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Review

Design of hot air drying for better foods

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Drying of food consists of three steps, namely pre-drying processing, dehydration and post-drying handling of the material. The pre-drying processes depend on the physical state of the material subjected to drying. Liquids are vacuum concentrated, treated with enzymes or foamed, while solids are sulfited, soaked in solutions of different compounds, dewatered by osmosis, blanched, frozen or treated by high pressure. Drying of the pre-treated material can be done under vacuum or at atmospheric pressure. Material undergoing drying can be heated by surface heating or by volumetric heating, and it can be stationary or set in motion. Storage stability of a dry material depends on the state at which the drying process is finished. The effect of all these steps on quality of the final product are discussed. It is shown that to design a process of hot air drying a thorough understanding of all the operations affecting quality is needed.

Introduction

Drying is probably one of the oldest methods of food preservation. Thousands of years of experience and trial-and-error methods as well as research done during the last hundred years resulted in development of a variety of drying methods and drying equipment. Although the influence of hot air drying on food quality is well recognized the understanding of processes caused by dewatering and adversely affecting material properties is limited. This is because evaporation of water at elevated temperature causes chemical, physical and biological changes in food, which can proceed simultaneously or in sequence, some can be advanced while others are just initiated.

Evaporation of water desiccates solid matrix of the material and increases concentration of solubles in remaining solution. Changes of pH, redox potential and solubility may affect structure and functionality of biopolymers. At the final stages of drying the phase transitions can take place. Increased concentration of solubles can promote chemical and enzymatic reactions due to higher concentration of reagents and catalysts, as well. Water removed from the material is, at least in part, replaced by air and contact with oxygen is substantially increased. Shrinkage and shape distortions, fading of natural color or discoloration, decreased flavor and unappetizing texture are the most evident deficiencies of dry products. Moreover, poor rehydration ability and reduced nutritional quality also evidence disadvantageous influence of drying on food.

Beside the adverse influence of drying on food quality the process is indispensable in many food industry sectors because of the increased shelf-life of the product, reduced packaging cost, lower shipping weights and environmental advantages. Moreover, drying used properly can result in unique properties not achievable by other technological procedures. Today's consumer expectation for better quality, safety and nutritional value drives research and improvement of drying technologies. One, probably the most important, way to reduce adverse influence of drying on food quality or to create usual properties of the final product is to design carefully the process and carry it on consciously.

Aims of food dehydration

Drying consists of removal of water to a final concentration, which assures microbial stability and guarantees expected shelf-life of the product. When designing a dehydration process two important questions must be taken into account:

– expected quality attributes of the product,
– the way the product will be used.

Both questions are interrelated since in many cases the way the product is used defines its quality indices. Expected

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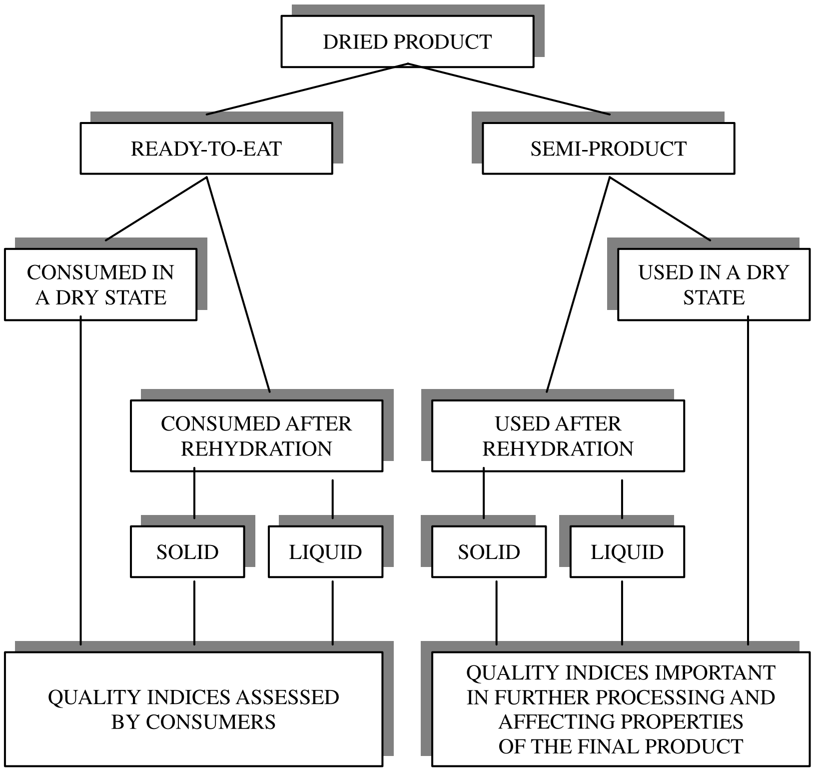

Fig. 1. Relationship between dried product properties and the way the product is used.

quality of a dry product, which will be used as ready-to-eat food, can be substantially different than that foreseen for the material used as a semi-product. Further analysis of this question shows that both ready-to-eat and semi-products can be used in a dry state or will need rehydration before consumption or further processing. This is illustrated in Fig. 1.

Considering ready-to-eat product, which is consumed in a dry state, the importance of quality indices become evident. The sensory attributes such as color, size, shape, are very important from the consumer point of view. Uniform color with tint, matching consumer notion, regular shape and convenient size are taken as signs of good quality and proper technology. Texture depends on the moisture content in the product. Elasticity, chewiness and some gumminess or juiciness can be appreciated in intermediate moisture food while in dry materials crunchiness or crispness are very important. For the latter products hygroscopic properties are significant because sorption of water strongly affects mechanical resistance and acoustic emission of crunchy materials (Duizer, 2001; Lewicki, Gondek, & Ranachowski, 2003; Marzec, Lewicki, & Ranachowski, 2002).

Ready-to-eat dry products, which need rehydration, can be consumed as moist solids or as liquids. Good examples of such materials are dried fruits, vegetables, legumes or meat, eggs and milk. Quality indices characteristic of a rehydrated material are quite different from those appreciated in ready-to-eat food consumed in a dry state. Solids eaten after rehydration should be characterized by color, size, shape and texture resembling the raw material. Hence, the rehydration rate and the rehydration degree are important parameters determining the quality of the product. Polymers, macromolecules and other constituents, should bind imbibed water, and its pressing out of the material should be limited. Water holding capacity becomes an important index of quality. Swelling accompanying rehydration and regain of the original size and shape also affect consumer assessment of the dry food quality.

The rehydrated material usually needs some preparation before consumption, mostly heating or cooking. Heating can be done by rehydration with hot water, but the procedure to be accepted by consumers must be fast. The product must be of instant type. Good examples of such products are mashed potatoes and puree vegetables. Quick cooking of rehydrated solids, in many cases, is an advantage.

Dry fruit and vegetable juices, powdered milk and dry coffee and tea extracts are examples of products, which are liquids after rehydration. Quality of these products is determined by such variables as wettability, dispersability, sinkability, or generally speaking by instant properties. In case of liquid containing particles and forming suspension the sedimentation rate may become an important quality factor.

The above discussed quality attributes of ready-to-eat dry product are purely physical in nature and assessed directly by the user. Aroma and taste are equally important, but they are appreciated during consumption and wetting with saliva or rehydration with water should liberate flavor characteristic to the given product. The consumer apprises both physical properties and flavor and they often decide about the acceptance or rejection of the product. However, they are safety and nutritional parameters, which cannot be valued by the consumer. To produce safe and nutritious food is the responsibility of the producer. Therefore, during designing of a dehydration process the safety of food must be assured in the first place and its nutritional value and quality attributes must meet consumer expectations.

Many dry products are produced as ingredients and they must fulfill requirements of the final product. Hence, their properties must meet not only the consumer expectations but also fit the requirements of further processing. The processing requirements are referred to ease of handling that is to such unit operations as conveying, mixing, dosing, etc. Thus flowability of dry material in bulk especially powders, low cohesiveness as well as low adhesion between particles and equipment surfaces will be important physical properties of the dry semi-products. For some materials mechanical strength will be important in order to minimize disintegration of particles during handling.

Dry semi-products as ingredients of the final product can be used in a dry state or after rehydration. For example in production of dry soup mixes all ingredients are in a dry state while in production of some sauces dry components are rehydrated before use or during processing. The way the dry semi-products are processed adds some additional requirements as far as physical properties are concerned. Ingredients of a dry mixed product must be compatible in their properties such as solubility, rate of water absorption, ease of wetting, higroscopicity or swelling. It is not feasible to produce a dry soup mix in which ingredients reach eatable quality at different time. In many mixes a recognizability of ingredients after rehydration is required. Therefore, their color, size and shape have to be easily identified and comparable with the raw material.

Dry ingredients used in production of fluid foods are rehydrated before mixing or rehydrate during processing. Rehydrated material must be characterized by high water holding capacity, appropriate mechanical strength and, in some cases, must be identified and comparable with the raw material.

Production of mixes based on dry products or containing dry ingredients must assure safety and nutritional quality of the final product. Thus, the contribution of the dry components to those quality attributes must be taken into account. Moreover, the final mix is characterized by a specific flavor, and the influence of each ingredient on it is important. In some cases the flavor of the mix is created by the flavor of one component, for example onion soup or beef noodle soup. In other cases, the flavor of the final product is an amalgamate of flavors of all ingredients or is created by the addition of flavoring materials. Hence, the way the dry semi-product is used enforces special requirements as far as flavor, especially aroma, is preserved during dehydration.

The above presented requirements resulting from the ways the dry product will be used shows that dehydration is a versatile method to design and create properties of the material needed in further processing and expected by consumers. However, to use drying efficiently a thorough knowledge of the process and processing variables is necessary.

Drying of food consists of three steps, which influence quality of the final product. These steps are: pre-drying processing, drying per se and post-drying treatment. The effect of each step on quality of the product depends very much on the kind of processed material and the way the product will be used.

Pre-drying processing

Pre-drying processing depends on the kind of the material to be processed. In case of liquids the pre-drying concentration is done either by water evaporation or membrane separation and cryconcentration.

Vacuum concentration in thin film evaporators is still commonly in use. Time-temperature history of the concentrated liquid is very important because during water evaporation some reactions can be initiated, and a certain loss of quality occurs. Besides economic advantages evaporation of water under vacuum makes it possible to strip aroma compounds and then to add them back to a dry powder. Hence, drying of liquids preceded by water evaporation under vacuum, yields products with aroma close to that of raw material.

Some liquids are treated with enzymes either before concentration or dehydration. The aim of this pretreatment is reduction of viscosity to avoid gelling and haze formation or removal of some compounds to assure natural color of the product. Production of dry fruit juices is the example of the former treatment, while production of egg powder is the example of the later enzymatic processing.

Liquid and paste-like foods can be whipped into stable foams and then air-dried. Foams dry rapidly and form very porous open structure. Usually addition of foaming agents is needed. Foam-mat drying developed in early 1960 s (Morgan, Graham, Ginnette, & Williams, 1961) becomes again a subject of interest (Karim & Wai, 1999; Sankat & Castaigne, 2004). Foaming of liquid or purée type foods makes possible their drying in a short time with assurance of high quality and instant properties of the product. The drawback of the method is the output of the dryer because foams are dried in a thin layer, hence the load per unit of the dryer surface is very small.

In case of solids multiple pre-drying processes are used. Generally they can be divided into chemical and physical treatments. The chemical treatments of the material before drying include sulfiting, immersion in sodium chloride, calcium chloride or sugars, use of surfactants and impregnation with biopolymers.

The effect of sulfiting in retarding nonenzymatic browning is well known (Burr & Reeve, 1973; Ozkan & Cameroglu, 2002). Immersion in solutions containing sulfites disinfects surface and reduces oxidation of liable food components, especially carotenoids (Jayaraman & Das Gupta, 1995; Negi & Roy, 2000; Sian & Soleha-Ishak, 1991). Moreover it facilitates drying (Kaymak-Ertekin, 2002; Levi, Ramirez-Martinez, & Padua, 1980; Piga, Poiana, Pinna, Agabbio, & Mincione, 2004; Ramirez-Martinez, Levi, Padua, & Bakal, 1977) due to reaction with proteins and breaking disulfide bonds, which also results in reduced firmness of the material (Riva & Masi, 1988). Reduced shrinkage (Riva & Masi, 1988) and improved rehydration (Barbanti, Mastrocola, Pinnavaia, Severini, & Dalla Rosa, 1991; Kaymak-Ertekin, 2002) are observed in dried materials pre-treated with sulfites. Inhibition of pectin esterase was reported by Levi *et al.* (1980). Sulfiting causes bleaching of anthocyanins and affects color of some fruits subjected to dehydration (Sian & Soleha-Ishak, 1991).

Treatment with calcium salts retards nonenzymatic browning of fruits and vegetables (Burr & Reeve, 1973). Calcium binds to the plant cell walls and cross-links, especially with pectins of the middle lamella (Ahmed, Mirza & Arreola, 1991; Glenn & Poovaiah, 1990; Moledina, Kaydar, Ooraikul & Hadziyev, 1981) hence affects texture and shrinkage (Lewicki & Michaluk, 2004) of material undergoing drying. It is also reported that treatment with calcium reduces respiration of fresh cut tissue (Bangerth, Dilley & Dewey, 1972; Poovaiah, 1986).

Soaking of material in NaCl solution prior to drying apparently affects no firmness (Riva & Masi, 1988) but, depending on concentration of salt, can cause some dewatering of the tissue. Dewatered material dries faster and better preserves color during drying (Baroni & Hubinger, 1998). Improved rehydration was also reported (Kaymak-Ertekin, 2002).

Immersions in acid solutions preceding drying affect material stability during further processing. Immersion in ascorbic acid solution (3.40%) or citric acid (0.21%) reduced bacterial load of tomatoes subjected to dehydration and rendered bacterial population below detectable levels after drying and storage (Yohan-Yoon, Stopforth, Kendall, & Sofos, 2004). Beef treated with marinade of different compositions and dried thereafter showed that survival of *Listeria monocytogenes* was affected by pre-drying treatment (Calicioglu, Sofos, Samelis, Kendall, & Smith, 2002a). A similar results were observed with *Escherichia coli* (Calicioglu, Sofos, Samelis, Kendall, & Smith, 2002b). Ascorbic acid solution (3.4%) reduced substantially *E. coli* counts on apples slices subjected to hot air drying (Burnham, Kendall, & Sofos, 2001).

Pre-drying treatment with sugars is done in two modes. The first one comprises relatively low concentration and short time treatment while the second one results in osmotic dewatering and substantial changes of properties of the material.

Dipping of plant tissue in solutions containing 15–30% sugars for 1–10 min improves rehydration of dried material (Curry, Burns & Heidelbough, 1976; Neuman, 1972; Speck, Escher, & Solms, 1977) preserves its microscopic structure (Jayaraman, Das Gupta, & Babu Rao, 1990; Neuman, 1972) and reduces shrinkage (Mazza, 1983). On the other hand, osmotic dewatering adversely affects reconstitution properties of dry material (Lenart, Iwaniuk, & Lewicki, 1993) and causes softening of the tissue (Lewicki & Łukaszuk, 2000; Monsalve-Gonzales, Barbosa-Camovas, & Cavalieri, 1993; Sitkiewicz, Lenart, & Lewicki, 1996). Ultrastructural damage to the tissue structure was also observed (Alvarez, Aguerre, Gomez, Vidales, Alzamora, & Gerschenson, 1994; Lewicki & Porzecka-Pawlak, 2005). However, this pre-treatment protects color, reduces oxidation of carotenoids (Shi & Le Maguer, 2001) and limits shrinkage of the material undergoing hot-air dehydration (Witrowa-Rajchert, Lewicki, & Lenart, 1995). In general, osmotic dewatering as a pre-treatment extends drying time (Lenart, 1995) and leads to quality attributes much different from those characteristic of a dried material pre-treated with other methods.

Infiltration of porous structure with biopolymers can increase mechanical strength and reduce shrinkage during dehydration, as well as improve texture of the dry material. Dextrans provided superior texture to dehydrated carrot and potato (Mudahar, Buhr, & Jen, 1991; Mudahar, Toledo, & Jen, 1990). In some cases application of biopolymers on the surface of the processed material facilitates drying and improves quality of the final product (Lewicki, Witrowa-Rajchert, & Nowak, 1998; Tripathi & Nath, 1989).

Surfactants and alkali affect pronouncedly dehydration of fruits in those cases in which they are dried whole, with the skin. Dipping of grapes in ethyloleate containing K_2CO_3 reduced drying time by half (Masi & Riva, 1988), while surfactant pre-treatment of basil leaves increased drying rate by a factor of 14 (Rocha, Lebert, & Marty-Andonin, 1993). Pre-treatment of apricots with ethyloleate containing metabisulphite decreased drying time (Mahmutoglu, Pala, & Unal, 1995). Drying time of plums was shortened by pre-treatment in ethyl oleate containing K_2CO_3 (Cinquanta, Di Mattco, & Esti, 2002).

The frequent treatment preceding drying is blanching. It can be done either at high temperature and short time (HTST) or at low temperature and long time (LTLT).

Beneficial effects of blanching depend on the way the process is done.

The HTST blanching is done at temperatures close to boiling and lasts for few minutes. During blanching solubles leak to the surrounding water hence the chemical composition of the material changes to some extent. Beneficial effects of the HTST blanching can be summarized as follows:

– inactivation of enzymes, which in untreated tissue could be active at least during initial stages of drying. Pectin methylesterase, peroxidase and polyphenoleoxidase are inactivated (Akissoe, Hounhouigan, Mestres, & Nago, 2003; Levi *et al*., 1980; Tripathi & Nath, 1989);
– changes in tissue structure. Loosening of the cellular network and separation along the middle lamella is observed (Gerschenson, Rojas, & Marangoni, 2001; Grote & Fromme, 1984), which results in softening of the tissue. Moreover, reduced cohesiveness of the matrix improves absorption of water and yields better rehydrating product (Kaymak-Ertekin, 2002);
– shorter drying time and increased drying rates. Heat treatment causes loss of turgor and affects permeability of the cellular membranes (Alvarez *et al*., 1994; Alzamora, Gerschenson, Vidales, & Nieto, 1996) which results in longer period of the constant rate drying (Strahm & Flores, 1994) and increased drying rates (Kostaropoulos & Saravacos, 1995; Piga *et al*., 2004; Rocha *et al*., 1993);
– better microbiological quality. Heating although short at temperature close to boiling decreases microbial load on the surface of the material (Bimi, Anand-Raj, Kumar, Amaldhas, & Sarma, 2004; Burnham et al., 2001;
– better color retention (Badifu, Akpapunam & Mgbemere, 1995; Piga *et al*., 2001);
– improved further processing. In puff drying of potatoes HTST blanching was necessary for successful puffing (Shilton, Bekhit, & Niranjan, 1998; Varnalis, Brennan, & MacDougall, 2001a).

Blanching at high temperature has also some adverse effects on properties of the material. Some biopolymers contract during blanching and cause shrinkage (Konanayakam & Sastry, 1988), which presses out cell fluids resulting in loss of solubles (Biekman, Kroese-Hoedeman, & Schijvens, 1996). Volatiles are more susceptible to changes during storage in those materials, which were blanched before dehydration (Di Cesare, Nani, Fusari, Viscardi, & Vitale, 2001; Di Cesare, Nani, Viscardi, Fusari, & Vitale, 2001). In general, blanching adversely affected quality of the dried apricots (Prain, Olaeta, & Undurraga, 1994).

The LTLT blanching results mainly in increased firmness and reduced shrinkage of the material during drying. It is done at temperatures ranging from 50 to 70 °C and lasts as long as 1 h. At these temperatures pectin methylesterase is activated, partial deestrification of pectin occurs and salt bridges with divalent ions, mostly calcium, are formed. It limits tissue softening and adds some mechanical strength (Gierschner, Jahn, & Philippos, 1995a,b; Heredia-Leon, Talamas-Abbud, Mendoza-Guzman, Solis-Martinez, Jimenez-Castro, Barnard, & Quintero-Ramos, 2004; Mohamed & Hussein, 1994; Seow, Ng, & Bourne, 1992; Stanley, Bourne, Stone & Wismer, 1995).

Freezing as a pre-treatment proceeding drying is a subject of few publications. Eshtiaghi, Stute, and Knorr (1994) reported higher drying rates of materials frozen before drying. Frozen fruits and vegetables prior to dehydration showed superior rehydration (Kompany, Allaf, Bouvier, Guigon, & Maureaux, 1991). Freezing disorders tissue structure (Garrote, Silva, & Bertone, 1988) and results in better diffusion (Oliveira & Silva, 1992) and shorter drying times (Eshtiaghi *et al*., 1994; Lewicki & Galewski, 1974).

Pre-treatments with high pressure or microwave energy were also investigated as means to improve quality of dried products. High pressure pre-treatment resulted in good color retention but the rehydration was incomplete (Eshtiaghi *et al*., 1994). Application of microwave heating reduced water content by 10–20% in raisins and resulted in faster drying and better color of the final product in comparison to commercial product. Microwave pre-treatment affected drying rate to the same degree as blanching in boiling water (Kostaropoulos & Saravacos, 1995).

Drying

While choosing the mode of drying and suitable equipment the following variables must be taken into account. Firstly it must be decided whether material undergoing drying can be contacted with air or not. If contact with air should be avoided or limited drying under vacuum or use of superheated steam can be considered.

Vacuum drying is used to dry heat-sensitive products because evaporation of water proceeds at temperatures as low as 30 °C. Heat is supplied by conduction and temperature of the product can easily be controlled. Due to molecular transport of evaporated water the process is long and can take as long as 24 h. Dry products are of very good quality but the shelf-life is dependent on the post-drying processes applied. Drying time can be reduced by application of pressure-regulatory system. The system operates by changing pressure in intermittent or prescribe cyclic pattern in the drying chamber (Maache-Rezzoug, Rezzoug, & Allaf, 2001). An excellent quality of dry material was obtained is such a fluctuating pressure system in which heat was supplied by microwaves (Szarycz, Kramkowski, Kaminski, & Jaloszynski, 2002).

Freeze-drying is a method in which water is removed from the material by sublimation. The process is long and done in a more expensive equipment than that used in atmospheric drying but the quality of the product is considered as the highest of any dehydration techniques. To achieve long shelf-life, the freeze-dried material needs special post-processing handling. Freezing preceding sublimation affects tissue structure (Lewicki & Pawlak, 2003; Lewicki & Porzecka-Pawlak, 2005) and can result in structure collapse during rehydration (Lewicki & Wiczkowska, 2005).

Superheated steam can be used as a drying medium. It works in a closed cycle as a carrier of evaporated water and a supplier of heat. Drying is done in an oxygen-free system with improved efficiency and good control of the dryer. High temperature of steam destroys microorganisms and the microbial quality of dried product is very good (Sokhansanj & Jayas, 1995).

If contact with air is permitted and drying under atmospheric pressure can be done the important variable for the product quality is the drying rate. Drying rate is affected by the way the material is contacted with air and the mode of heat supply.

Material undergoing drying can be stationary or in motion in respect to air. Stream of air contacted with stationary material gives low drying rates and uneven drying, especially if a layer of the product is thick. To facilitate drying the stream of air can be blown through the layer of a porous material. Then more even drying is also achieved, and properties of the product are more homogenous. Nevertheless drying of stationary material is usually long and yields products of inferior quality due to extended contact with oxygen and high temperature.

Setting a material in motion improves contact with air and facilitates heat and mass transfer. Drying rates increase and result in better quality of dried products. The material can be set in motion in rotating drums, by application of agitators or taking advantage of kinetic energy of the stream of air. Spouted bed drying and fluidized bed drying are the examples of the later way of causing material motion. A fluidized bed is easily formed with granular materials. Not readily fluidized materials can be dried in a spouted bed or fluidization can be achieved by application of vibrations to the bed of the material (Chua & Chou, 2003). Liquids can be dried this way if the inert material, in the form of beads, balls, forms the bed. Liquid spread in a thin layer on the beads dries fast and is removed by friction forces present in fluidized or spouted bed (Peron, Peksa, Kramkowski, & Rybikowski, 2001).

Impinging hot air can also set the material in motion. The process, depending on air temperature, can be used to dry or to fry foods (Lujan-Acosta & Moreira, 1997). Improved quality is obtained if superheated steam is used as impinging agent (Li, Sayed-Yagoobi, Moreira, & Yamsaengsung, 1999).

Regardless whether the material is stationary or it is in motion the most of the resistance to mass transfer is within the material. Under such situation intermittent drying proved to be advantageous. Time-dependent schemes of heat supply or air flux can be used separately or both at the same time (Chua, Mujumdar, & Chou, 2003).

Intermittent or step changing air flux was used to affect quality of dried material. When the airflow is interrupted the material relaxes and water concentration gradients decrease. Water diffuses to the surface and is easier evaporated when the airflow is again initiated. A total consumption of air is substantially reduced (Ratti & Mujumdar, 1993). Reduced contact with air fruited with better retention of β-carotene, and better rehydration of dried carrot (Pan, Zhao, Dong, Mujumdar, & Kudra, 1999).

Similar results were obtained with squash slices dried with a tempering period (Pan, Zhao, & Hu, 1999). Ascorbic acid retention was better in material dried intermittently in comparison to that dried in a continuous way. The longer was the tempering period the better was the retention of ascorbic acid (Chou, Chua, Howlander, Mujumdar, & Ho, 2000). Changes in air velocity are reflected in the product temperature, but the response is slow (Piotrowski & Lenart, 1998) and the adverse effects on product quality are much smaller than those observed with intermittent air temperature drying (Piotrowski & Lenart, 1999).

Energy needed for food dehydration can be supplied in numerous ways. The most popular is using hot air as a carrier of heat. Convective heat transfer coefficient is low, especially in those cases when material is stationary and air velocities are small. This is the surface heating process and temperature gradients are present within the material. The surface is exposed to drying temperature for much longer time than the interior of the material, and it can be used to create special properties of the dry product (Varnalis, Brennan, & MacDougall, 2001b). Hot air temperature is very important and is limited by the heat sensitivity of the material and expected quality of the final product. The adverse effect of temperature on quality of the dried material can be minimized by application of intermittent or stepwise change of its level during dehydration.

Intermittent temperature variation has a beneficial effect on quality of dried material. Better retention of ascorbic acid and color in guava, banana and potato was noted in comparison to conventional drying (Chua, Chou, Ho, Mujumdar, & Hawlander, 2000a; Chua, Mujumdarm, Chou, Hawlander, & Ho, 2000b). Research done by Piotrowski and Lenart (1998) showed that plant material temperature changes according to the step change of inlet air temperature, and the delay is short. The intermittent change of hot air temperature adversely affected appearance, color, firmness and taste of apple cubes dried in a cabinet dryer (Piotrowski & Lenart, 1999).

Acquistucci (2000) investigated continuous increase of drying air temperature and its effect on the quality of pasta. It was shown that fast increase of hot air temperature from 30 to 75 °C favored the Maillard reaction but the mode of temperature increase had no effect on the extent of nutritional damage caused by drying.

Infrared radiation can also be used to supply latent heat of water evaporation. It is not strictly speaking, surface heating only, because infrared energy is absorbed by surface layers to a depth dependent on the kind of heated material (Ginzburg, 1969). Moreover, surrounding air is practically not heated, hence, the energy is delivered directly to the material. Drying time is reduced in comparison to that of convective process (Nowak & Lewicki, 2004). Temperature of the drying material can be regulated by intensity of irradiation or by blowing air along the heated surface. Since, only surface exposed to infrared radiation is intensely heated the process can be used to create special properties of the final product. It has been shown that infrared drying improve quality of herbs (Chua & Chou, 2003). Application of intermittent infrared drying alone or in combination with convective drying was proposed (Zbicinski, Jacobsen, & Driscoll, 1992). Under these conditions both shorter drying time and improved quality were observed (Dostie, Seguin, Maure, Ton-That, & Chatingy, 1989; Tan, Chua, Mujumdar, & Chou, 2001).

Volumetric heating is advantageous in comparison to the surface heating. Temperature gradients are small and transport of water proceeds in an uniform temperature field. If material is porous a water vapor pressure gradient directed toward the surface can occur (Turner & Jolly, 1991). In microwave heating increased drying rates are observed (Drouzos & Schubert, 1996) and better quality of the final product is reported (Yongswatdigol & Gunasekaran, 1996). Microwaves can be applied continuously or in intermittent way in combination with continuous convective drying (Lewicki, Witrowa-Rajchert, & Sawczuk, 2001). Intermittent microwave drying of cranberries under vacuum yielded product of high quality, which was the better the larger was the ratio between power-off to power-on times (Gunasekaran, 1999). Quality of carrot and potato dried by intermittent microwave energy supplied to continuous convective drying was better than that observed with continuous microwave input (Chua *et al*., 2003). More uniform temperature distribution and internal pressure result in smaller shrinkage in comparison to that occurring during convective drying (Raghavan & Venkatachalapathy, 1999). Microwave vacuum dried carrots showed better retention of flavor compounds in comparison to that observed with freeze-dried and convective dried samples (Kotulski, Zawirska-Wojtasiak, & Wasowicz, 2001).

Volumetric heating can also be done by application of dielectric heating using waves with ratio frequencies. Especially combination of radio frequency heating with convective heating can substantially reduce drying time, minimize shrinkage and ensure a uniform level of dryness throughout the product (Chou & Chua, 2001),

In all systems in which the stream of air carries out evaporated water lowering its humidity can increase a drying potential of the air. It can be done either by the use of desiccants or by application of heat pump. Desiccant drying is suitable for drying heat sensitive materials such as herbs and mushrooms (Chua & Chou, 2003; Gürtas Seyhan, & Evranuz, 2000). Product excellent quality is obtained in a system easy to run and maintain, and inexpensive.

Heat pump drying uses a refrigeration unit to heat and dehumidify the air, which circulates in the system. Control of air temperature and humidity results in a well-controlled drying system assuring required product quality. Heat pump drying can yield food with good quality at reduced energy consumption (Rossi, Neues, & Kicokbusch, 1992). Intermittent variation of drying parameters or coupling convective heating with other modes of heat supply is proposed in recent publications (Chou & Chua, 2001; Chua *et al*., 2003).

Electric field was successfully used in accelerating convective mass transfer (Cao, Nishiyama, Koide, & Lu, 2004; Chen, Barthakur, & Arnold, 1994). No negative effects on the product quality were found but the time of drying was substantially reduces. In drying of potato slabs in a system enhanced with corona discharge, the process time was shorter more than 2-fold. In the case of rough rice drying time was reduced by 23–59% depending on the voltage applied. It is interesting to note that temperature of the material is almost the same as that in purely convective drying. Temperature of rough rice dried by convection augmented with 30 kV electric field was 1.63 °C higher than that of rice dried only by convection (Cao *et al*., 2004).

Post-drying processing

Considering post-drying processing it must be kept in mind that the dry product is not in a thermodynamic equilibrium state. Pre-drying treatments and drying *per se* incurred to the material a lot of stresses and initiated some processes which can continue during storage. Stresses can undergo relaxation and progress of physical and chemical changes strongly depends on the molecular mobility of the food components (Karel, 1991). The molecular mobility depends on water content and temperature of the material. At higher water contents or higher temperature mobility of molecules within the water phase is high and the material is susceptible to chemical, physical and biological deterioration. Hence, material should be dried to such final water content, which assures its expected shelf-life. Moreover post-drying treatments should minimize or protect the material from further changes.

The available literature shows that product is the most stable when it is in a glassy state (Le Meste, Champion, Roudaut, Contreras-Lopez, Blond, & Simatos, 1999; Slade & Levine, 1991). At least some dried products are in a glassy state and they should remain in that state during storage. The change from the glassy to rubbery state, at constant water content, occurs at a range of temperatures and is characterized by an average temperature called the glass transition temperature (T_g). At temperature lower than T_g product is in a glassy state and above it becomes sticky, structure collapses and flavor compounds are released (Roos, 1995). Hence, the product being in a glassy state should be stored at temperatures lower than T_g and fluctuations of temperature should be avoided (Kamman, Labuza, & Warthesen, 1981; Wu, Fitenmiller, & Power, 1974).

The T_g temperature is strongly affected by water content. Water acts as plasticizer and its increase decreases T_g substantially. It means that product being in the glassy state should be protected against water adsorption. It can be done by choice of appropriate packaging material.

Dried products, which do not reach the glassy state during processing, are in a rubbery or visco-elastic state. Although the mobility of molecules is limited changes of physical and chemical nature take place. Kinetics of these changes is strongly dependent on temperature and water content. Hence, keeping wetness of the material constant and storing it at justifiably low temperature assures expected shelf-life of the product.

A special consideration must be directed toward products containing lipids and lipid soluble substances, i.e. carotenoids. High porosity of dried materials increases contact with oxygen and promotes oxidation of lipid-like substances. In these products contact with air should be limited or excluded. It can be done by choice of barrier packaging material to oxygen and packaging in inert gas, like nitrogen. Oxidation of hygroscopic components of food can be limited by adjusting water content to the optimal level (Sian & Soleha-Ishak, 1991).

Post-drying processing is also intended to add value to the final products. In the case of powders it consists of agglomeration and coating (Fellows, 1988). Other products can be coated, enrobed or pressed in order to obtain new products or to increase their shelf-life.

Concluding remarks

Drying is a complex process, which affects food properties in many ways. Most of the changes incurred to the material by dehydration are disadvantageous to quality of the final product. However, the changes can be minimized by appropriate design of the drying process.

Designing drying of food must be done in a comprehensive way considering pre-drying and post-drying processes. Drying proceeded by adequately chosen preparation of the material yields a product with expected quality. That quality can be maintained during storage by application of appropriate post-drying processing. Because of complex influence on the product and many variables, which can be controlled during processing, drying is a versatile way to treat food and to create properties, which cannot be obtained with other processing methods.

A thorough knowledge of *pros* and *cons* of the drying process is needed in order to design the process and to obtain product of desired quality. Knowledge the way the drying influences food properties can be efficiently used to create new quality attributes and new functionality of the product.

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