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Review

New hybrid drying technologies for heat sensitive foodstuffs

S.K. Chou and K.J. Chua*

Department of Mechanical Engineering, National University of Singapore, Singapore (tel: +65-874-2234; fax: +65-779-1103.; e-mail: mpechuae@nus.edu.sg)

Drying is an indispensable process in many food industries. The drive towards improved drying technologies is spurred by the needs to produce better quality products. Improvement in quality of most food products translates into significant increase in their market value. The recent development of new hybrid drying technologies to improve food quality is in line with the present trend of 'quality' enhancement with reduced environmental impact. This review paper summarises some recent developments in hybrid drying technologies of interest to food industry. Numerous emerging technologies are listed and discussed in detail. The potential application areas for these hybrid drying technologies in product quality enhancement are identified.

Introduction

In many agricultural countries, large quantities of food products are dried to improve shelf-life, reduce packaging costs, lower shipping weights, enhance appearance, encapsulate original flavour and maintain nutritional value. According to Okos, Narsimhan, Singh, and Weitnauer (1992), the goals of drying process research in food industry are three-fold:

- Economic considerations: To reduce cost and improve capacity per unit amount of drying equipment, to develop simple drying equipment that is reliable and requires minimal labour, to minimize off-specification product and develop a stable process that is capable of continuous operation.
- Environmental concerns: To minimize energy consumption during the drying operation and to reduce environmental impact by reducing product loss in waste streams.
- Product quality aspects: To have precise control of the product moisture content at the end of the drying process, to minimise chemical degradation reactions, to reduce change in product structure and texture, to obtain the desired product colour, to control the product density and to develop a flexible drying process that can yield products of different physical structures for various end-users.

Though the primary objective of food drying is preservation, depending on the drying mechanism, the raw material may end up a completely different material with significant variation in product quality (Achanta & Okos, 2000). The principle motivation in developing hybrid drying technologies is to minimise product degradation and yet produce a product with the desired moisture content. The characteristics of food quality parameters are paramount considerations during the employment of different drying mechanisms to yield quality dried products. This paper serves to provide an overview of the newly developed hybrid drying technologies applicable for food products that are particularly sensitive to thermal treatment. Drying technologies incorporating convective and radiative heat transfer modes will be presented along with novel technologies such as super-heated steam drying, pressure-swing, microwave and radio-frequency drying. Other mechanical means to promote better drying rates without significant quality degradation will also be described. For drying of less heat sensitive foodstuffs, recent research in employing cyclic time-temperature varying profiles to enhance product quality and reduce drying time will be discussed. Experiments have indicated improvements as high as 20 and 50%, respectively, for reducing ascorbic

* Corresponding author.

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acid degradation and non-enzymatic browning of agricultural products when compared to constant temperature drying schemes. Recent works have recommended the implementation of simple on-line control strategies to yield high quality dried products. The impact of each hybrid drying technologies on energy will also be discussed in the light of recent interest in efficient use of energy. It is generally found that these drying technologies often result in shorter drying time to achieve the desired product moisture content resulting in a favourable improvement in the energy required per unit of water removed. Finally, for industries producing large quantities of dried foodstuffs, the potential of utilising a drying system involving multiple drying chambers will be discussed.

Product quality degradation during dehydration of food products

To understand how the employment of hybrid drying technologies would improve product quality, it is first important to understand the degradation process of foodstuffs. The quality of many food products degrades during dehydration above room temperature. The added heat and exposure time of the product at elevated temperature affects the rate of nutrient quality degradation. The types of food degradation during drying are listed in Table 1.

The loss of nutrient can be viewed as the decomposition of a particular chemical compound. This decomposition of a single monomolecular reaction may be described using zero or first-order kinetics equations (see Box 1).

As the temperature of the product increases, the reaction rate constant is increased. The dependence of the reaction constant on temperature implies that low temperature drying process would result in less nutrient degradation. A longer constant drying rate period increases the nutrient retention because, owing to evaporative cooling, product is at a lower temperature.

Box 1. Kinetic models for nutrient degradation of common food quality parameters

Nutrient degradation:
Decomposition of a single monomolecular reaction

$$C \xrightarrow{k_R} DC \quad (1)$$

T-dependence of k_R:

$$k_R = k_o \exp\left(-\frac{E_A}{R_g}\frac{1}{T}\right) \quad (2)$$

Arrhenius expression

$$\ln k_R = \ln k_o - \frac{E_A}{R_g}\frac{1}{T} \quad (3)$$

Rate of loss of the nutrient (zero-order equation)

$$\frac{d(C)}{dt} = -k_R \quad (4)$$

Rate of loss of the nutrient (first-order equation)

$$\frac{d(C)}{dt} = -k_R C \quad (5)$$

C = concentration of nutritive compound C at time t
DC = concentration of compound
E_A = reaction activation energy (kJ/mol)
k_o = constant, independent of temperature (min^{-1})
K_R = reaction rate constant, dependent on temperature (min^{-1})
R_g = Ideal gas constant (8.314 J/mol K)
t = Time (min)
T = temperature at whichthe reaction occurs (K)

Time-variable drying schemes

Several studies have been carried out to investigate different time-dependent drying schemes in different dryers on energy and product quality. These studies (summarised in Table 2) have found several interesting features of time-dependent drying. These features are:

Thermal energy savings.

- Shorter effective drying time.
- Higher moisture removal rates.
- Lower product surface temperature.
- Higher product quality. These include reduced shrinkage, cracking, and brittleness, improved colour and nutrient retention.

In convective drying, air temperature, humidity and velocity have a significant effect on the drying kinetics and quality of food products. It is then possible to minimise the product quality degradation solely based on the direct control of these parameters? Devahastin and Mujumdar (1999) have demonstrated via a mathematical model the feasibility and advantages of operating a dryer by varying the temperature of the inlet drying air in terms of reducing drying time by up to 30%. As technology advances, more options are available to improve product quality. One potential avenue in reducing quality degradation in food products during drying is to employ time-varying temperature profiles

Table 1. Factors that influence food quality during drying

Chemical	Physical	Nutritional
Browning reaction	Re-hydration	Vitamin loss
Lipid oxidation	Solubility	Protein loss
Colour loss	Texture	Microbial survival
Gelatinization	Aroma loss	

Table 2. Summary of different time-dependent drying studies

Study	Material and dryer type	Drying scheme
Sabbah, Foster, Hauge, and Peart (1972)	Corn (thin layer)	Dryaeration: Tempering periods: 0–4 h
Troeger and Butler (1980)	Peanuts	Intermittent drying: Airflow interrupted for 1 h in a 4 h drying period
Harnoy and Radajewski (1982)	Maize (bin dryer)	Intermittent drying: Aeration periods: 1–6 min Rest periods: 3–90 min
Giowacka and Malczewski (1986)	Wheat (fluidized bed)	Sinusoidal heating
Hällstrom (1986)	Compound fertiliser (fluidized bed)	Intermittent drying: Drying periods: 2.5–6 s Rest periods: 4.5–6 s
Zhang and Litchfield (1991)	Corn (thin layer)	Intermittent drying: Drying period: 20 min Rest periods: 0–120 min
Hemati, Mourad, Steinmatz, and Lagurie (1992)	Corn (flotation fluid bed)	Intermittent drying: Drying period: 20 min Rest periods: 0–60 min

that minimise quality change and dry the products to the desired moisture content within an allowable production time. Several researchers have studied the degradation of quality of dried products under sine or square wave temperature fluctuations (Kamman, Labuza, & Warthesen 1981; Wu, Eitenmiller, & Power, 1974) during storage. However, little work has been reported on the effect of temperature profiles on quality during convective drying process.

The impact of constant temperature drying on product quality is well known. Most of the product quality parameters such as non-enzymatic browning (NEB) and ascorbic acid (AA) content are often manifested by a progressive loss with increasing temperature. Chua, Mujumdar, Chou, Hawlader, and Ho (2000) have demonstrated that a two-stage heat pump dryer can be controlled to produce prescribed time-varying air temperature profiles to study the effect of non-uniform temperature drying on colour change of food products. They have also shown that by subjecting food products to different temperature profiles in a heat pump dryer, it is possible to reduce the change in individual colour parameters as well as in the overall colour change in the food products. High sugar content products such as banana favour a time-varying profile with a starting temperature of 30°C while high moisture products such as potato with low sugar content allow the use of higher temperature profiles to yield higher drying rates without any pronounced change in the overall colour change. Prescribing the appropriate cyclic temperature variation schemes, Chua *et al.* have shown that the percentage reductions in overall colour change for potato, guava and banana were 87, 75 and 67%, respectively.

On the basis of an extensive experimental study of the kinetics of batch drying and ascorbic acid (AA) degradation of guava pieces under isothermal as well as time-varying drying air temperatures, Chua, Chou, Ho, Mujumdar, and Hawlader (2000) have shown that with proper selection of the temperature schedule, the AA content of the guava pieces can be up to 20% higher that in isothermal drying without significant enhancement in drying time. Mishkin, Saguy, and Karel (1984) mentioned that optimisation may be attained by selecting a favourable combination of air temperature and time. Results from Chua, Majumdar, Chou, Ho, and Hawlader (2000) indicate that employing reduced air temperatures at the onset of drying followed by temperature elevation as drying proceeds yield better quality dried potato pieces. Recently, Pan, Zhao, Dong, Mujumdar, and Kudra (1999) have demonstrated clearly the advantage of intermittent drying as far as product quality is concerned. They have shown that in a vibrated bed batch drying of carrot pieces the retention of beta-carotene in the dried product is higher in intermittent drying while at the same time the net energy consumption is reduced and even the actual drying time can be shortened somewhat.

On-line control strategies to enhance product quality

The complex chemical reactions involved in the destruction of heat-sensitive materials during drying are well documented. Optimisation based on reduction of quality degradation of such processes is difficult. The traditional approach in food technology is based on employing well-known technologists and trial and error tests. Quite often, the task is time consuming and arduous. In most competitive food industries, such an approach is no longer considered appropriate. Yet modern food technology makes it imperative that solutions be found which will allow optimisation of complex processes with respect to complex quality factors (Karel, 1988).

Based on the current state of technology, the direction towards solutions to this problem lies in the combinations of line-sensors and expert systems with feedback response to allow immediate quality-related decision to be made. Sensors are placed in strategic locations to measure real-time quality parameters. The signals are then fed to expert systems, usually a software system that has the ability to receive and transmit decision signals to controllers. It is well known that reduced quality of food products because of browning effects and ascorbic acid degradation is mainly due to the thermal effect of the drying air. It is thus possible to reduce these quality effects through a proper feedback system to regulate the air temperature to reduce product temperature and thereby improve product quality.

Chua, Mujumdar, Chou, Ho, *et al.* (2000) illustrated an example of a real-time process control strategy for a heat pump dryer to improve the colour and reduce surface cracking of the dried products through time variation of the drying air temperature. A thermo-vision camera was used to capture the surface temperature profiles. Based on pre-defined constraints on the surface temperature, a signal from the computer is then sent to the PID controller to tune the temperature of the drying air. In this way, the quality degradation of the product can be minimised without compromising the drying rate excessively to achieve the desired final moisture content. Another example of a real-time process control of a dryer to reduce nutrient loss was also demonstrated by Chua, Mujumdar, Chou, Ho, *et al.* Experiments were carried out with hypodermic thermocouple needles to measure the transient temperature profiles of food products (Chou, Hawlader, & Chua, 1997). Based on these measured values, it is possible to tune the drying air temperature to prevent the internal product temperature from reaching a threshold value hence reducing thermally-induced nutrients degradation.

Hybrid drying system

The diversity of food products has introduced many types of dryers to the food industry. Often the selection of the appropriate dryer is based on the drying characteristics of the food product. For heat sensitive food products, the methods of supplying heat to the product and transporting the moisture from the product become the critical considerations for selecting the right dryer to achieve the desired product moisture content. In the following sections, the possibility of employing recent hybrid drying technologies for drying of foodstuffs is presented. The ability of these technologies to minimise quality degradation in the final dried product is also described.

Heat pump drying

There has been a growing interest in recent years in applying the heat pump drying (HPD) technology to foods and biomaterials where low-temperature drying and well-controlled drying conditions are required to enhance the quality of food products. High value products, which are extremely heat-sensitive, are often freeze-dried. This is an extremely expensive drying process (Baker, 1997). Therefore, there has been great interest to look at the heat pump drying system as a substitute system for freeze dried products. Table 3 presents a summary of recent work on heat pump drying of selected food products. The advantages and limitations of the heat pump dryer are as follows.

Advantages

- Higher energy efficiency with improved heat recovery results in lower energy consumed for each unit of water removed.
- Better product quality with well-controlled temperature schedules to meet specific production requirements.
- A wide range of drying conditions typically −20 to 100°C (with auxiliary heating) and relative humidity 15–80% (with a humidification system) can be generated.
- Excellent control of drying environment for high-value products and reduced electrical energy consumption for low-value products.

Limitations

- CFCs are used in the refrigerant cycle which are not environmentally friendly at this time.
- Requires regular maintenance of components (compressor, refrigerant filters, etc.) and charging of refrigerant.
- Increased capital costs.
- Limited drying temperature.
- Process control and design.

For many of the research studies conducted in Table 3, the common conclusion was that the heat pump dryer offers products of better quality with reduced energy consumption. This is particularly true of food products that require precisely controlled drying atmosphere (temperature and humidity). Heat-sensitive food products, requiring low-temperature drying, can take advantage of HPD technology since the drying temperature of the HPD system can be adjusted from −20 to 60°C. With proper control, it is also possible for HPD to produce freeze-drying conditions at atmospheric pressure (Prasertsam & Saen-saby, 1998b). As far as food drying is concerned, HPD offers an alternative to improve product quality through proper regulation of the drying conditions. Chua, Mujumdar, Chou, Hawlader, *et al.* have demonstrated that HPD can produce pre-selected cyclic temperature schedules to improve the quality of various agricultural products they dried in their two-stage HPD. They have shown that with appropriate choice of temperature-time variation, it is possible to reduce the overall colour change and ascorbic acid degradation by up to 87 and 20%, respectively.

Table 3. Recent work conducted on heat pump drying of selected food products

Researchers	Application(s)	Conclusions
Chou, Chua, Hawlader, and Ho (1998); Chou, Hawlader, Ho, and Chua (1998); Chua, Mujumdar, Chou, Ho, *et al.* (Singapore)	Agricultural and marine products (mushrooms, fruits, sea-cucumber and oysters)	The quality of the agricultural and marine products can be improved with scheduled drying conditions.
Prasertsan and Saen-saby, (1998a) and Prasertsan, Saen-saby, Prateepchaikul, and Ngamsritrakul (1997); (Thailand)	Agricultural food drying (bananas)	HPD is suitable for drying high moisture materials and the running cost of HPD is cheap making them economically feasible.
Theerakulpisut (1990) (Australia)	Grain	An open cycle HPD performed better during the initial stage when the product drying rate is high.
Meyer and Greyvenstein (1992) (South Africa)	Grain	There is a minimum operating period that makes the HPD more economical than other dryers.
Rossi, Neues and Kicokbusch (1992) (Brazil)	Vegetable (onion)	Drying of sliced onions confirmed energy saving of the order of 30% and better product quality due to shorter processing time.
Strømmen and Krammer (1994) (Norway)	Marine products (fish)	The high quality of the dried products was highlighted as the major advantage of HPD and introducing a temperature controllable program to HPD makes it possible to regulate the product properties such as porosity, rehydration rates, strength, texture and colour.

The ability of the HPD to regulate drying conditions quickly is another advantage for food drying. In countries where the level of the air humidity is high, high spoilage rates occur during the rainy season when the drying air is very moist. Clearly, HPD can reduce product spoilage by maintaining the humidity of the drying air through the regulation of latent heat removal at the evaporator.

Besides yielding better food quality, Rossi *et al.* (1992) has reported that onion slices dried by HPD used less energy in comparison to a conventional hot air system. Food products with high water content can be dried efficiently with a HPD. As the drying air absorbs more of this available energy, this latent heat energy can be transferred at the evaporators for higher heat recovery. Lower energy input is then required at the compressor to enable sensible heating of the air when it passes through the condenser.

Ginger dried in a heat pump dryer was found to retain over 26% of gingerol, the principal volatile flavour component responsible for its pungency, compared to only about 20% in rotary dried commercial samples (Mason, Britnell, Young, Birchall, Fitz-Payne, & Hesse, 1994). The higher volatile retention in heat pump dried samples is probably due to the reduced degradation of gingerol when lower drying temperatures are employed compared with higher commercial dryer temperatures. The loss of volatises varies with concentration, with the greatest loss occurring during the early stages of drying when the initial concentration of the volatile components is low (Saravacos, Marousis, & Raouzes, 1988). Since heat pump drying is conducted in a closed chamber, any compound that volatilizes will remain within the drying chamber, and the partial pressure for that compound will gradually build up within the chamber, retarding further volatilization from the product (Perera & Rahman, 1990).

To summarize, when the quality of dried food products is paramount, HPD offers an attractive option to enhance product quality and reduces spoilage through better regulation of the drying conditions.

Fluidized bed drying

Fluidized bed drying (FBD) has found many applications for drying of granular solids in the food, ceramic, pharmaceutical and agriculture industries. For drying of powders in the 50–2000 μm range, FBD competes successfully with other more traditional dryer types, e.g. rotary, tunnel, conveyor, continuous tray, etc. FBD has the following advantages (Mujumdar & Devahastin, 1999):

- High drying rates due to excellent gas-particle contact leading to high heat and mass transfer rates.
- Smaller flow area.
- Higher thermal efficiency.
- Lower capital and maintenance costs compared to rotary dryers.
- Ease of control.

However, FBD suffers from certain limitations such as:

- High power consumption due to the need to suspend the entire bed in gas phase leading to high pressure drop.
- High potential of attrition, in some cases of granulation or agglomeration.

- Low flexibility and potential of defluidization if the feed is too wet.

Recent novel fluidized bed dryers incorporating heat pump drying mechanism have been developed at the Norwegian Institute of Technology (Alves-Filho & Strømmen, 1996; Strømmen & Jonassen, 1996). The drying chamber receives wet material and discharges dried product through the product inlet and outlet ducts. The desired operating temperature is obtained by adjusting the condenser capacity while the required air humidity is maintained by regulating the compressor capacity via frequency control of the motor speed. According to Alves-Filho and Strømmen, this set-up can produce drying temperatures from −20 to 60°C and air humidities ranging from 20 to 90%. With these features, heat-sensitive food materials can be dried under convective air or freeze drying conditions. It is also possible to sequence these two operations (convective and freeze drying). It will be advantageous for drying of food and bio-products since freeze drying causes minimal shrinkage but produces low drying rates while convective air drying can be applied to enhance drying rates. Therefore, a combination of drying processes, e.g. freeze drying at −5°C followed by convective drying of 20–30°C, enables the control of quality parameters such as porosity, rehydration rates, strength, texture, colour, taste, etc. (Alves-Filho & Strømmen). Experiments performed at NTNU on various heat-sensitive materials such as pharmaceutical products, fruits and vegetables have shown that fluidised bed drying offers a better product quality but at higher cost. Since this technique produces a premium quality product, the incremental increase in drying cost may be offset by the higher market value fetched by these better quality products.

Soponronnarit, Yapha, and Prachayawarakorn (1995) have designed several prototype fluidized bed paddy dryers such as the cross-flow fluidized bed dryer. Using these fluidized dryers, Soponronnarit, Wetchacama, Swasdisevi, and Poomsa-ad (1999) studied the effects of drying, tempering and ambient air ventilation on moisture reduction and quality of paddy. Their experimental results show that after the three processes, the moisture content of the paddy can be further reduced from 33 to 16.5% with additional drying time of approximately 53 min. The quality of the paddy in terms of head rice yield and whiteness was observed to be acceptable. Sopornronnarit, Taweerattanapanish, Wetchacama, Kongseri, and Wongpiyachon (1998) found that the head yield increases more than 50% when the paddy was dried by the fluidization technique, employing drying air temperatures in the range of 140–150°C. As the initial moisture content of the paddy increases, the head yield increases accordingly. The final moisture contents of the paddy that maximize the head yield are in the range of 23.4–28.2%.

Superheated steam drying

Superheated steam drying is a non-polluting and safe drying method requiring low energy consumption. The principle behind this drying mechanism is based on using superheated steam for drying incorporating a vapour recompression cycle to recover heat. The entire system comprises a heat treatment chamber, a compressor, a heat exchanger for heat recovery and a blower system. The drying medium is superheated steam that performs drying in a closed-cycle picking up moisture from the product in the heat treatment chamber and condensing the evaporated water in a heat exchanger. Superheated steam drying for food products posses the following advantages (Sokhansanj & Jayas, 1987):

- Improved drying efficiency, sometimes as much as 50% greater than a conventional drying system.
- Environmentally friendly because it is a closed system and does not emit obnoxious gases to the environment.
- Product oxidation-free because there is no direct contact of hot oxygen-containing gas with the product.
- Hot steam is a better agent compared to dry air in destroying all stages of insects, moulds and micro-organisms found in foodstuffs.
- Better control of the dryer operation by adjusting the quantity of steam bled into the compressor resulting in achieving the desired dryness of the product.

Infrared drying

Infrared (IR) drying helps to reduce the drying time by providing additional sensible heating to expedite the drying process. IR energy is transferred from the heating element to the product surface without heating the surrounding air (Jones, 1992). Several researchers have demonstrated the significant advantages of IR drying. These advantages (Navarii, Andrieu, & Gevaudan, 1992) include:

- High heat transfer rates can be obtained with compact heaters.
- Easy to direct the heat source to drying surface.
- Quick response times, allowing easy and rapid process control (if needed).
- Incorporating IR into an existing dryer is simple and capital cost is low.

IR drying has been the subject of investigations by recent researchers. Works by Paakkonen, Havento, Galambosi, and Pyykkonen (1999) has shown that IR drying improves the quality of herbs and Zbicinski, Jakobsen, and Driscoll (1992) investigating convective air drying and IR drying have suggested intermittent irradiation drying mode coupled with convective air drying for heat sensitive materials such as food products. A schematic of an IR-assisted dryer is shown in Fig. 1.

Alternatively, to dry heat-sensitive materials, a combined radiant-convective drying method or an intermittent drying mode may be applied. An infrared-augmented convective dryer could be used for fast removal of surface moisture during the initial stages of drying, followed by intermittent drying over the rest of the drying process. This mode of operation ensures a faster initial drying rate. Therefore, an IR-assisted convective dryer would offer the advantage of compactness, simplicity, ease of control and low equipment costs (Mujumdar, 2000). Also, there are the possibilities of significant energy savings and enhanced product quality due to the reduced residence time in the drying chamber. On the flip side, the high heat flux may scorch the product and cause fire and explosion hazards (Mujumdar, 2000). Clearly, good control of the IR operation is essential to achieve the desired results in terms of drying kinetics and product quality, as well as to ensure safe operation. So a good feedback control is one that enables the IR power source to be cut off if excessively high temperatures are measured in the chamber, which may lead to overheating of the product.

Microwave drying

The physical mechanisms involved in heating and drying with microwaves are distinctly different from those of conventional means. Microwaves (MW) can penetrate into dielectric materials and generate internal heat (Jia, Clements, & Jolly, 1993). The internal heat generated establishes a vapour pressure within the product and gently 'pumps' the moisture to the surface (Turner & Jolly, 1991). Because of this moisture pumping effect, the moisture is forced to the surface and case hardening does not occur, enabling increased drying rates and improved product quality. Because of this unique advantage, microwave drying has been used in a number of industries, for example timber, paper, textile, food and ceramic industries (Schiffmann, 1987). However, the progress of microwave drying at the industrial level has been relatively slow because of its high initial capital investment and low energy efficiency when compared with conventional drying technologies. To improve on the economic aspects of microwave drying, it is necessary to incorporate energy conservation features. The use of microwave as a drying technology can perhaps produce a more commercially viable drying technology. The advantages of microwave drying can be summarized as:

- Enhanced diffusion of heat and mass
- Development of internal moisture gradients which enhance drying rates
- Increased drying rates without increased surface temperatures
- Better product quality

Presently, industrial microwave dryers could be commercially viable for food industries that require short drying time and higher product throughput at the expense of higher energy input. Also, food industries dealing with products that are susceptible to case hardening may consider microwave drying to be a good alternative in quality enhancement.

Radio-frequency drying

A limitation of heat transfer in conventional drying with hot air alone, particularly in the falling rate period, can be overcome by combining radio frequency (RF) heating with conventional convective drying (Thomas, 1996). RF generates heat volumetrically within the wet material by the combined mechanisms of dipole rotation and conduction effects which speed up the drying process (Marshall & Metaxas, 1998). A typical RF assisted convective dryer comprises a convective drying system retro-fitted with a RF generating system capable of imparting radio frequency energy to the drying material at various stages of the drying process.

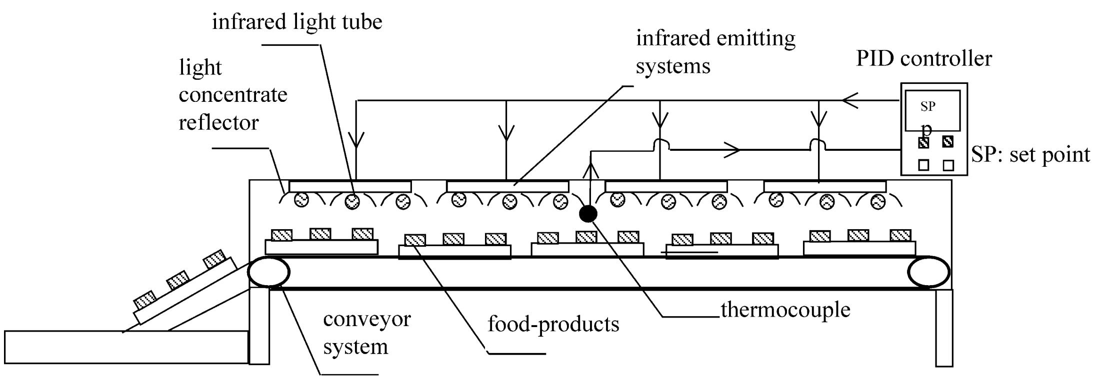

Fig. 1. Schematic diagram of IR assisted heat pump dryer.

Food materials that are difficult to dry with convection heating alone are good candidates for RF assisted drying. Food materials with poor heat transfer characteristics have traditionally been problem materials when it comes to heating and drying. Radio frequency heats all parts of the product mass simultaneously and evaporates the water *in situ* at relatively low temperatures usually not exceeding 180 or 82°C (Thomas, 1996). Since water moves through the product in the form of a gas rather than by capillary action, migration of solids is avoided. Warping, surface discoloration, and cracking associated with conventional drying methods are also avoided (Thomas, 1996).

The following are some of the characteristics that RF dryer possesses:

- RF drying improves the colour of products especially those that are highly susceptible to surface colour change since RF drying starts from the internal to the product surface, minimizing any surface effect.
- Cracking, caused by the stresses of uneven shrinkage in drying, can be eliminated by RF assisted drying. This is achieved in the dryer by even heating throughout the product maintaining moisture uniformity from the centre to the surface during the drying process.

The potential for direct application of RF drying in the food industries is appreciable for the following reasons:

- Simultaneous external and internal drying significantly reduces the drying time to reach the desired moisture content. The potential for improving the throughput of product is good. For example, in the bakery industry, the throughput for crackers and cookies can be improved by as much as 30 and 40%, respectively (Clark, 1997).
- By greatly reducing the moisture variation throughout the thickness of the product, differential shrinkage can be minimized. This promotes RF dryer for drying materials with high shrinkage properties.
- Closer tolerance of the dielectric heating frequency, (1) 13.56 MHz±0.05%, (2) 27.12 MHz±0.60% and (3) 40.68 MHz±0.05%, significantly improves the level of control for internal drying and thus has potential in industry that produces food products that require precision moisture removal (Clark, 1997).
- The moisture levelling phenomenon of RF drying ensures a uniform level of dryness throughout the product. Industries that have products requiring uniform drying, such as ceramics, can consider RF drying as a good alternative.

Pressure regulating drying

A very useful way to enhance the quality of heat-sensitive food products and yet achieve the desired product dryness is through the use of a pressure-regulatory system. The operating pressure range is usually from vacuum to close to one atmosphere. A totally vacuum system may be costly to build because of the need for stronger materials and better leakage prevention. Therefore, the system that is proposed here is recommended to operate above vacuum condition. The period of operating at lower pressure may be continuous at a fixed level, intermittent or a prescribed cyclic pattern. The suitability of employing the appropriate type of pressure-swing pattern depends chiefly on the drying kinetics of the product and its thermal properties.

More heat-sensitive materials often undergo a freeze drying process to minimize any quality degradation that may arise due to temperature effects. Generally, freeze drying yields the highest quality product of any dehydration technique. However, the cost of freeze drying has been found to be at least one order-of-magnitude higher than conventional drying system such as a spray-dryer.

According to Nijhuis *et al.* (1996), freeze drying (known as a suitable dehydration process for pharmaceutical and food products) is not suitable for the production of homogeneous films, as the films obtained are generally very spongy. Also, a freeze-dried product tends to be porous and the problem of rapid rehydration may arise once the product is exposed to a more humid environment. Moreover freeze drying is very energy intensive. The equipment is also more expensive than atmospheric pressure dryers. It is best suited for heat-sensitive materials, or when solvent recovery is required, or if there are risks of fire and/or explosion.

Maache-Rezzoug, Rezzoug, and Allaf (2001) have recommended a pressure-swing drying mechanism for food products requiring the production of homogeneous thin sheets. The experiments they conducted recently to dry a collagen gel in order to obtain a homogeneous film were carried out using a new process: dehydration by successive decompression. Their process involves a series of cycles during which the collagen gel is placed in desiccated air at a given pressure then subjected to an instantaneous (200 ms) pressure drop to a vacuum (7–90 kPa). This procedure is repeated until the desired moisture is obtained. A comparative study between this new pressure-swing drying process and conventional methods indicated that the respective saving in drying time could be as high as 480 and 700 minutes in comparison to vacuum and hot air drying systems.

Integrating such a pressure-swing system to any convective dryer would significantly improve product

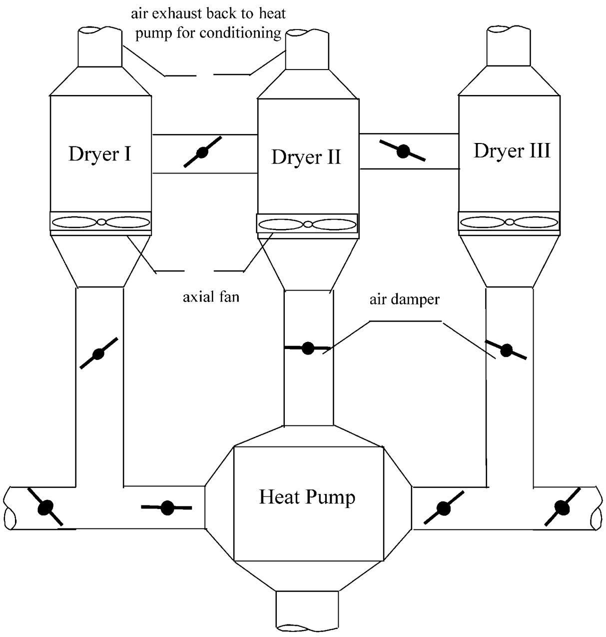

Fig. 2. Schematic layout of multiple-chambers heat pump drying process.

quality, via the use of lower drying temperature, and at the same time reduce the drying time which would result in a smaller drying chamber to obtain similar product throughput.

Future trends in drying — multiple dryers

Looking into the future of industrial dryers for food products, it is possible to design a drying system to serve several chambers drying an assortment of food products at the same time. A good example is one which uses a single low capacity heat pump to supply drying air to several different chambers according to a pre-programmed schedule. This is feasible because many food products have long falling rate periods. There are several advantages of operating a dryer with multiple drying chambers. They are:

1. Improved quality of products such as surface colour and reduced case hardening.
2. Improved energy efficiency with proper channelling of conditioned air to chambers.
3. Reduced capital cost and floor space requirement.
4. Easy temperature schedule control for different products in different drying chambers.

When only a marginal amount of convection air is needed to evaporate moisture, the drying chambers can be operated in sequence. The air from the heat pump can be directed sequentially to two or more chambers or can be divided up according to a pre-set schedule to two or more drying chambers, which may dry the same or different products. Thus, the heat pump can be operated at near optimal level at all times. Even if drying times for each chamber may increase due to the intermittent heat input, the overall economics should improve considerably. A smaller heat pump can double or triple the drying capacity, especially with the help of supplementary heating by IR, MW or RF.

A schematic diagram of a multiple-chamber drying process is shown in Fig. 2. It employs a heat pump system for air-conditioning. When the drying rate of the product approaches the second falling rate, the drying air is channelled to a secondary chamber to dry the freshly changed product of higher moisture content. Auxiliary heating may then be used to provide additional thermal requirement for drying.

From an economic perspective, the most attractive aspect of multiple-chambers drying is the reduction in capital cost, because one dryer is capable of accomplishing the drying task of two or more separate heat pump drying units. Further, a control strategy can be easily implemented through control of air dampers.

Conclusion

The versatility and importance of hybrid drying technologies is apparent from a cursory examination of the current literature. In this article, a short review has been provided on recent developments as well as trends in novel drying technologies. Some of the hybrid drying techniques, if combined in an intelligent fashion, would promote efficient drying in terms of enhanced product quality and reduction in energy consumption. However, R&D effort is still required to study system scale-up, optimization and control of these hybrid systems. We may not have covered all available novel drying technologies in the food industries in this review paper (for additional details on other less known but interesting novel drying technologies, refer to Kudra and Mujumdar (2001), but we hope the described hybrid technologies would give dried food producers a better understanding of the available technologies to enhance their product quality. As shown in this paper, there is a need for R&D in food drying and related areas particularly with the advent of new technologies. Mujumdar (1998) has pointed out the need for continuous industry–academic interaction for more effective R&D in drying technology. For a speedy transfer of novel technologies to the industry, both tangible and intangible contributions are needed from both the users and vendors of drying equipment to eventually commercialize them. It is hoped that in the coming decade more hybrid systems can be borne out to tackle even the most complex food drying problems.

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