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Drying and Dehydration Processes in Food Preservation and Processing

Panagiotis A. Michailidis and Magdalini K. Krokida

Laboratory of Process, Analysis and Design, School of Chemical Engineering, National Technical University of Athens, Zografou, Greece

1.1 Introduction

Drying is the removal of a liquid from a material (usually consisting of a macromolecules matrix) and is one of the most important and oldest unit operations used for thousand years in a variety of materials, such as wood, coal, paper, biomass, wastes and foods. According to Ratti (2001), drying generally refers to the removal of moisture from a substance. In the case of food materials, the application of drying aims to reduce the mass and usually the volume of the product, which makes their transportation, storage and packaging easier and more economic, but most important is their preservation and to increase their shelf-life. This is particularly important for seasonal foods, as they become available for a much longer period after drying. As water content decreases due to drying, the rate of quality deteriorating reactions decreases as well or is even suspended, leading to a product that is microbiologically steady.

Drying provides the most diversity among food engineering unit operations as there are literally hundreds of variants actually used in drying particulate solids, pastes, continuous sheets, slurries or solutions. Each drying method

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and the specific process parameters selected can cause undesirable effects on the product, including shrinkage, case hardening, change of the porosity and porous size distribution, colour change, browning, loss of aromatic compounds, reduction of nutrient and functional molecules, and others.

The most important and widespread drying methods are discussed in the present chapter. Emphasis has been paid on the presentation of the effects of each technique on the properties (structural, nutritional, quality) of the food undergoing drying.

1.2 Drying kinetics

A convenient way to express the reduction of moisture content of a material during drying is to use a drying kinetic equation, which expresses the moisture content or moisture ratio as a function of time. Several drying equations have been presented in the literature (Estürk, 2012). The simplest of them is the exponential model or Lewis equation, which includes a constant, known as the drying constant. This is a phenomenological coefficient of heat and mass transfer. Drying kinetics replace the complex mathematical models for the description of the simultaneous heat and mass transport phenomena in the internal layers of the drying material and at the interface with the surrounding space. It is a function of the material characteristics (physical properties, dimensions) and the drying environment properties, including temperature, humidity and velocity of air, chamber pressure, microwave power, ultrasound intensity and other factors depending on the drying method(s) used. The drying constant is determined experimentally in a pilot plant dryer based on drying experiments of the examined material under different values of the drying parameters.

1.3 Different drying processes

1.3.1 Hot-air drying

Hot-air (or conventional) drying (HAD) is one of the oldest, most common and simplest drying methods for dewatering of food materials. Thus, it is frequently used to extend the shelf life of food products. It is one of the most energy-consuming food preservation processes, but its main disadvantage focuses on the drastically reduced quality of the hot-air treated foods compared to the original foodstuff. High temperatures during HAD have a great influence on colour degradation and the physical structure of the product, such as the reduction in volume, decrease in porosity (shrinkage) and increase in stickiness. This phenomenon takes place when the solid matrix of the material can no longer support its own mass. The phenomena underlying HAD outline a complex process involving simultaneous mass and energy (mainly heat) transport in a hygroscopic and shrinking system. The solid to be dried is exposed to a continuously flowing hot stream of air or inert fluid (N_2, CO_2) where moisture evaporates as heat is transferred to the food (Ratti, 2001).

During drying, evaporation of water desiccates the solid matrix of the food material and increases the concentration of solubles in the remaining solution. Changes in pH, redox potential and solubility may affect the structure and functionality of biopolymers, while in the final stages of drying phase transitions may occur. Increased concentration of solubles can promote chemical and enzymatic reactions due to higher concentrations of reagents and catalysts. The removed water is, at least partially, replaced by air and the contact with oxygen is substantially increased (Lewicki, 2006). The mechanisms related to the water movement include capillary forces, diffusion due to concentration gradients, flow due to pressure gradients or to vaporization and condensation of water, diffusion of water vapour in the pores filled with air and diffusion on the surface.

One of the most common dryers for many applications, including air drying of food materials, is the conveyor belt dryer, which is depicted schematically in Figure 1.1. Dryers of this type usually consist of sections placed in series,

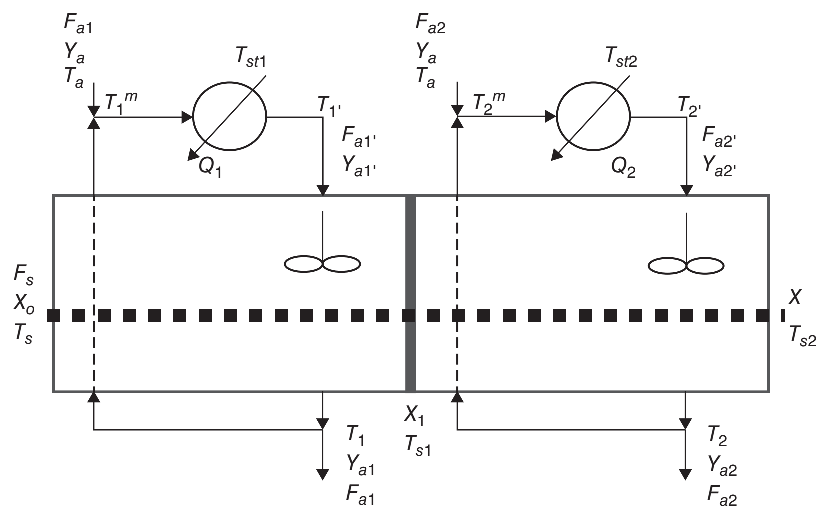

Figure 1.1 Representation of a one-section two-chamber conveyor belt dryer (F_s, dry solids feed flow rate; F_{ai}, dry air flow rate exiting chamber i after the splitter (this is equal to the fresh dry air flow rate entering chamber i, where $i = 1$, 2 in the case of the presented dryer), F_{ai}', dry air flow rate passing through chamber i; Q_i, heat duty in chamber i; T_s, initial solids temperature; T_{si}, solids temperature exiting chamber i; T_a, ambient air temperature; T_i, air temperature exiting chamber i; T_i', initial air temperature feeding in chamber i; T_i^m, air temperature after the mixing of recirculated and fresh air in chamber i; T_{sti}, steam temperature in the exchanger of chamber i; X_0, initial solids moisture content; X_1, solids moisture content exiting chamber 1; X, final solids moisture content; Y_a, ambient absolute humidity; Y_{ai}, absolute humidity of air exiting chamber i; Y_{ai}', absolute humidity of air feeding in chamber i)

each of which includes a certain number of chambers. The conveyor belt is common for all the chambers of a section. The properties of drying air such as temperature and velocity in each chamber can be adjusted independently from the rest of the section's chambers by means of a heat exchanger and fan installed in each chamber. Additionally, the air circulation is also independent in each chamber and through the mixing of recirculated and fresh air to the proper ratio achieves the desired properties such as that of the air humidity. The dryer presented in Figure 1.1 is a one-section two-chamber dryer.

1.3.2 Vacuum drying

Vacuum drying (VD) is an efficient technique for reducing moisture content of heat-sensitive materials that may be changed or damaged if exposed to high temperature. Characteristics of VD are the high drying rate due to the low vapour pressure in the drying environment, the low drying temperature as the boiling point of water reduces with a pressure drop, the oxygen-deficient drying environment and the reduction of energy consumption. These characteristics contribute to conservation of qualities such as colour, shape, aroma, flavour and nutritive value of the dried product (Šumić *et al.*, 2013) and induce degradation of nutritional compounds, oxidation of beneficial substances or formation of toxic compounds (Dueik, Marzullo and Bouchon, 2013). Due to molecular transport of evaporated water the process is long and can last up to 24 hours. Dry products are of very good quality but the shelf-life is dependent on the post-drying processes applied (Lewicki, 2006). VD is ideal in situations where a solvent must be recovered or when materials have to dry to very low levels of moisture.

Lee and Kim (2009) studied the drying kinetics of radish slices in a vacuum dryer at a pressure of 0.1 mPa. They observed the absence of a constant drying rate period. An increase in the drying temperature and a decrease in slice thickness caused a decrease in the drying time. The effective diffusivity varied from 6.92 to 14.59×10^{-9} m^2/s over the temperature range of 40–60 °C and followed an Arrhenius-type relationship.

Šumić *et al.* (2013) investigated VD of frozen sour cherries in order to optimize the preservation of health-beneficial phytochemicals, as well as the textural characteristics. The optimum conditions of ~54 °C and ~148 mbar were established for VD of the food material considering the maximum amount of total phenolics content, vitamin C, anthocyanin and maximum antioxidant activity and the minimum total colour change, a_w value and firmness of the product. Under optimal conditions, the value of the following quality indicators of dried sour cherry was predicted: total phenolics was 744 mg CAE (chlorogenic acid equivalents)/100 g dry weight (d.w.), vitamin C 1.44 mg/100 g d.w., anthocyanin content 125 mg/100 g d.w., antioxidant activity IC50 3.23 mg/ml, total solids 70.72%, water activity a_w value 0.65, total colour change 52.61 and firmness 3395.4 g.

1.3.3 Microwave drying

Microwave drying (MWD) results in the dewatering of a food material by heating it in a microwave oven using microwave energy, which is an electromagnetic radiation in the frequency range between 3 MHz and 30 000 GHz. The main factors affecting this method include sample mass, microwave power level and heating duration. Microwave heating of dielectric materials is governed by dipole rotation and ionic polarization. When a moist sample is exposed to microwave radiation, molecules such as H_2O carrying dipolar electrical charges rotate as they attempt to align their dipoles with the rapidly changing electric field. The resultant friction creates heat, which is transferred to neighbouring molecules. The internal temperature of a moist and microwave heated sample may reach the boiling point of water and the free moisture evaporates inside the product, causing a vapour pressure gradient that expels moisture from the sample. The internal temperature remains at boiling point until all free moisture is evaporated, followed by a rapid increase, which causes losses of volatiles, chemical reactions and eventual charring. One of the most important advantages of MWD is the reduction of drying time as heat is generated internally, resulting in a high rate of moisture removal. However, MWD possesses a few difficulties during application; these are uneven heating and underdrying or charring.

The food industry is now a major user of microwave energy, especially in the drying of pasta and post-baking of biscuits. The use of large-scale microwave processes is increasing and recent improvements in the design of high-powered microwave ovens has reduced equipment manufacturing costs. The operational cost is lower because energy is not consumed in heating the walls of the apparatus or the environment (Vadivambal and Jayas, 2007). A drawback with microwave heating is that there is no common method to monitor or control the electromagnetic field distribution and its effect after the microwave is switched on.

MWD affects most of the product properties. It has shown positive ratings for drying rate, flexibility, colour, flavour, nutritional value, microbial stability, enzyme inactivation, rehydration capacity, crispiness and a fresh-like appearance. The rehydration characteristics of microwave dried products are expected to be better as the outward flux of escaping vapour during drying contributes to the prevention of structure collapse. The quantum energy of microwaves is quite low and does not cause extensive chemical changes and thus helps in the retention of nutrient activity (Vadivambal and Jayas, 2007).

1.3.4 Freeze drying

The food material must be frozen and then subjected to dewatering by ice sublimation under very low pressure to conduct vacuum freeze drying, known simply as freeze drying (FD). FD is the result of three discrete stages:

1. Freezing stage. Initially, the product has to be frozen to achieve a solid structure that avoids collapse while the drying process is realized by sublimation. This stage has a great influence on the whole process because it sets the structure of the ice crystals (shape and size), which ultimately affects the heat and mass transfer rates. Attention needs to be devoted to the control of the uniformity of the cooling gas temperature (Hottot, Vessot and Andrieu, 2004).
2. First drying (sublimation) stage. Sublimation (solid ice transforms to water vapour without the conversion into liquid water) requires a large amount of energy (~2800 kJ/kg of ice). The heating of the frozen material generates a sublimation front that advances gradually inside the frozen solid and its temperature is practically constant. Mass transfer occurs by migration of the internal vapour through the solid's dry layer. Under the low temperature and with the absence of water transfer through the pores, the food matrix does not collapse and develops a significant porosity.
3. Second drying stage. This stage involves the removal of the unfrozen water by evaporation (desorption) and begins when the ice has already been removed by sublimation. The bound water is removed by heating the product under vacuum; as its removal is slower than the removal of free water it affects significantly the overall drying time. The heat supplied in this stage should be controlled because the structure of the solid matrix may undergo significant modification if the temperature of the product rises. The energy delivered to the solid can be supplied by conduction, convection and/or radiation (Voda *et al.*, 2012).

FD is a very versatile drying method but its cost is very high due to the need of freezing the raw materials and operating under high vacuum for dehydration (Claussen *et al.*, 2007; Ratti, 2001). A significant advantage of FD is the minimum change of most of the initial food material properties, such as structure, shape, appearance, texture, biological activity and nutrient compounds, and the retention of colour, flavour, aroma and taste. This is possible as the food is processed at low temperatures in the absence of air. Other advantages of FD include the ability of almost complete removal of water, the high porosity of the final product, which leads to a fast rehydration rate and high rehydration capacity, and the ability to convert the material to powder with low mechanical requirements (e.g. by adding it in an extrusion cooking feed mixture). Chemical (e.g. oxidation and modification) reactions and/or enzymatic reactions are significantly limited and vitamin degradation is reduced in comparison to classical drying techniques.

A major disadvantage of FD is the duration of the process (1 to 3 days). This is due to poor internal heat transfer inside the product and a low working pressure as the principal heat transfer phenomenon is radiation. Product characteristics, such as texture, degree of ripeness and dry matter content, and processing conditions, such as loading density, height of the product layer, specific surface of the product and condenser capacity, are variables that have a considerable effect on the FD time, but they are also essential for the rehydration ratio and texture of the final product (Hammami and René, 1997).

FD is applicable to pharmaceuticals, biotechnology products, enzymes, nutraceuticals and other high value and quality materials. In food industry, it is restricted to high value-added products, such as coffee, tea and infusions, ingredients for ready-to-eat foods (vegetables, pasta, meat, fish, etc.) and several aromatic herbs.

Hammami and René (1997) studied the production of high-quality freeze-dried strawberry pieces. A working pressure of 30 Pa and heating plate temperature of 50 °C were the optimal conditions used to maximize the final product quality, including appearance, shape, colour, texture and rehydration ratio. Voda *et al.* (2012) investigated the impact of FD, blanching pre-treatment and freezing rate on the microstructure and rehydration properties of winter carrots by μCT (micro-computed tomography), SEM (scanning electron microscopy), MRI (magnetic resonance imaging) and NMR (nuclear magnetic resonance) techniques. It was concluded that the freezing rate determines the size of ice crystals being formed, which leave pores upon drying. The samples frozen at a lower temperature showed smaller pores as the ice crystals are expected to grow less under fast cooling conditions. During freezing, the growth of an ice crystal ruptures, pushes and compresses cells and this damage is more pronounced in slowly frozen tissue, which yields bigger ice crystals.

Duan, Ren and Zhu (2012) developed a microwave freeze drying (MFD) technique to dry apple slices. Nevertheless, MFD is a very sensitive procedure due to the inherently nonuniform distribution of the microwave field, which leads to an uneven temperature distribution in the drying material, leading to overheating and quality deterioration. Based on the dielectric properties of the material, a changed microwave loading scheme could lead to perfect product quality and greatly reduce the drying time. MFD took ~6 hours of processing time, which was ~60% less than that for conventional FD.

1.3.5 Spray drying

Spray drying (SD) is a special process used to transform a feed from a liquid state to a dried particulate form by spraying the feed into a hot drying medium. The feed can either be a solution, suspension, emulsion or paste. Different types of food materials can be produced, such as powders, granules and agglomerates at different sizes. In the SD process, the fluid is atomized using a rotating disc or a nozzle and the spray of droplets comes immediately in contact with a flow of hot drying medium, usually air. During evaporation from a small liquid droplet, moving through the turbulent body of hot fluid under the influence of gravity and its own initial kinetic energy, a complicated function of simultaneous conduction and convection of heat from the fluid to the droplet surface, and diffusion and convection of water vapour back into the body of fluid take place. The boundary layer is separated by the interaction of the fluid with the droplet surface; its shape changes rapidly and the solute in the droplet becomes concentrated and finally solid. The rapid evaporation maintains a low droplet temperature so that a high drying air temperature can be applied without affecting the quality of the product. The drying process may last only a few seconds. The low product temperature and short drying time allow SD to process extremely heat-sensitive materials. The process is continuous and easy to be controlled, and satisfies aseptic/hygienic drying conditions. Disadvantages of the method are the relatively high cost, the low thermal efficiency and the large air volumes at low product hold-up. SD is used in the production of coffee, tea extract, tomato paste, powdered cheese eggs, enzymes (amylase used in baking and brewing, protease used in brewing, meat and fish tenderizing and cheese making, glucose oxidase used in carbonated beverages, pectinase used in coffee fermentation and juice clarification, rennin used in cheese making, lactase used in ice cream, dextranase, lipase, pepsin and trypsin), skim milk, spirulina, soups, maltodextrin, soya protein, sweeteners, etc.

A variation of SD is superheated steam spray drying, which can be used with no fire and explosion hazards, no oxidative damage, the ability to operate at vacuum or high operating pressure conditions, ease of recovery of latent heat supplied for evaporation and minimization of air pollution due to operation in a closed system. In the past few years, spray freeze drying has received much attention. It consists of the following stages:

- atomization of liquid solutions or suspensions using ultrasound, one or two fluid nozzles or vibrating orifice droplet generators,
- freezing of the droplets in a cryogenic liquid or cryogenic vapour, and
- ice sublimation at low temperature and pressure or alternatively atmospheric freeze drying using a cold desiccant gas stream.

Goula and Adamopoulos (2005) investigated the production of tomato powder by SD tomato pulp in a modified spray dryer connecting the spray dryer inlet air intake to an air dehumidifier. It was observed that the moisture content of the powder decreased with an increase in air inlet temperature and compressed air flow rate, and with a decrease in drying air flow rate. Bulk density increased with a decrease in drying air flow rate and air inlet temperature, and with an increase in the compressed air flow rate. Solubility increased with a decrease in drying and compressed air flow rate and with an increase in the air inlet temperature. Without preliminary air dehumidification, the moisture content of the powder was higher and its bulk density and solubility were lower, indicating that the rapid particulate skin formation improved the product recovery and its properties.

One of the most important applications of SD is the food encapsulation and micro-encapsulation. These techniques are an efficient way of raising the shelf-life of food during storage. The most common materials used for micro-encapsulation using SD are gums, like gum Arabic, low-molecular-weight carbohydrates, such as maltodextrins and saccharose, cellulose, gelatine, lipids and proteins, e.g. soy proteins. Borrmanna *et al.* (2012) investigated the shelf-life of vitamin C encapsulated with *n*-octenylsuccinate (*n*-OSA)-derived starch in passion fruit juice produced by SD. SD proved itself as an inexpensive alternative to freeze drying, capable of retaining vitamin C during a long time of storage and easily diluted in cold water in order to reconstitute passion fruit juice for human consumption.

Fazaeli *et al.* (2012) studied the effects of some processing parameters on moisture content, water activity, drying yield, bulk density, solubility, glass transition temperature and microstructure of spray-dried black mulberry juice powders. The effect of SD conditions revealed that a higher inlet air temperature, increase of carrier agent concentration or decrease of maltodextrin DE caused an increase in process yield and solubility and a decrease in bulk density, moisture content and water activity. The blend of maltodextrin 6DE and gum Arabic proved to be more efficient (drying yield of 82%) than the other blends, resulting in better physical properties and powder morphology.

1.3.6 Osmotic dehydration

Osmotic dehydration (OD) is a simple and useful technique for removal of water from fruits and vegetables, realized by placing the solid food in aqueous solutions of sugars and salts possessing high osmotic pressure. The correct term to be used is ‘osmotic dewatering’ since the final product still has a high moisture content, a lot higher than 2.5%. During OD three simultaneous countercurrent flows occur:

- a significant amount of water flows out of the food into the solution (water loss),
- a transfer of solutes from the solution into the food (soluble solids uptake) and
- a leakage of solute molecules (hydrosolubles), such as sugars, salts, organic acids and minerals, across the membrane into the solution.

The first two flows take place due to the water and solute activity gradients across the cell’s membrane, while the third one, which is minor from a quantitative point of view but may be essential as far as organoleptic or nutritional qualities are concerned, occurs due to the differential permeability of the cell membranes (Torreggiani, 1993).

Through OD, the introduction of a preservative agent or any solute of nutritional interest, which is capable of giving the product better sensory characteristics and reduced water activity, is possible (Buggnhout *et al.*, 2008). Mass transfer during OD is affected by several parameters, such as osmotic solution composition, concentration, temperature, osmosis duration, pressure and type and extent of agitation.

OD is usually used as a pre-treatment and not for the production of dried food materials as a 30–40% reduction of food water is considered to be the optimum. Thus OD is followed by other dehydration methods like HAD, VD and FD. OD, which is effective even at ambient temperature, preserves texture and colour. The amount of water remaining in the material, however, does not ensure its stability, as water activity is generally higher than 0.9. Nevertheless, compared to fresh fruits, the osmotic-treated ones present increased microbiological stability for further processing and subsequent storage period due to sugar uptake, owing to the protective action of the saccharides. The semi-dried fruit ingredients produced by OD are included in a wide range of complex foods such as ice creams, cereals, dairy, confectionery and baking products (Tortoe, 2010). A significant advantage of OD is its low energy consumption compared to other drying methods such as HAD and FD.

Vasconcelos *et al.* (2012) studied OD of Indian fig with two binary solutions (sucrose/water and glucose/water) and a ternary solution (sucrose/NaCl/water). They found that temperature had a greater influence on the water loss, while concentration had a greater influence on the solid gain in all three hypertonic solutions investigated. The best conditions for OD of Indian fig to maximize water loss and minimize solid gain were in glucose solution of 40° Brix at 40 °C for 165 min. The properties of foods undergoing OD can be enhanced by combining osmotic treatment with other drying techniques acting simultaneously.

1.3.7 Atmospheric freeze drying

Atmospheric freeze drying (AFD) is an alternative to vacuum freeze drying (FD). The most effective method to apply AFD is by using a fluidized bed dryer. The drying rate depends on the operating temperature, pressure and material thickness. AFD is a much slower method compared to FD due to being an internally controlled mass transfer process. The drying time can be 2 to 4 times higher than FD for materials of the same dimensions, depending on the pressure in the dryer. Lower pressures and smaller dimensions of the food particles tend to reduce the drying time (Kudra and Mujumdar, 2002).

One way to apply AFD is to use a second material compatible with the food, such as starch granules or zeolite. The aim of these materials is to transfer heat for the ice sublimation and to absorb the moisture released. Both materials are in a fluidized state due to the feed of cold air. The mixture is separated and the absorbent is heated and regenerated in order to lose the excess moisture and immerse again in the dryer after cooling. Silica gel can also be used to entrap the water removed in the form of ice, following its regeneration (Reyes *et al.*, 2010).

Another practical and convenient approach is the utilization of a heat pump. Bantle, Kolsaker and Eikevik (2011) used this method to study the drying kinetics of different food materials undergoing AFD. The wet air from the drying chamber was cooled under its saturation point in the evaporator of the heat pump, which caused water to condense out. The drying air was again heated up to its working temperature in the heat pump condenser and fed back into the drying chamber. R404 was used as the refrigerant, which allowed adjustment of the drying conditions from −10 °C and relative humidity (RH) of 20–25% to 30 °C and 5% RH depending on the inlet air velocity.

Reyes *et al.* (2010) studied the drying conditions of Murtilla using AFD in a pulsed fluidized bed and vacuum FD. They concluded that in the first drying stage (sublimation) only the rate of freezing was a significant variable, which can be attributed to the generation of small ice crystals that increased the rate of drying by increasing the area of sublimation. In the second drying stage (elimination of bound water), fast freezing with infrared radiation (IR) allowed a final moisture content to be achieved that was similar to freeze-dried products in equivalent total drying periods. Slow freezing without application of IR preserved the polyphenol content better than fast freezing, whereas the antioxidant activity showed a lesser decrease with the application of IR.

Claussen *et al.* (2007) developed a simplified mathematical model (AFD-sim) based on uniformly retreating ice front (URIF) considerations to simulate industrial AFD of different foodstuffs in a tunnel dryer. The outputs from this model were the prediction of drying time, dry zone thickness and average moisture content versus relative tunnel position.

1.3.8 Sonic drying

Sonic drying depends on the energy generated in the form of sound waves. Many researchers studied the increase of drying rate in an ultrasonic field and presented a number of theories. It seems that the effect of sound in moisture removal is quite complex and caused by a decrease in viscosity, reduction of the laminar sublayer thickness due to an increase in turbulence of the air stream in contact with the material, increase of moisture evaporation due to breakage of the boundary layer and an increase in the moisture migration due to the expansion of vapour bubbles inside capillaries. Gallego Juarez (1998) concluded that diffusion at the boundary between a suspended solid and a liquid is substantially accelerated in an ultrasonic field and heat transfer is increased by approximately 30–60% depending on the intensity of the ultrasound. The mechanism of ultrasound drying (USD) is based on the principle that ultrasound travels through a medium like any sound wave, resulting in a series of compression and rarefaction. At sufficiently high power, the rarefaction exceeds the attractive forces between molecules in the liquid phase, which leads to the formation of cavitation bubbles to release energy for many chemical and mechanical effects.

Ultrasound techniques are simple, relatively cheap and energy saving, and thus became an emerging technology for probing and modifying food products. High-power (low-frequency) ultrasound modifies the food properties by inducing mechanical, physical and chemical/biochemical changes through cavitation (Kudra and Mujundar, 2002). In addition, probes that generate high power ultrasound are cheap, portable and modifiable to suit different purposes in the food industry (Awad *et al.*, 2012).

Kudra and Mujumdar (2002) presented five main sound generators applicable in the drying industry, which are: piezoelectric, magnetostrictive, electromagnetic, electrostatic and mechanical. Mechanical generators are the most common equipment used for the generation of sound in gases at frequencies up to 25 kHz, which include the Galton whistle, Hartman whistle, wedge resonator, dynamic siren, modified Hartman whistle and Branson sound generator.

The assistance of air drying with an ultrasound field can reduce drying time to about half, depending on sound energy and frequency. Sonic-assisted drying does not create hot areas inside the material and neither does it enhance moisture vaporization due to temperature increase. This is important for food drying as heat-sensitive compounds are not deteriorated by sound waves.

Nowacka *et al.* (2012) investigated the utilization of ultrasound as a mass transfer enhancing method prior to drying of apple tissue. The ultrasound treatment caused a reduction of the drying time by 31–40% in comparison to untreated tissue. Garcia-Perez *et al.* (2012) tested the feasibility of power ultrasound to intensify low-temperature drying processes for carrot, eggplant and apple cubes. The drying time was shortened by between 65 and 70%. Bantle and Eikevik (2011) used ultrasound in an AFD process of peas and concluded that the effective diffusion could be increased by up to 14.8%. The higher effective diffusion is significant for drying at low temperatures (−6 to 0 °C), whereas for higher temperatures (10 to 20 °C) the effect of ultrasound was marginally smaller.

Schössler, Thomas and Knorr (2012) studied the cellular effect of contact power ultrasound on potato cell tissue with the impact on water removal. Ultrasound-related cell disruption was limited to a thin layer (< 1 mm) directly at the sonicated surface of the potato tissue. At deeper tissue layers, structural changes were attributed to water removal.

1.3.9 Heat pump drying

Heat pump drying (HPD) is a variation of hot-air drying or generally fluid drying in which, through a mechanical arrangement, heat from the exhaust drying fluid is recovered and offered again to the moist material or even the moisture from the exhaust drying fluid is removed and the fluid recirculates in the dryer. In a heat pump dryer, which is a combination of a heat pump and a drying unit, both the latent and sensible heat can be recovered, improving the overall thermal performance and yielding effective control of air conditions at the inlet of the dryer. Energy savings of about 40% by using heat pump dryers have been reported as compared to electrical resistance dryers (Queiroz, Gabas and Telis, 2004). Heat pump dryers used in industrial applications have been proven as drying systems that ensure the product's quality in food and agricultural products and are able to control temperature, relative humidity and velocity of the drying medium and drying duration. The heat pump has been modified to a gas engine-driven heat pump, ground source heat pump, solar heat pump, photovoltaic/thermal heat pump, chemical heat pump and desiccant heat pump (Goh *et al.*, 2011).

A few limitations of a heat pump dryer include (Daghigh *et al.*, 2010):

- the requirement of an auxiliary heating for high-temperature drying due to the critical pressure level of some refrigerants,
- the initial capital cost that may be high due to many refrigerant components,
- the requirement of a period for the system to attain desired drying conditions,
- the requirement of regular maintenance of components, and
- the leakage of refrigerant to the environment where there is a crack in a pipe due to pressurized systems.

A heat pump dryer (Figure 1.2) includes a drying cabinet, a heat pump, which consists of an evaporator, a condenser, a compressor and an expansion valve, and auxiliary equipment. Moist solids and hot air (or inert gas) are fed into the cabinet and come in contact with each other. Solids are fed on a conveyor belt of trays. Fluid circulates with a desirable velocity via an appropriate fan. Moisture is transferred from the solids to the fluid. Moist fluid passes through the heat pump evaporator and cools as the refrigerant vaporizes. The fluid becomes saturated and, as its temperature further reduces, water is removed from it and is collected as a condensate in a water collector. Fluid (gas) separates from water in this collector. Refrigerant vapours are fed to the compressor, and their pressure and temperature increase. The refrigerant is then fed into the two condensers. Through the internal condenser, the refrigerant condensates and heat is transferred to the cold fluid (gas) coming from the water collector, to be heated again and recirculated to the drying cabinet. An external condenser is also used for adjustment of the fluid temperature to the target value. The more refrigerant fed into the internal condenser, the higher is the drying fluid temperature. The external condenser usually uses cooling water for heat removal. The refrigerant from the two condensers passes through an expansion valve and its pressure reduces to the working pressure of the evaporator. An auxiliary steam heater is also shown in Figure 1.2. Under steady-state conditions, its heat duty is equal to

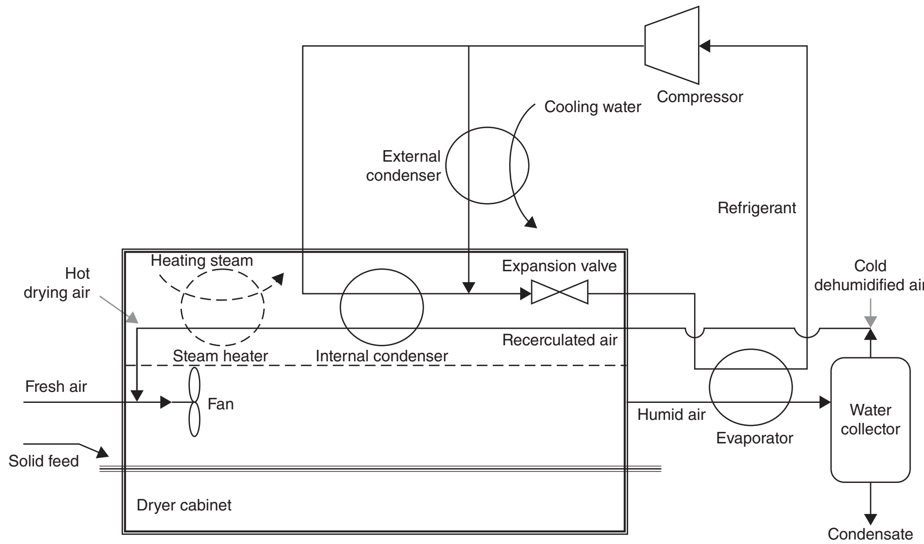

Figure 1.2 Heat pump dryer

zero. Nevertheless, its existence is necessary during the start-up of the unit as well as for its better control in case of troubleshooting of the heat pump.

Table 1.1 presents the mathematical model of the described heat pump dryer. In this model, it is assumed that the mass of dry air (or inert gas) remains constant in the dryer and under steady-state conditions the water removed from the moist solids and transferred to the drying medium inside the drying cabinet is equal to the water removed from the moist fluid in the heat pump evaporator-water collector system. Thus, the recirculated low-humidity dewatered drying medium is considered as a closed system. In a real dryer, drying fluid losses are possible and the complete recirculation may not apply. In these cases, fresh ambient air or stored inert gas also enters the dryer. The presented model can be easily modified to describe these cases, by adding the mass and energy (enthalpy) equations for a mixing point of ambient and recirculated fluid. Further, a mass balance equation should be included for the drying medium removed from the system. Table 1.2 presents the process variables of the heat pump dryer for the terms used in Table 1.1.

HPD may use inert gases like N_2 and CO_2 for food dewatering. The moisture removed from the material is collected by the inert gas used. Since the use of inert gases is much more expensive than the use of air, the inert gas should be recycled to the drying process and not rejected to the atmosphere. To be able to do this, its moisture has to be removed, as it decreases the drying rate. This can be easily achieved by cooling the fluid stream in the heat pump evaporator in order for the moisture to be liquefied and the separated inert fluid to be recirculated for further moisture removal after heating again in the

Table 1.1 Mathematical model of a heat pump dryer

$$F_w = F_s(X_i - X_o) = F_a(Y_{vo} - Y_{vi})$$

$$Y_{vo} = Y_{vi} + \frac{F_w}{F_a}$$

$$F_s(C_{ps} + X_i C_{pw})T_a + F_a(C_{pa} + Y_{vi}C_{pv})T_i = F_s(C_{ps} + X_o C_{pw})T_o + F_a(C_{pa} + Y_{vo}C_{pv})T_o + F_w(\Delta H_w + C_{pv}T_o - C_{pw}T_a)$$

$$P_{so} = \exp\left(a_1 - \frac{a_2}{a_3 + T_o}\right)$$

$$Y_{so} = \frac{mP_{so}}{P - P_{so}}$$

$$T_{di} = \frac{a_2}{a_1 - \ln\left(\frac{Y_{vi}P}{m+Y_{vi}}\right)} - a_3$$

$$Q_e = F_a\lfloor C_{pa}(T_o - T_{di}) + C_{pv}(Y_{vo}T_o - Y_{vi}T_{di}) + (Y_{vo} - Y_{vi})\Delta H_w \rfloor + F_w C_{pw} T_{di}$$

$$Q_c = F_r\left[\Delta H_r \frac{T_{ac} + 273}{T_e + 273} - C_{pr}\left(T_{ac} - T_e\right)\right]$$

$$F_r = \frac{Q_e}{\Delta H_r - C_{pr}(T_{ac} - T_e)}$$

$$E_c = F_r \Delta H_r \frac{T_{ac} - T_e}{T_e + 273}$$

$$Q_{ah} = F_a(C_{pa} + Y_{vi}C_{pv})(T_i - T_{di})$$

$$Q_r = Q_c - Q_{ah}$$

$$Y_{so} > Y_{vo}$$

heat pump condenser or/and through a different heating source (Doungporn, Poomsa-ad and Wiset, 2012). Drying under an inert atmosphere presents multiple advantages, such as:

- higher drying rate due to higher heat and mass transfer,
- absence of oxidative reactions, which is especially critical in the drying of sensitive materials present in food products (Perera and Rahman, 1997),
- reduction of browning and shrinkage, and quick rehydration (O'Neill *et al.*, 1998),
- very high overall quality, retention of vitamin C and the colour of the product similar to products obtained from vacuum or freeze drying (Hawlader, Perera and Tian, 2006), and
- decrease of temperature increments leading to superior product quality (Hawlader *et al.*, 2006).

Doungporn, Poomsa-ad and Wiset (2012) studied thin-layer drying characteristics of Thai Hom Mali paddy using different drying gases (hot air, CO_2

Table 1.2 Process variables of a heat pump dryer

a_1 (−)	Antoine constant
a_2 (−)	Antoine constant
a_3 (−)	Antoine constant
C_{pa}(kJ/kg K)	Heat capacity of dry air
C_{pr} (kJ/kg K)	Heat capacity of refrigerant
C_{ps} (kJ/kg K)	Heat capacity of solids
C_{pv}(kJ/kg K)	Heat capacity of water vapor
C_{pw}(kJ/kg K)	Heat capacity of water (liquid removed from the solids)
E_c (kW)	Refrigerant compressor power
F_a (kg (d.b.)/s)	Drying air flow rate (d.b. is dry basis)
F_r (kg/s)	Refrigerant flow rate
F_s (kg (d.b.)/s)	Dry solids flow rate (dry basis)
F_w (kg/s)	Rate of water removal from the solids
m (−)	Air/water molecular weight ratio
P (atm)	Ambient pressure, working pressure of the dryer
P_{so} (atm)	Vapour pressure at saturation of the outlet air from the dryer
Q_{ah} (kW)	Heat load added to the recirculated drying air
Q_c (kW)	Cumulative heat duty of the two heat pump condensers
Q_e (kW)	Heat duty of the heat pump evaporator
Q_r (kW)	Heat load removed from the external condenser
T_a (°C)	Ambient temperature, initial temperature of solid
T_{ac} (°C)	Heat pump condenser temperature
T_{di} (°C)	Dew point temperature of dryer cabinet inlet air, dew point temperature of air exiting heat pump evaporator
T_e (°C)	Heat pump evaporator temperature
T_i (°C)	Dryer cabinet inlet air temperature
T_o (°C)	Dryer cabinet outlet air temperature
X_i (kg/kg d.s.)	Initial moisture content of the solids (d.s. is dry solids)
X_o (kg/kg d.s.)	Final moisture content of the solids
Y_{so} (kg/kg d.a.)	Saturation absolute humidity of the dryer cabinet outlet air (d.a. is dry air)
Y_{vi} (kg /kg d.a.)	Absolute humidity of dryer cabinet inlet air
Y_{vo} (kg/kg d.a.)	Absolute humidity of dryer cabinet outlet air
ΔH_r (kJ/kg)	Latent heat of vaporization of the refrigerant
ΔH_w (kJ/kg)	Latent heat of vaporization of water (at 0 °C, reference temperature)

and N_2) at a temperature range 40–70 °C in a heat pump dryer. The drying rate was not affected by the drying medium but increased with the drying temperature. The Midilli model in the form of the Arrhenius type was the best model for describing the drying behaviour of the product. Figure 1.3 presents the flowsheet of the heat pump and Table 1.3 summarizes the flow, composition and properties of each stream. The phase equilibrium has been calculated through thermodynamic models. One of the most interesting results of this simulation is the dilution of a small amount of nitrogen to the cold water removed from the water collector. An addition of ~5.7 kg per day of N_2 is

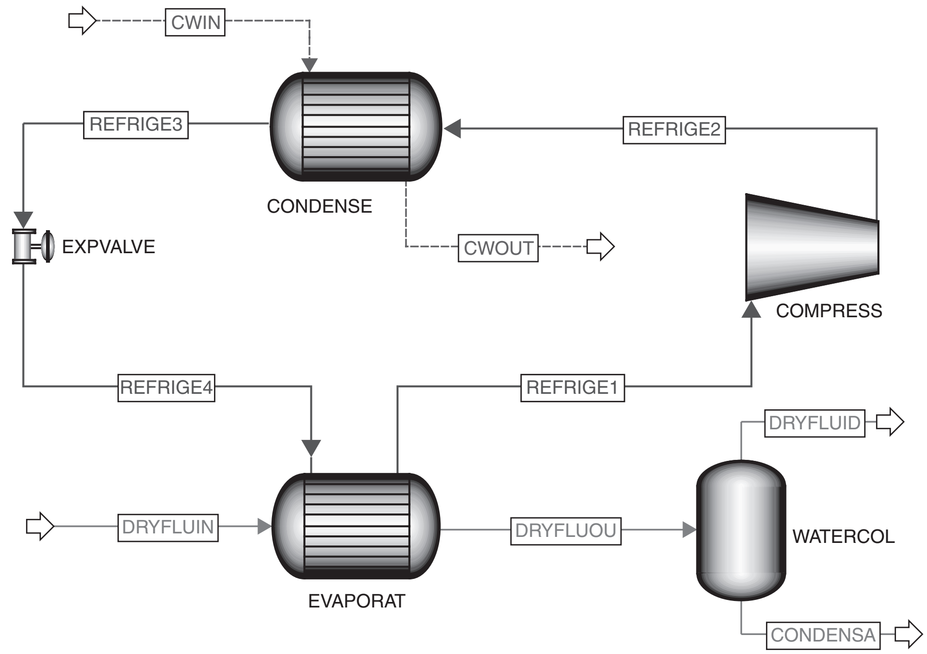

Figure 1.3 Heat pump for the dewatering of nitrogen–water vapour mixture

necessary to cover the losses. Furthermore, the water separated in the water collector is cold and has to be heated fast before freezing. Table 1.4 presents some useful performance data.

1.3.10 Infrared drying

Infrared drying (IRD) is an emerging method presenting significant advantages, including a relatively shortened drying time, high energy transfer rate and therefore high drying efficiency, reduced energy consumption, efficient transmission through the air or evacuated space, lower air flow through the product, uniform temperature in the product, superior product quality, space saving, ease of automation and a clean working environment compared to other drying methods. IRD is based on the interaction of infrared wavelength radiation from a source with the internal structure of a food material. IR radiation impinges on the moist material to be dried, penetrates it and the radiation energy is converted into heat. The increased temperature in the inner layers of the material results in an increase of vapour pressure, which promotes moisture migration to its surface and the removal by the surrounding ventilating air (Khir *et al.*, 2012). IR energy is transferred from a heating element to the product without heating the surrounding air, resulting in a higher temperature in the inner layers of the product compared to the air. During the first period of

Table 1.3 Properties of the streams of the heat pump in Figure 1.3

Stream	Drying fluid before cooling	Drying fluid after cooling	Dry fluid	Condensate	Refrigerant exiting evaporator	Refrigerant exiting compressor	Refrigerant exiting condenser	Refrigerant exiting expansion valve	Cooling water inlet	Cooling water outlet
Stream symbol	DRYFLUIN	DRYFLUOU	DRYFLUID	CONDENSA	REFRIGE1	REFRIGE2	REFRIGE3	REFRIGE4	CWIN	CWOUT
Temperature (°C)	65	−13.2	−13.2	−13.2	−17.5	48	37.6	−17.5	20	31.4
Pressure (bar)	1.013	1.013	1.013	1.013	0.507	3.546	3.546	0.507	1.013	1.013
Vapour fraction (–)	1	0.956	1	0	1	1	0	0.354	0	0
Mole flow (kmol/h)	130.6	130.6	124.9	5.73	37.2	37.2	37.2	37.2	999.1	999.1
Mass flow (kg/h)	3600	3600	3496.6	103.3	2160	2160	2160	2160	18000	18000
Volume flow (m^3/h)	3625.1	2664.3	2664.2	0.1	1559.2	279.7	3.87	554.24	18.022	18.223
Enthalpy (MMkcal/h)	−0.31	−0.443	−0.049	−0.394	−1.152	−1.096	−1.285	−1.285	−68.259	−68.07
	Mass flow (kg/h)									
N-BUT-01	0	0	0	0	2160	2160	2160	2160	0	0
WATER	108	108	4.9	103.08	0	0	0	0	18 000	18000
NITRO-01	3492	3492	3491.7	0.237	0	0	0	0	0	0

	Mass frac (–)									
N-BUT-01	0	0	0	0	1	1	1	1	0	0
WATER	0.03	0.03	0.001	0.998	0	0	0	0	1	1
NITRO-01	0.97	0.97	0.999	0.002	0	0	0	0	0	0
	Mole flow (kmol/h)									
N-BUT-01	0	0	0	0	37.16	37.16	37.16	37.16	0	0
WATER	5.99	5.99	0.273	5.722	0	0	0	0	999.1	999.1
NITRO-01	124.6	124.6	124.6	0.008	0	0	0	0	0	0
	Vapour phase									
Enthalpy (cal/gm)	−86.003	−14.009	−14.009		−533.112	−507.33		−533.113		
Heat capacity (cal/gm K)	0.255	0.248	0.248		0.36	0.43		0.36		
Conductivity (kcal m/h m^2)	0.024	0.02	0.02		0.01	0.016		0.01		
	Liquid phase									
Enthalpy (cal/g)		−3813.1		−3813.1			−594.8	−628.7	−3792.1	−3781.6
Heat capacity (cal/gm K)		0.883		0.883			0.678	0.56	0.913	0.931
Conductivity (kcal m/h m^2)		0.422		0.422			0.088	0.107	0.515	0.529

Table 1.4 Performance data of the equipment

Condenser	
Heat duty (Gcal/h)	0.18902
Logarithmic mean temperature difference (°C)	11.36
Evaporator	
Heat duty (Gcal/h)	0.133353
Logarithmic mean temperature difference (°C)	21.91
Compressor	
Isentropic efficiency (–)	0.72
Mechanical efficiency (–)	0.75
Indicated horsepower (kW)	64.8
Net work required (kW)	86.4
Isentropic power requirement (kW)	46.6
Power loss (kW)	21.6
Calculated pressure ratio (–)	7
Outlet temperature (°C)	48
Isentropic outlet temperature (°C)	37.6
Head developed (m)	7925
Inlet heat capacity ratio (–)	1.105

drying when the sample surface is coated with a very thin layer of water, the IR is extraordinarily energy efficient and speeds up the drying process (Kowalski and Mierzwa, 2011). The drying takes place from inner to outer layers via both radiation and convection phenomena. IRD is particularly valid for products with a significant moisture content, for which long-wave radiation (over 3 μm) is almost totally absorbed by moisture as there is a very good correlation of IR wavelengths with the absorption bands of water, while dry material is highly permeable to such radiation.

Niamnuy *et al.* (2012) studied the drying of soybean, and the interconversion and degradation of soy isoflavones during gas-fired infrared combined with hot-air vibrating drying (GFIR–HAVD). The de-esterification is the predominant reaction of isoflavone changes during drying, and the conjugated glucosides have less stability than the aglycones form of isoflavones. GFIR–HAVD at 150 °C gave the highest drying rate and conversion rates of various glucosides to aglycones. However, the high degradation rates of all isoflavones occurred at a temperature of 150 °C and hence a drying temperature of 130 °C is recommended as the most suitable temperature to optimize drying rate, conversion rates of various glucosides to aglycones and degradation rates of all isoflavones. Kowalski and Mierzwa (2011) studied the hybrid drying of microwave, infrared and hot-air drying and came to the conclusion that MWD is enhanced for red bell pepper; the process consisted of eight phases. In phases 1, 3, 5 and 7, the process was enhanced with IR.

A phase was terminated when the temperature attained a specified level. In phases 2, 4 and 6, only the microwave (MW) energy was supplied. Shrinkage and deformation of samples were smaller, the aroma was better preserved and colour was conserved to a satisfactory degree compared to hot-air-dried products, while energy consumption was also smaller.

1.3.11 Superheated steam drying

Superheated steam drying (SSD) is an emerging technology, which uses superheated steam as the drying medium for heat supply to a product to be dried and carry off evaporated moisture instead of hot air as used in HAD. This equipment is more complex than a hot-air dryer. There is no fire or explosion hazard. The application of low, near-atmospheric (preferable due to reduced equipment cost) or high pressure (at ~5 bar, referred to as high pressure superheated steam drying) operation is possible. Any convection dryer such as fluidized bed, flash, rotary, conveyor type, etc., can be transformed into superheated steam dryer, while additional heat sources (radiation, microwave, etc.) can also be combined. The net energy consumption can be low enough (up to 80% reduction) when integration systems are applied for the heat recovery (Raghavan *et al.*, 2005). Thermal properties of steam are superior compared to air at the same temperature, resulting in a higher heat transfer coefficient. Furthermore, vapour transfer is faster than liquid diffusion, thus improving mass transfer during drying as well. Since the drying medium does not contain oxygen, there is no risk of oxidation of food substances (enzymatic browning and lipid oxidation) and the product quality is quite good, including the preservation of nutrients and colour, although heat-sensitive materials may be prone to damage. Case-hardened skin is unlikely to be formed in this method and the treatment strips out more of the acids that contribute to an undesirable taste or aroma of the products. Pasteurization, sterilization, deodorization or other heat treatments (e.g. blanching, boiling, cooking) of the product may take place simultaneously with drying and the product presents higher porosity due to evolution of steam within the product as boiling in the interior opens up the elastic wet solid. This results in lower bulk density and better rehydration behaviour.

SSD has been applied successfully to many food materials, including potato chips, tortilla chips, shrimp, paddy, soybean, Asian noodles, pork, chicken, fermented fish, sugar beet pulp, spent grain from a brewery, okara, sunflower seed, cacao bean and pressed beet pulp after extraction of sugar, where high pressure superheated steam drying can de used.

A variant of SSD is low-pressure superheated steam drying (LPSSD), which is used in the cases where products to be dried melt, undergo glass transition or are damaged at the saturation temperature of steam. This method takes place at a pressure of 5–10 kPa, combines the ability to dry the product at a low temperature with some advantages of SSD and leads in product quality preservation and an enhanced drying rate. It is suitable for highly heat-sensitive products such as herbs, fruits, vegetables, edible films, functional foods and ingredients, as well as other bioactive materials for which the SSD is prohibited.

Devahastin *et al.* (2004) used carrot cubes as a model heat-sensitive material to investigate various quality parameters of the dried product undergoing LPSSD or VD. They recorded that convective heat transfer was poorer under reduced pressures, leading to lower drying rates, but the quality of the dried product was superior compared to that obtained using conventional VD. The effect of the operating pressure was less significant than that of the steam temperature. The shrinkage patterns resulting from LPSSD and VD processes were quite different even though the values of shrinkage were similar. Steam drying provided a much better rehydration capability of the food due to the formation of less dense layers compared to VD.

LPSSD can be combined with other dehydration methods to improve product quality. Nimmol *et al.* (2007) studied the effect of LPSSD and far-infrared radiation (FIR) on drying of banana slices. The LPSSD–FIR dried banana showed more crispness than the VD–FIR banana, especially at higher drying temperatures. LPSSD–FIR at 90 °C required a shorter drying time than VD–FIR but the colour was darker. Furthermore, the dried banana slices had higher values of colour changes compared with those that underwent LPSSD alone.

1.3.12 Intermittent drying

Intermittent drying (ID) is a drying technique in which the heat is applied in a noncontinuous way. In the tempering period, moisture is redistributed inside the material. This produces two effects:

- a quality increase (avoiding cracking of material), and
- an increase in the drying rate when heat application is rebooted (Holowaty, Ramallo and Schmalko, 2012).

A reduction in energy consumption is expected in the industrial drying of food materials when this technique is applied.

ID has been successfully applied in the dewatering of many products such as rice, banana, guava, potato, soybean and wheat. Holowaty, Ramallo and Schmalko (2012) investigated the dehydration of yerba maté branches in a bed dryer using two different tempering periods of 15 and 30 min, and concluded that both periods produced the same effect and the final moisture content of the product was practically similar to that of continuous drying. Estürk (2012) studied the drying of sage herb taking into consideration the thermal damage during drying. He used MWD–air drying (AD) (continuous and intermittent) and convective HAD of sage to determine their effect on colour and essential oil content. The continuous MWD–AD had the fastest drying rate. The drying time of the HAD was about 63.5 to 82.4 times longer than that of the continuous MWD–AD and about 17.0 to 31.6 times longer compared to the intermittent MWD–AD depending on the mode used.

1.3.13 Instant controlled pressure drop drying

Instant controlled pressure drop (DIC, from the French *détente instantanée contrôlée*) is a drying technology from the 1980s as a treatment using a high temperature (up to 180 °C) and short time (usually less than 60 s) followed by an instant pressure drop towards a vacuum (with a pressure drop rate > 0.5 MPa/s and a pressure of approximately 5 kPa), which allows the water to abruptly autovaporize, causing controlled expansion of the product. Usually a first stage of partial drying takes place, decreasing the product moisture content to 0.2–0.3 kg H_2O/kg dry matter (d.m.), before submitting it to DIC treatment, followed by HAD for 1–2 hours. The DIC treatment usually starts by creating a vacuum condition, followed by injecting steam to the material, which keeps in contact for several seconds and then proceeds to apply a sudden pressure drop towards a vacuum. The application of DIC with HAD in fruits and vegetables can lead to lightly or highly expanded products. DIC treatment has to be applied to low moisture content products in order to act as closely as possible to the glass transition zone, which allows the expansion to be maintained. Products undergoing DIC can be of a snack type and can easily be crushed, leading to expanded granule powders with quality attributes higher than traditionally dried or spray-dried powders. This method is used for texturing fruits, vegetables and seaweeds, and presents many advantages such as reduction of energy consumption and overall production cost, controllability, improvement of the quality in terms of sensorial, functional, convenience and nutritional attributes, increased safety and hygiene, as it causes perfect decontamination due to its thermal (high temperature) and micromechanical (instant pressure drop) effects, as well as enhancement of mass transfer as it creates an open cell structure. The purpose of the texturing step is to modify the texture of food material, to improve its quality, including physical properties, and to intensify functional behaviour. Texturing comes in the form of material swelling, which leads to increased porosity and specific surface area and reduced diffusion resistance of moisture during the final dehydration step (Mounir and Allaf, 2008).

1.3.14 Sun drying and solar drying

Sun drying is the most ancient drying method, using the sun radiation to remove water from a product. It applies mainly in agricultural and farming food materials in places where the insolation is high and the outdoor temperature is higher than 30 °C. It is a simple, costless method but drying time is very high (up to 10 days) and there is a need for extensive land. In general, the product quality is poor due to enzymatic and Maillard reactions, pigment degradation, caramelization and ascorbic acid oxidation (Kowalski and Mierzwa, 2011). Weather conditions often preclude the use of sun drying because of spoilage due to rehydration during unexpected rains. Direct exposure to the sun might cause case hardening, while marauding animals and insects, contamination by pests and the growth of toxic fungi can cause loss of a product portion.

Solar drying reclaims the sun's energy by controlling the radiative heat. Solar drying decreases drying time, increases efficiency due to reduced harvest losses, retains more of the nutritional value as drying takes place at an optimum temperature and produces significant cost savings by reducing conventional fuel demand. It has been applied in grains, fruits, meat, vegetables, fish, etc. Solar drying can be achieved by direct exposure to the sun's radiation or by incorporating external means, such as fans, to transfer solar energy in the form of heated air from the collector area to the drying chambers. Products dried by the first technique include banana, pineapple, mango, carrots, etc., while the latter is used for drying higher moisture content foodstuffs such as papaya, kiwi fruits, cabbage and others. A coal stove or agricultural wastes can be incorporated as auxiliary heating sources, while sometimes wood smoke can be used for drying (Chua and Chou, 2003).

1.3.15 Supercritical drying

Supercritical drying (SCD) is an emerging drying method which results not simply in water removal from a food material but, furthermore, in the retention of its original (micro) structure and the corresponding porous network functionality (Brown *et al.*, 2010, 2008). When SCD is applied at appropriate operating conditions, a single homogeneous phase can be formed between the supercritical fluid and the co-solvent. If used, there are no vapour–liquid interfaces and the food to be dried does not suffer from surface tension forces and capillary-induced tensile stresses, which generally damage and cause the collapse of the structure. CO_2, which is the most commonly used supercritical fluid, has a low critical temperature (~31 °C) and the drying can be realized in a near to ambient temperature. Supercritical carbon dioxide ($scCO_2$) is a non-polar solvent and the solubility of water in it is very low. Ethanol, ethyl acetate and other organic solvents when added in small quantities to $scCO_2$ can significantly increase the solubility of polar substrates in $scCO_2$. The organic solvent causes a displacement of water and the solvent/water mixture is removed with $scCO_2$. The equipment for this process is more complicated compared to conventional drying techniques.

Brown *et al.* (2008) investigated supercritical carbon dioxide drying ($scCO_2D$) of carrot by applying X-ray microtomography and light microscopy. The experiments were carried out at 20 MPa pressure using ethanol as the co-solvent. Carrots dried in the $scCO_2$–EtOH environment retained their shape much better and presented less dense structures compared to air-dried carrots, which underwent shrinkage. Brown *et al.* (2010) also examined the SCD for water removal from agar gels and compared this method to HAD and FD. They observed that for formulations containing sucrose, which displayed the best structural retention, voidage was found to increase in the order: HAD (4% voidage) $<$ $scCO_2$ (48%) $<$ $scCO_2$–EtOH (68%) $<$ FD (76%).

1.3.16 Flash drying

Drying of fruits and vegetables can be realized with the application of another drying technique, which is the convective multiflash drying (CMFD) process. This process is based on the application of successive cycles of heating and vacuum pulses. The product is heated at atmospheric pressure using hot air, which causes partial dehydration of the product. When the product reaches the desired temperature, a sudden pressure reduction is applied, which leads to water evaporation (flash drying) and product cooling. Additional heating–vacuum pulse cycles can be applied to achieve the desired characteristics of the dried product. During water removal, the product undergoes texturization. As it is possible to apply many cycles, the heating temperature can be compatible with the food's sensitivity to heat treatment. This method allows the production of dehydrated fruits with moisture content, water activity and mechanical properties similar to those observed in commercial freeze-dried fruits. CMFD is an efficient dehydration technique that can be completed in shorter times (3–4 hours) and at lower capital costs, with simpler equipment and less energy requirements than FD. Banana and mango processed by CMFD were at least as crispy as the freeze-dried fruits and the colour was well preserved due to the use of moderate temperatures (Zotarelli, Porciuncula and Laurindo, 2012).

1.3.17 Pulse drying

High-temperature–short-time (HTST) pulse drying is a method used to alter the structural properties of the dried material by changing the values of the drying parameters used in conventional HAD. Hofsetz *et al.* (2007) studied the effect of the HTST pulse on HAD of banana slices and compared the properties of the material with those obtained with the HAD process. The different drying treatments led to distinctive structural changes in the food, affecting its porosity and shrinkage. The combined HTST–HAD process simultaneously puffed and dried the banana slices, resulting in reduced shrinkage compared to the air-dried samples. For air-dried samples, the increase in porosity reached a value of 32% while during the HTST–HAD process the porosity increment reached values of 45–53% at the end of drying, resulting in the formation of a highly porous structure, which occurred together with an expansion in volume. The HTST pulse for the puffing of banana ranged from 130 to 150 °C for 23–12 min, respectively, succeeded by HAD at 70 °C. It was observed that the dehydrated bananas produced by HTST–HAD presented a crust on the external surface and big pores inside the samples, and it is believed that this crust offered resistance to shrinkage. The air-dried samples showed no crust formation and a medium–small pore structure.

The HTST drying pulse combined with HAD represents an alternative to eliminate the preceding blanching stage and promote better sensory characteristics to the final product, especially those associated with crispness. Following HTST pulse drying, the food must be further air dried to reduce the water activity to a value that will inhibit the growth of pathogenic and spoilage microorganisms, and reduce enzyme activity and the rate at which undesirable chemical and deterioration reactions occur.

1.3.18 Pulse combustion drying

Pulse combustion drying (PCD) is an emerging method based on intermittent (pulse) combustion of a solid, liquid or gaseous fuel. Such periodic combustion generates intensive pressure, velocity and, to a certain extent, temperature waves propagated from the combustion chamber via a diffuser to the dryer. Pulse combustion intensifies the rates of heat and mass transfer due to the oscillatory nature of the momentum transfer. The increased drying rates result from the impact of the sound pressure waves, which separate the surface moisture from the material undergoing drying by breaking the cohesion between the water molecules and solid particles. This greatly increases the surface area of the particles and causes rapid evaporation of water. The residence time of dispersed material is less than 5 milliseconds, which allows the drying of even thermally labile products. Pulse drying with special modified equipment has been applied in vitamins, yeast, spices, vegetable protein, fibres, whole eggs, food colourings, caramel and biopesticides, presenting quality and unit cost comparable to spray drying (Kudra and Mujumdar, 2002).

1.4 Conclusions

Drying is one of the most ancient and important processes for preservation, processing and distribution of foods and biological materials. Freeze drying is the most versatile drying method concerning the final product quality but its application is limited due to high operating costs. Hot-air drying, one of the oldest drying methods, still remains the workhorse of the drying technology.

Traditional methods, like vacuum drying, as well as emerging technologies, such as infrared drying, sonic drying and atmospheric freeze drying, aim to improve the quality compared to hot-air drying by keeping the cost at low levels. On the other hand, there are methods such as osmotic drying and instant controlled pressure drop (DIC) drying that target primarily in the compositional change or texturization of the product as they reduce the moisture content. The trend of food drying, as becomes evident from recent studies, is the development of hybrid methods, which combine advantages of two or more individual techniques to achieve the best possible quality and the most efficient energy utilization.

Abbreviations

AFD	Atmospheric freeze drying
DIC	Instant controlled pressure drop (*détente instantanée contrôlée* in French)
FD	Freeze drying
HAD	Hot-air drying
HPD	Heat pump drying
ID	Intermittent drying
IRD	Infrared drying
MWD	Microwave drying
OD	Osmotic dehydration
PCD	Pulse combustion drying
SD	Sonic drying
SSD	Superheated steam drying
VD	Vacuum drying

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