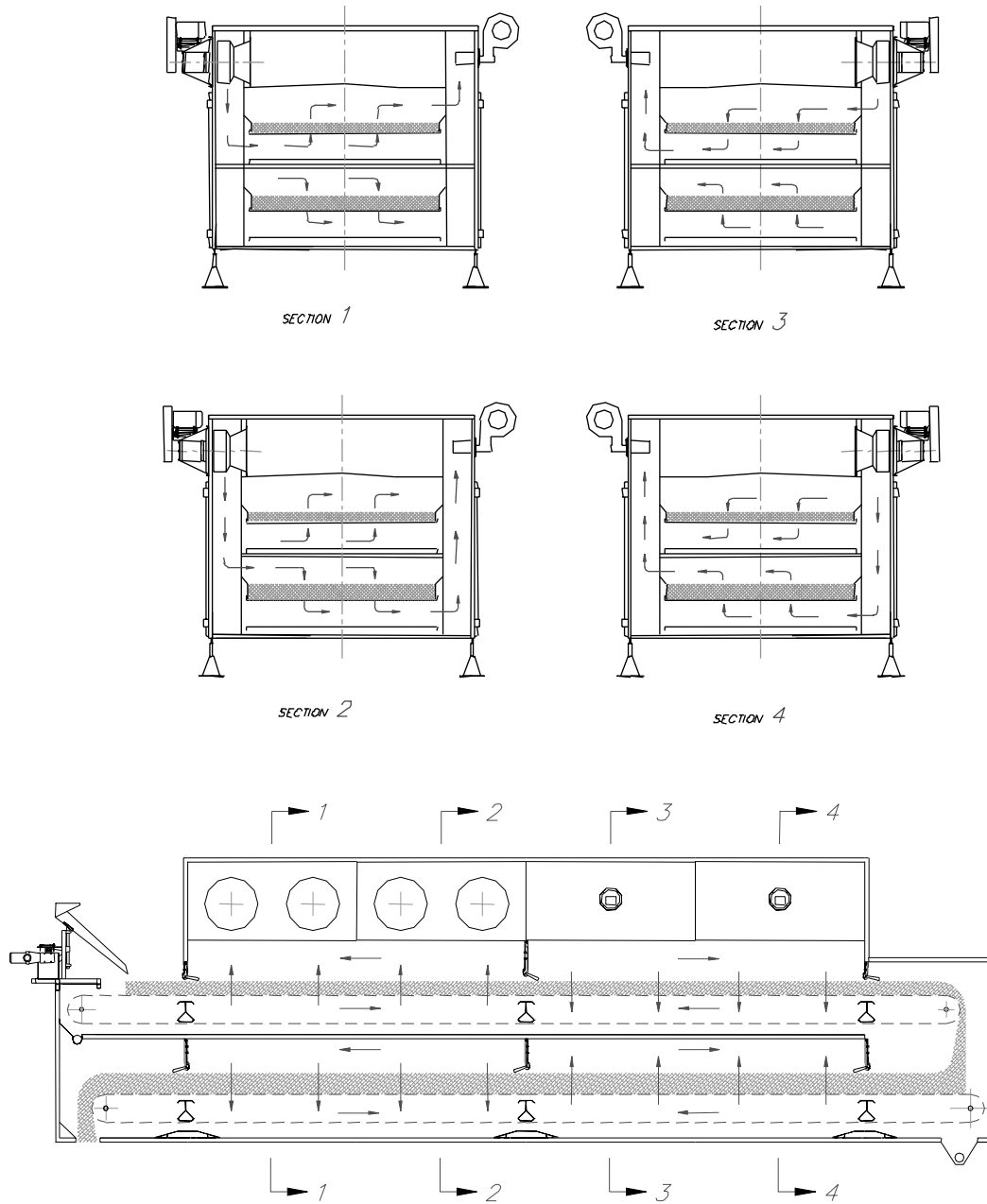


Fig. 11. Wenger *TrueTemp* Dryer Series VII (courtesy of Wenger Mfg., Inc, Sabetha, KS., 2000).



Fig. 12. Conveyor band dryer for breakfast cereal (courtesy of Mitchell Dryers, 2000).

The two main features of spray drying are: (a) the formation of droplets or spray and (b) the contact with air. The atomization step produces a spray for optimum evaporation conditions and, subsequently, a product within specifications. Atomization results from the breakdown of liquid bulk into small droplets, and the different atomization techniques available vary according to the type of energy used to produce the droplets. The classification of atomizers used in spray drying is summarized in Fig. 15. Movement of the spray is classified according to the dryer layout as co-current, counter-current, or mixed flow as shown in Fig. 16. The spray movement can be explained with reference to a

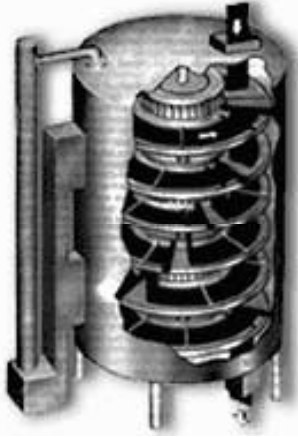


Fig. 13. Turbo-Dryer® from Wyssmont (courtesy of Wyssmont Co. Online, 2000).

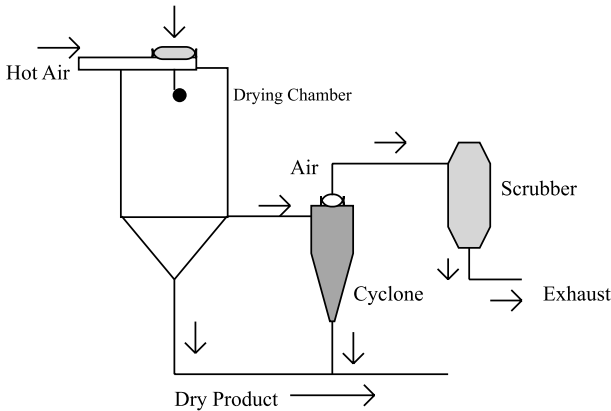


Fig. 14. Open cycle, co-current spray drying layout (adapted from Dittman & Cook, 1977).

single droplet. Masters (1991) discusses in more detail the movement of spray under different flow conditions. The temperature profile within a spray dryer is another important aspect, which is a function of the flow pattern, as shown in Fig. 17.

The shape characteristics of spray-dried products depend on whether the drying air temperature is above or below the boiling point of the droplets, as shown in Fig. 18. Particles can be porous and rigid, rigid with fractures, pliable, non-porous plastic, and spongelike, among others.

The bulk density of a spray-dried product can be increased with: (1) increase in the feed rate, (2) increase in temperature of difficult atomizable products, (3) increase in temperature of the powder, (4) increase in solid content, (5) increase in the outlet air temperature, (7) atomization through a rotary atomizer, and (8) use of counter-current configuration. Meanwhile, the bulk density will decrease with: (1) increase in temperature of easy atomizable feed, (2) increase in inlet air temperature, (3) coarse homogeneous particle size atomization, (4) feed aeration and (5) the use of co-current configuration.

Drum dryers conduct an indirect heat transfer through a solid surface, they are generally used to produce powdered and flaked ingredients. Drum dried products are widely used in bakery goods, beverages, cereal, granola, and dairy foods.

The dryers consist of hollow metal cylinders that rotate on horizontal axes while heated internally by steam, hot water, or other heating medium. Drum dryers can be classified as single drum or twin drum. An important aspect considered when using a drum dryer is the uniform thickness of the film applied to the drum surface. Also, the speed of rotation and heating temperature should be considered in the analysis. All of these factors affect the drying rate of the dryer. The main advantages of drum drying include high drying rates and economic use of heat. R. Simon (Dryers) Ltd. (2000) has developed different types of drum dryers, commercially available drum dryers configurations are shown in Fig. 19.

5.3. Third generation

Freeze dehydration and osmotic dehydration fall into this generation of drying technology. While freeze dehydration was developed to overcome structural damages and minimize losses of flavor and aroma compounds (Karel, 1975; Dalgleish, 1990), osmotic dehydration (Raoult-Wack, Lafont, Ríos, & Guilbert, 1989) is mainly intended for processing fruits and vegetables by immersion in a hypertonic solution (i.e., sugar, salt, glycerol).

5.3.1. Freeze dehydration

The freeze-drying process consists mainly of two steps: (1) the product is frozen, and (2) the product is

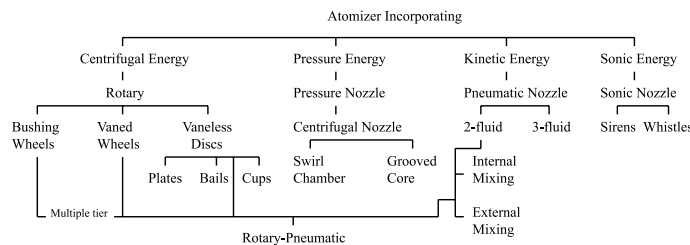


Fig. 15. Classification of atomizers (adapted from Masters, 1991).

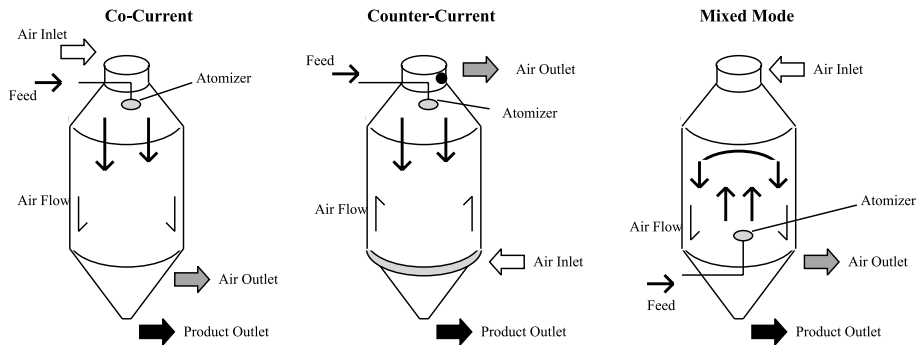
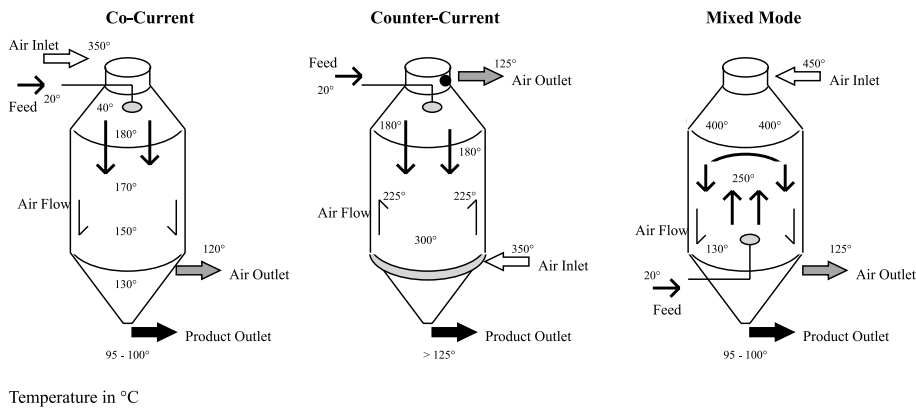


Fig. 16. Classification of dryers according to spray movement (adapted from Heldman & Singh, 1981; Masters, 1991; Shaw, 1994).



Temperature in °C

Fig. 17. Temperature profiles in spray dryers (adapted from Masters, 1991).

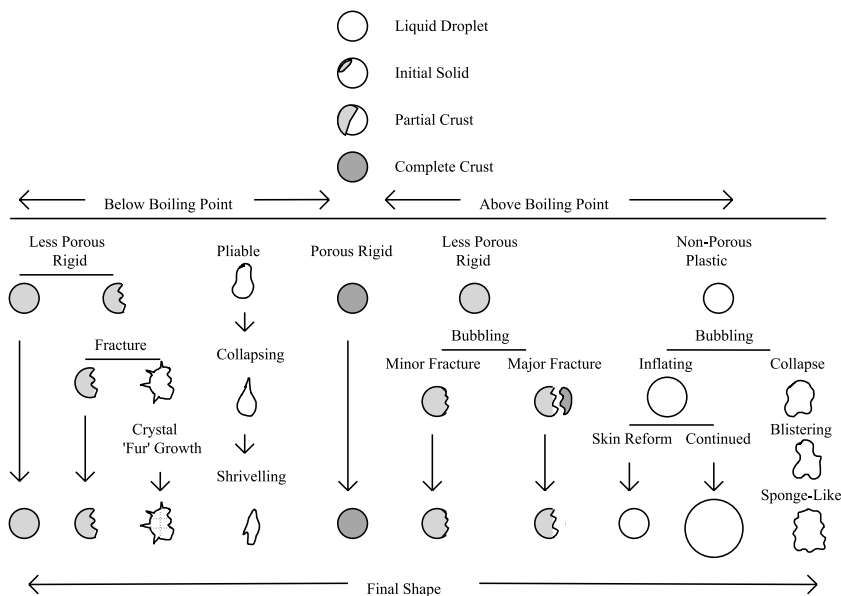


Fig. 18. Characteristics of droplets undergoing drying (adapted from Charlesworth & Marshall, 1960, reproduced with permission of the American Institute of Chemical Engineers© 1960 AIChE. All rights reserved).

dried by direct sublimation of the ice under reduced pressure. Freeze-drying, or lyophilization, was initially introduced in the 1940s on a large scale for the production of dry plasma and blood products (Rey,

1975). Later, antibiotics and biological materials were prepared on an industrial scale by freeze-drying. Fig. 20 shows the basic configuration of a freeze drying system.

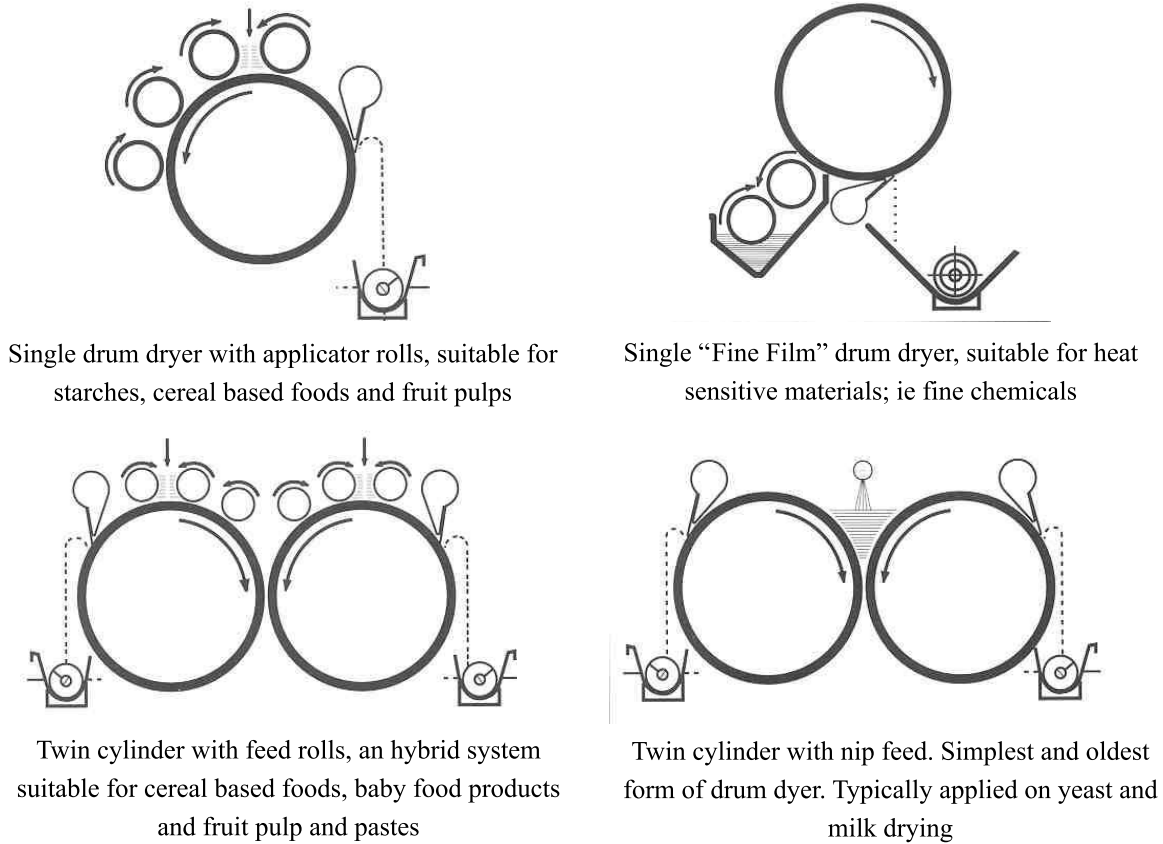


Fig. 19. Drum dryers (reproduced with permission of R. Simon (Dryers) Ltd., Nottingham, England, 2000).

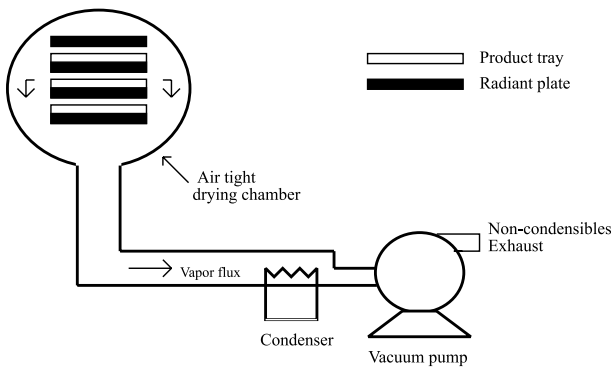


Fig. 20. Basic freeze drying system (adapted from Liapis & Marchello, 1984).

Freeze drying has been shown to be an attractive method for extending the shelf life of foods (Ma & Arsem, 1982). The drying of food products in freeze-drying has two main characteristics (Longmore, 1971):

1. Virtual absence of air during processing: the low processing temperature and the absence of air prevent deterioration due to oxidation or chemical modification of the product.
2. Drying at temperatures lower than ambient temperature: Products that decompose or undergo changes in

structure, texture, appearance, and/or flavor as a consequence of high temperature can be dried under vacuum with minimum damage.

The process consists of two main stages: freezing and drying. Freezing must be very rapid to obtain a product with small ice crystals and in an amorphous state (Mellor, 1978). The drying process involves lowering the pressure to allow ice sublimation. Fig. 21 presents the

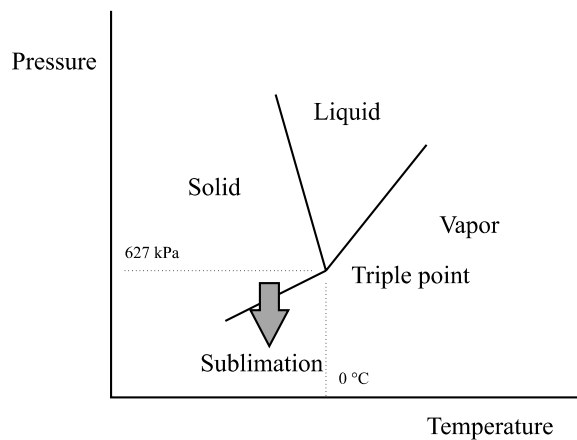


Fig. 21. Phase diagram of water (adapted from Karel, 1975).

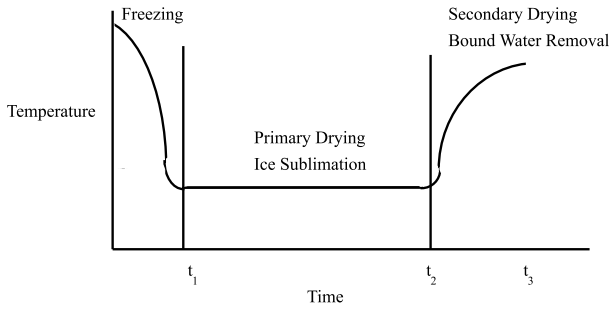


Fig. 22. Freeze drying steps (adapted from Mellor, 1978).

phase diagram of water, and Fig. 22 presents the freeze-drying steps.

Three important design variables for consideration in freeze-drying include: (1) vacuum inside the chamber, (2) radiant energy flux applied to the food, and (3) temperature of the condenser. The initial drying rate is high due to little resistance to either heat or mass flux. However, buildup of a resistive layer on the frozen material slows down the rate as the drying proceeds. The dry layer surrounding the product serves as an insulation material, affecting the heat transfer to the ice front. Also, the mass transfer from the ice front is reduced as thickness of the dry layer is increased. This is because of reduction in the diffusion process from the sublimation interface to the product surface.

5.3.2. Osmotic dehydration

The concentration of food products by means of product immersion in a hypertonic solution (i.e., sugar, salt, sorbitol or glycerol) is known as osmotic dehydration (Raoult-Wack et al., 1989), water removal in this process can be aided with the use of vacuum (Fito, 1994; Fito & Pastor, 1994). Osmotic dehydration systems consist mainly of a storage tank where the osmotic solution is prepared, followed by a pump to control the flow rate at the processing tank. The product is placed in the processing tank where the osmotic solution is pumped in at a constant rate. Fig. 23 summarizes the configuration of a typical osmotic dehydration system. An industrial application of osmotic dehydration is presented in Fig. 24, as discussed by Raoult-Wack et al. (1989).

5.4. Fourth generation

Dehydration technology, which involves high-vacuum, fluidization, and the use of microwaves, RF, refractance window, and the hurdle approach, represents the latest advance in this area of food processing. Each of these technologies has a specific application, based on the final quality attributes of the intended

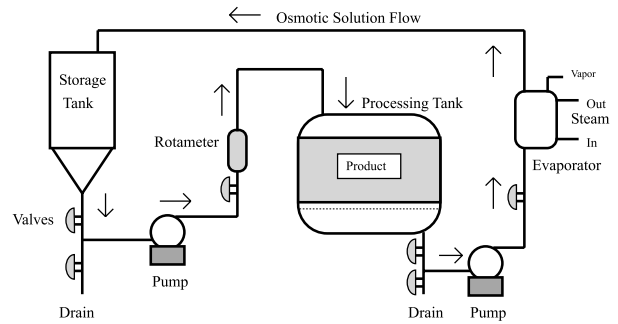


Fig. 23. Osmotic dehydration system (Barbosa-Cánovas & Vega-Mercado, 1996).

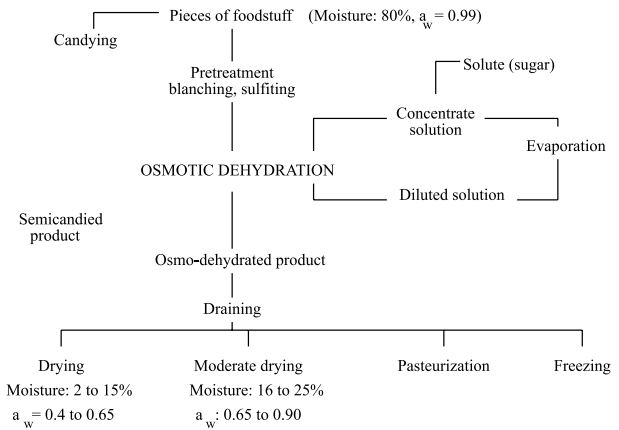


Fig. 24. Industrial application of osmotic dehydration (Raoult-Wack et al., 1989).

products, as well as the physical/chemical characteristics of the raw materials being processed. Microwaves and RF are of increased interest among food researchers and processors because of the energy saving possibilities they might represent.

5.4.1. Microwaves

Microwave heating/drying takes advantage of the polarization that takes place at molecular and atomic levels. The heat developed in a material by an alternating electromagnetic field results from the polarization process within the product when the molecules within the material rotate and move laterally millions of times per second in an attempt to align with the changing electric field. The heat dissipated in a product when exposed to an alternating electromagnetic field can be expressed as:

$$P = 1.41f \left( \frac{E}{d} \right)^2 \epsilon' \tan \delta \times 10^{12}, \tag{28}$$

where  $f$  is the frequency of the electromagnetic field,  $E$  the voltage,  $d$  the distance between the electrodes,  $\epsilon'$  the dielectric constant of the material,  $\tan \delta$  the loss tangent, and  $P$  the power in  $W/in^3$ .

There are three main frequencies available for microwave technology: (a) 915 MHz, used in certain cases due to technical complications; (b) 2.45 GHz, which is already used throughout the world in household microwave ovens; and (c) 28–30 GHz, not feasible on an industrial large scale, although it is a low-cost alternative. The arrangement of atoms in a water molecule makes it polar, and thus easy to heat using microwave.

Feng and Tang (1998, 1999) reported the advantages of combining hot air drying and microwaves in drying diced fruits (apples and blueberries). The laboratory scale system shown in Fig. 25 comprises a microwave power source operated at 2450 MHz, a cavity, hot air source, spouted bed, and water load. The amount of energy converted from microwave to thermal energy can be expressed as:

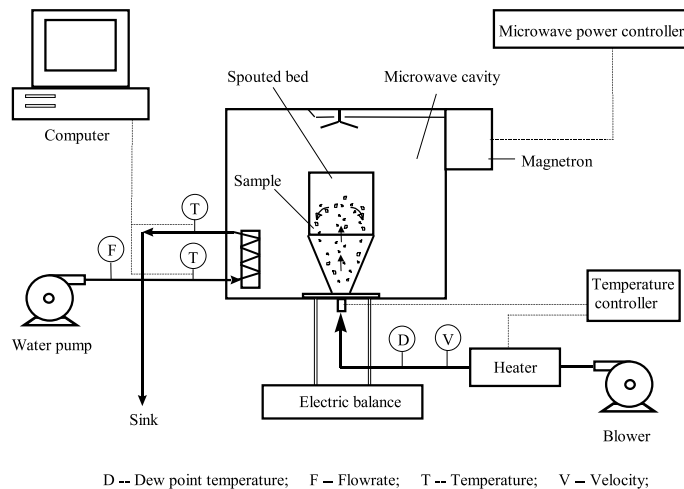
$$E_G = 5.56 \times 10^{-4} \times f \varepsilon'' E^2, \tag{29}$$

where  $E_G$  is the conversion of microwave energy into thermal energy ( $W/cm^3$ ),  $f$  the frequency (GHz),  $\varepsilon''$  the relative dielectric loss factor, and  $E$  the electric field (V/cm).

Several manufacturers report industrial applications of microwave heating. Pitt-Des Moines (2000) and the Dried Foods Technology Laboratory at California State University in Fresno have developed a research-type, pilot-scale system that converts a conventional air dryer into a state-of-the-art Microwave Vacuum Dryer (MIVAC®) for the preparation of dried food products. The system was originally designed to enlarge the market for California seedless grapes, developing the so-called puffy grape. Today this new process successfully dehydrates over 100 different fruits, vegetables, and other foods at temperatures below 130°F. The microwave/vacuum process occurs inside a 40-ft long stainless steel vessel under vacuum. The vessel contains a conveyor system, a microwave unit and a radiant

heat source (Fig. 26(a)–(c)). The microwave unit at Dried Food Technology Laboratory in California Sate University in Fresno, is capable of delivering a power of 18 kW at 2450 MHz or 30 kW at 915 MHz. The product being dehydrated is transported by a conveyor into the three drying zones of the vacuum microwave (Fig. 26(c)). Within the first zone the product is subjected to a high level of microwave energy and a vacuum of about 10–30 Torr. In the second zone the product is subjected to a moderate microwave level depending on the moisture content of the product. The finishing zone may or may not be accompanied by a low level of microwave energy to ensure equalization of the moisture content. In this zone the product is also cooled and transported by the conveyor system to the packaging operation.

Linn High Therm GmbH (2000) has developed drying systems using microwave energy. Figs. 27 and 28 present two examples of Linn High Therm GmbH patented pass-through microwave ovens of the MDBT series used for continuous drying. In these microwave belt furnaces systems, the microwave generators (magnetrons) are arranged in a spiral around the longitudinal axis of the cylinder chamber to achieve a more uniform distribution of the field. The conveyor belt is led over floor plates that are equipped with secondary radiators (slot antennae). These have the effect of concentrating the field. The inlets/outlets are lined with a special absorber material in order to comply with allowed values for leaked radiation. Depending on the size of the opening, further absorber zones may be integrated to effect a further radiation reduction. In the case of larger openings, additional absorber curtains are used. The magnetrons used are air-cooled, whereby the heated cooling air flows into the oven and can absorb moisture. The moist air is then drawn out of the oven by a suction system. This

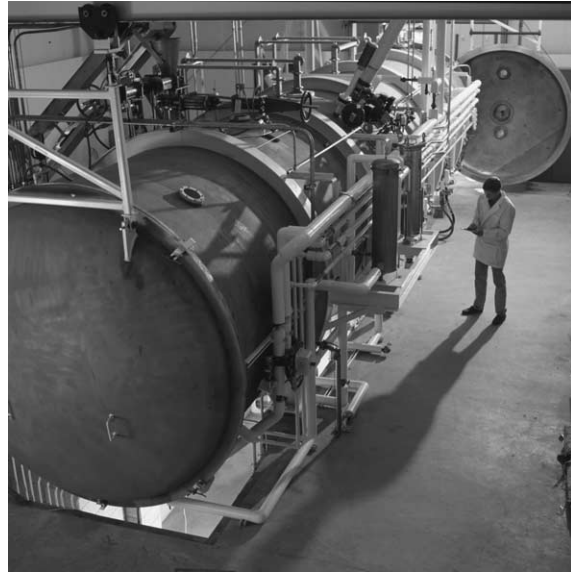


D -- Dew point temperature; F -- Flowrate; T -- Temperature; V -- Velocity;

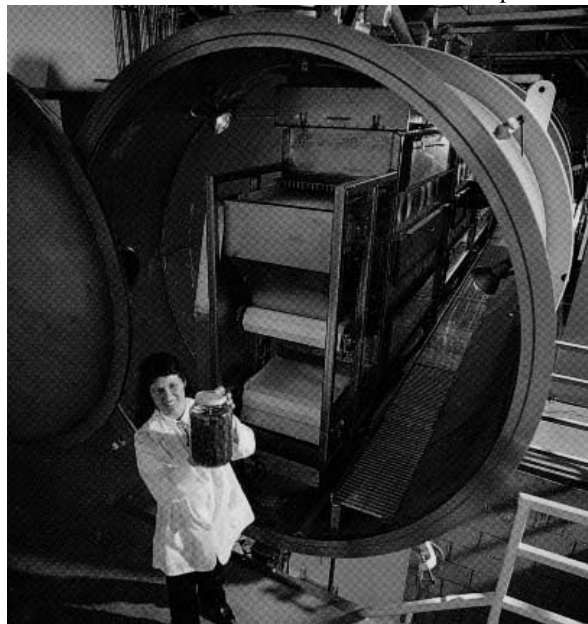
Fig. 25. Schematic of microwave and spouted bed drying system as developed by Feng et al. (1999).



a) MIVAC<sup>®</sup> power supply and feeding



b) 40 foot long MIVAC<sup>®</sup> microwave/vacuum processing system



c) Inside look of MIVAC<sup>®</sup> microwave and conveyor system

Fig. 26. 40-ft long microwave/vacuum MIVAC<sup>®</sup> processing system constructed by Pitt-Des Moines, Inc. (reproduced by permission of the Boeing Company, Pitt-Des Moines, Inc. and Dried Food Technology Laboratory, California State University Fresno, 2000).

passthrough microwave oven can be fitted with a microwave output of: <100 kW.

Industrial Microwave Systems (2000) developed the cylindrical reactor shown in Fig. 29. The system was designed with the focus on wave distribution and geometry to accommodate thermal processing and accurate target temperature control. Their applications for this system have been with highly viscous and high nu-

trient load fluids, in which case, the accurate target temperature control reduces nutrient degradation.

The use of microwaves is not limited to industrial drying operations. Processes such as baking, concentration, cooking, curing, enzyme inactivation (blanching), pasteurizing, precooking, puffing and foaming, solvent removal, moisture leveling, and thawing-tempering are also feasible using microwaves.



Fig. 27. Continuous microwave belt furnace 15 m and 60 kW (courtesy of Linn High Therm GmbH, 2000).

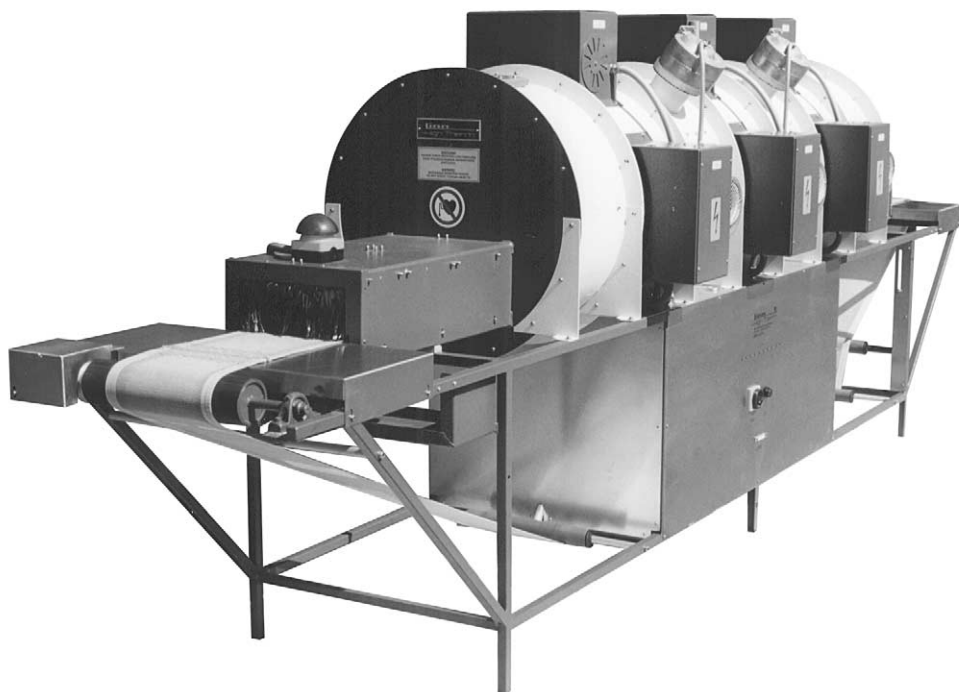


Fig. 28. Continuous microwave belt furnace 4.5 m and 8 kW (courtesy of Linn High Therm GmbH, 2000).

#### 5.4.2. Radio frequency

Radio frequency is being used for precooking, sterilization, tempering, and baking processes in the food industry. Similar to microwaves, RF uses electromagnetic energy to heat products with exceptional results in terms of time cycle and efficiency. Unlike conventional

conduction, convection, and radiant methods that depend on the heat transfer capability of the product, dielectric heating occurs instantly inside the product. Heating is more effective since the process does not depend on a temperature gradient. Radio frequency electromagnetic waves cover the frequency spectrum from



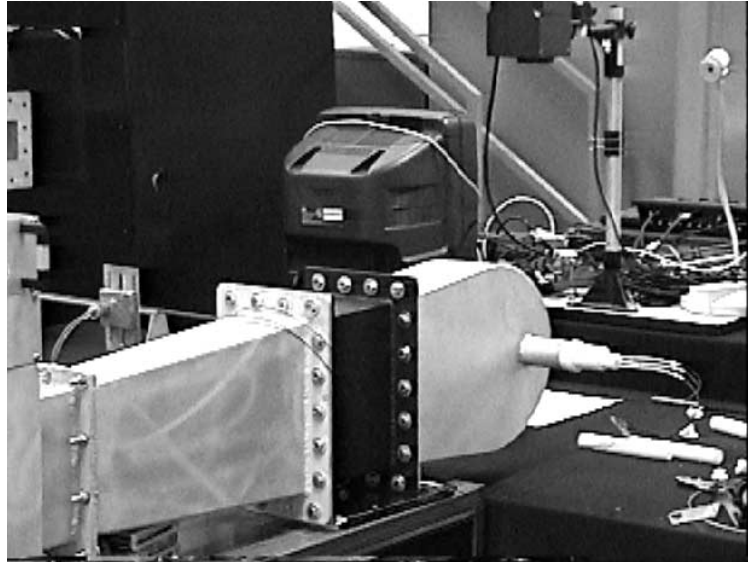


Fig. 29. Cylindrical reactor from Industrial Microwave Systems (courtesy of Industrial Microwave Systems, 2000).

30 to 300 MHz. Microwaves and RF technologies, affect materials differently and require different equipment. RF energy mainly acts through the electrical conductivity of the material, so the presence of ionic species (e.g., dissolved salts) tends to make materials good heating candidates, therefore RF generally heats more uniformly than microwave. Also RF energy is less expensive per kilowatt than microwaves; RF generator capacities range from a kilowatt to hundreds of kilowatts. RF heating has been used for commercial applications since World War II.

PSC-Power Systems (1999) has developed RF applications with the following benefits: (a) increased heating and processing speed, (b) improved product quality and yields because drying action is more uniform and often self-limiting, (c) usage of only 1/3 the floor space of conventional heating units, (d) instant on/off and temperature change, (e) amenable to automation and process control, (f) high energy efficiency – 60–70% compared with 10–30% for conventional units. Figs. 30 and 31 show some of the dryers developed by PSC-Power Systems.

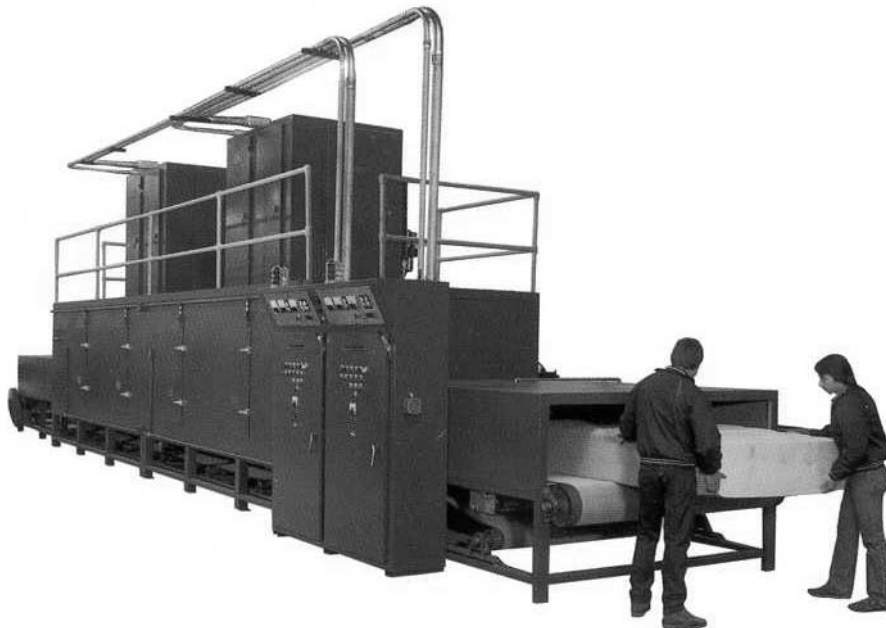


Fig. 30. PSC 200 kW dryer (courtesy of PSC-Power Systems, 1999).

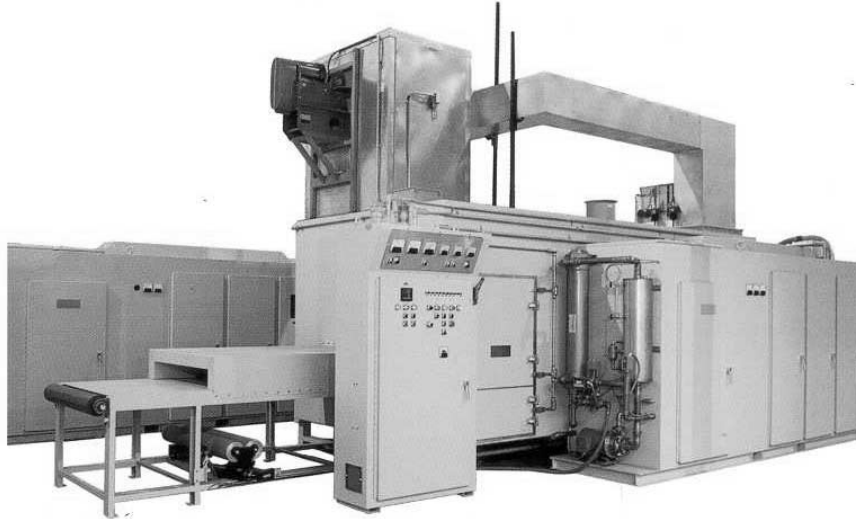


Fig. 31. PSC 200 kW hybrid/convection dryer (courtesy of PSC-Power Systems, 1999).

5.4.3. Refractance window

This is a new technology introduced by MCD Technologies (2000) in which water is used to transmit heat into the product being dried. The product is evenly ap-

plied to the surface of a conveyor belt (a sheet of special plastic floating on hot water) and infrared heat passes directly through the membrane and into the product. In this technology all three methods of heat transfer, ra-

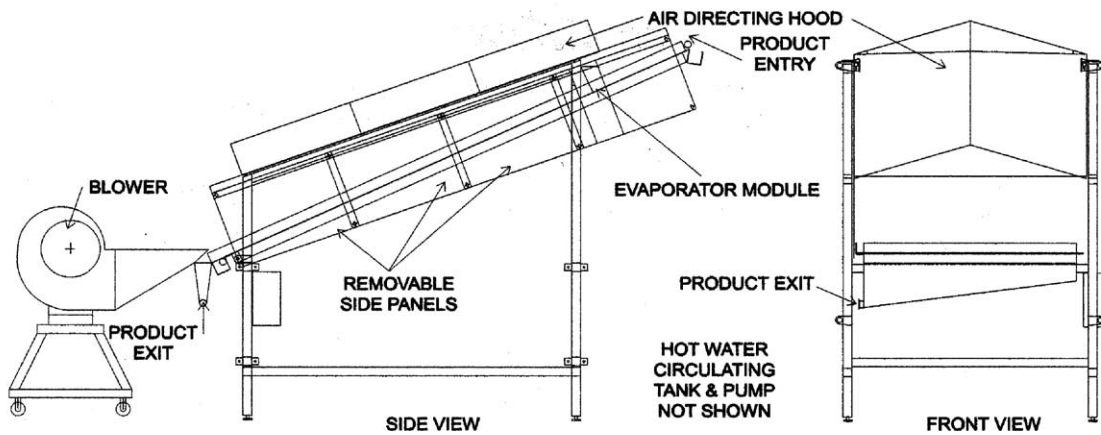
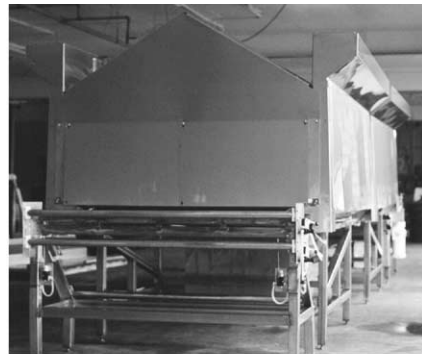


Fig. 32. Refractance Window® equipment (courtesy of MCD Technologies, 2000).

diation, conduction and convection occur for exceptionally effective heat transfer. However, as the material dries, the infrared “window” is closed since moisture no longer contacts the plastic, and the only heat transfer taking place is by conduction. Since plastic is a poor heat conductor, little heat is lost. This also causes the majority of infrared radiation to be bent back into the water, leaving only conducted heat as the drying means. Thus protecting the product by preventing color and flavor degradation. Furthermore Refractance Window™ drying, maintains product temperatures far below the temperature of the circulating water beneath the conveyor belt, also protecting products from oxidization. A broad variety of fruits, vegetables, meat, fish, poultry, eggs, flavorings, herbs and spices, dairy, cereals, starches and grains, as well as beverages products have been successfully dried by RW. Fig. 32 presents a photo and diagram of a refractance window prototype designed by MCD Technology.

## 6. Final remarks

Even though food dehydration is an old technique, due to technological advances in different fields, it is constantly evolving to offer better quality products and the development of new food products to satisfy the always increasing demand of novelty products. Since dehydration operations, in general, are very costly in terms of energy consumption, there is still a lot of room for improvements as shown in the section dealing with the fourth generation dryers. It is also very important to point out that the selection of the best drying technique is still determined by the type of product, its composition, and its physical properties.

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