Trends in Food Science & Technology 17 (2006) 524–534

TRENDS IN FOOD SCIENCE & TECHNOLOGY

Review

Trends in microwave-related drying of fruits and vegetables

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Microwave (MW)-related (MW-assisted or MW-enhanced) combination drying is a rapid dehydration technique that can be applied to specific foods, particularly to fruits and vegetables. Increasing concerns over product quality and production costs have motivated the researchers to investigate and the industry to adopt combination drying technologies. The advantages of MW-related combination drying include the following: shorter drying time, improved product quality, and flexibility in producing a wide variety of dried products. But current applications are limited to small categories of fruits and vegetables due to high start-up costs and relatively complicated technology as compared to conventional convection drying. MW-related combination drying takes advantages of conventional drying methods and microwave heating, leading to better processes than MW drying alone. This paper presents a comprehensive review of recent progresses in MW-related combined drying research and recommendations for future research to bridge the gap between laboratory research and industrial applications.

Introduction

The market for dehydrated vegetables and fruits is important for most countries worldwide (Funebo & Ohlsson, 1998). For example, US$ 7.6 billion worth of dehydrated vegetables, instant dried soup, and seaweed were consumed annually in Japan in 1998, excluding uses in restaurants and institutions (Japan Statistics Bureau, 2000). In China, the production of dehydrated vegetables is worth about US$ 800 million, including US$ 420 million for dehydrated red pepper, about 60–70% (about 230,000 tons) for export (Liu, 2003). In Europe the market for dehydrated vegetables was estimated to be worth US$ 260 million in early 1990s (Tuley, 1996). In the USA, there is a large market for dehydrated grape (raisin), garlic, onion and tomato (Liu, 2003). The world raisin production, mainly produced in the USA (297,557 tons) and Turkey (190,000 tons), was about 600,000 tons and valued at over US$ 125 million in 2000 (FAS Online, 2002). The growth in popularity of convenient foods in many Asian countries has stimulated increasing demand for high-quality dehydrated vegetables and fruits. This trend is expected to continue and even accelerate over the next decade in all emerging economies of the world.

Dehydration offers a means of preserving foods in a stable and safe condition as it reduces water activity and extends shelf-life much longer than that of fresh fruits and vegetables. Many conventional thermal methods, including airflow drying, vacuum drying, and freeze-drying, result in low drying rates in the falling rate period of drying (Clary, Wang, & Petrucci, 2005; Zhang, Li, & Ding, 2003, 2005). The long drying times at relatively high temperatures during the falling rate periods often lead to undesirable thermal degradation of the finished products (Mousa & Farid, 2002). MW drying offers opportunities to shorten the drying time and improves the final quality of the dried products.

Vega-Mercado, Gongora-Nieto, and Barbosa-Canovas (2001) considered the use of MW as the fourth generation drying technology. In general, a complete MW drying

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0924-2244/$ - see front matter
doi:10.1016/j.tifs.2006.04.011

process consists of three drying periods. (1) A heating-up period in which MW energy is converted into thermal energy within the moist materials, and the temperature of the product increases with time. Once the moisture vapor pressure in food is above that of the environment, the material starts to lose moisture, but at relatively smaller rates. (2) Rapid drying period, during which a stable temperature profile is established, and thermal energy converted from MW energy is used for the vaporization of moisture. In porous food structures, rates of moisture vaporization at different locations in foods depend, to a large extent, upon the local rates of thermal energy conversion from MW. (3) Reduced drying rate period, during which the local moisture is reduced to a point when the energy needed for moisture vaporization is less than thermal energy converted from MW. Local temperature then may rise above the boiling temperature of water. Even though loss factors of the food materials decrease with moisture reduction and the conversion of MW energy into heat is reduced at lower moisture content, product temperature may still continue to rise, resulting in overheating or charring. Development of temperature profiles in the MW heating period has been studied for various geometries. During MW drying processes, the heating period is relatively short and moisture loss is small (Bouraoui, Richard, & Durance, 1994). Much of the moisture loss takes place during the second period of MW drying, and moisture distribution in spherical foods is determined at this period through experimental measurements of moisture profiles and computer simulation. Dielectric heating with MW energy has found industrial applications in drying food products such as fruits and vegetables. There is a renewed interest in exploring the unique characteristics of MW heating for drying heat-sensitive materials (Funebo & Ohlsson, 1998).

MW drying alone has some major drawbacks that include uneven heating, possible textural damage, and limited product penetration of the MW radiation into the product. Other drying methods can be combined to overcome these drawbacks. For example, the uneven heating of single MW drying can be significantly improved by combined spouted bed drying if the material to be dried is of particulate nature that can be spouted (Feng & Tang, 1998).

In general, MW-related drying can meet the four major requirements in drying of foods: speed of operation, energy efficiency, cost of operation, and quality of dried products (Gunasekaran, 1999). The increased demand for plant-origin foods in fast-dehydrated form has increased interest in MW-assisted dehydration (Zhang & Xu, 2003). Several papers provide good reviews of the new drying technologies including hybrid drying technologies (Cohen & Yang, 1995; Nijhuis *et al.*, 1998; Vega-Mercado *et al.*, 2001; Zhang & Xu, 2003). However, there is a limited coverage of MW-related (or hybrid) dehydration technologies.

The objectives of this review article are to present an overview of the recent research progress in MW-related dehydration of fruits and vegetables. It also examines the relative advantages of those technologies and considers prospects for further research and possible industrial applications.

Limitations and advantages of MW-related drying

Limitations of MW drying alone and other slow drying methods

Several major drawbacks limit the application of MW drying by itself as a drying process. Although MW heating can readily deliver energy to generate heat in the moist portion within foods, one of its major drawbacks is the inherent non-uniformity of the electromagnetic field within an MW cavity. Success of MW heating of vegetables and fruits with high initial moisture contents often depends on uniformity of heating. Although this problem can be partially offset by using wave-guides and a rotating tray (Cohen & Yang, 1995), there are limits to the energy level that can be applied. Cohen and Yang (1995) reported that arcing occurred when the power was increased to above 500 W in their small-scale drying cavity. According to Clark (1996) and Nijhuis *et al.* (1998), excessive temperatures along the edges and corners of products may lead to overheating and irreversible drying-out resulting in possible scorching and development of off-flavors.

Due to the non-uniform electromagnetic field generated in cavities during MW drying, the materials to be dried should be in constant motion in the cavity to avoid any hot spots. Since only a limited amount of water is available during the final stages of drying processes, the material temperature can easily rise to a level that causes scorching. The final product temperature in MW drying is difficult to control, compared to that in hot-air drying in which product temperature never rises beyond air temperature.

Another major drawback is the penetration depth of the MW field into the products. Although MW power at 915 MHz penetrates to a greater depth than does at 2450 MHz, in large-scale drying applications, the penetration depth is still much smaller compared to that attained in radio frequency (RF) heating at 10–300 MHz (Wang *et al.*, 2003).

One more drawback is that too rapid mass transport by MW power may cause quality damage or undesirable changes in the food texture by ‘puffing’ (Nijhuis *et al.*, 1998). However, this may or may not be a limitation, depends upon the desired quality attributes of the final products.

Advantages of MW-related drying

To overcome some of the limitations of single MW drying, several strategies have been studied as follows: (1) combining MW drying with a great variety of other drying methods, (2) applying MW energy in a pulsed manner to maximize drying efficiency since continuous heating does not accelerate the rate of water removal when the process is mass transfer controlled (Gunasekaran, 1999).

To overcome the limitations of other slow drying processes, MW drying can significantly shorten the drying process by virtue of the following unique advantages: (1) adjustment of energy absorption level by the wet products automatically – moisture-leveling effect of microwaves; (2) possible selective heating of the interior portions – microwave focusing effect; (3) rapid energy dissipation throughout the material; (4) relatively minor migration of water-soluble constituents; (5) lower product temperatures in combination with vacuum; and (6) more efficient drying in the falling rate period (Feng & Tang, 1998; Nijhuis *et al.*, 1998; Torringa, Esveld, Scheewe, van den Berg, & Bartels, 2001).

Many researchers have successfully dried vegetables with high heat-sensitive compositions, and fruits with high sugar contents. In all cases the drying time is reduced significantly, and in most cases the quality of the dried food products is improved or kept the same as compared with only MW-dried or conventionally dried products (Zhang & Xu, 2003).

Combined MW-related drying applications

MW-assisted air drying (MWAD)

Hot air drying is an effective method of preserving perishable agricultural products (Min *et al.*, 2005). A high-moist product dried by hot airflow generally experiences a warming-up period, a constant drying rate period, and one or several falling rate periods. Drying with only hot airflow takes a long time and has low energy efficiency, especially during the falling rate periods. This is mainly caused by rapid reduction of surface moisture and consequent shrinkage, which often results in reduced moisture transfer and, sometimes, reduced heat transfer. Prolonged exposure to elevated drying temperature may result in substantial degradation of quality attributes, such as color, nutrients, and flavor (Zhang *et al.*, 2003, 2005). Severe shrinkage also reduces bulk density and rehydration capacity.

MW interacts directly with the polar water molecules to generate heat. Thus, MWAD significantly shortens drying time (Schiffmann, 1992). However, MW uses higher quality (and more expensive) electrical energy rather than thermal energy. Also, only 50–70% of the line power is converted into MW radiation by magnetrons and only a part of this field is absorbed by the drying material, depending on its loss factor, physical size and moisture content. But in properly designed systems, MW/convection drying can indeed improve product quality (Feng & Tang, 1998). MWAD is used in several industrial food processing applications in place of conventional hot air drying to reduce drying time and to improve food quality (Schiffmann, 1992).

Many research reports focus on vegetables and fruits, including apple (Ahrne, Prothon, & Funebo, 2003; Contreras, Martin, Martinez-Navarrete, & Chiralt, 2005; Funebo & Ohlsson, 1998; Funebo *et al.*, 2002), potato (Ahrne *et al.*, 2003; Bouraoui *et al.*, 1994; Jia, Islam, & Mujumdar, 2003; Khraisheh, Cooper, & Magee, 1997), carrot (Jia *et al.*, 2003; Prabhanjan, Ramaswamy, & Raghavan, 1995), kiwifruit (Maskan, 2001), olive (Gogus & Maskan, 2001), grape (Tulasidas, Raghavan, & Norris, 1993), mushroom (Funebo & Ohlsson, 1998), orange slices (Ruiz Diaz, Martínez-Monzó, Fito, & Chiralt, 2003), and asparagus (Nindo, Ting, Wang, Tang, & Powers, 2003). However, industrial applications of such drying methods are limited now.

There are three methods in which MW energy may be combined with hot air drying (Andrés, Bilbao, & Fito, 2004). They are as follows. (1) By applying the MW energy at the beginning of dehydration processes. In these cases, the interior of the products is quickly heated to the evaporation temperature and the vapor is forced outwards thus permitting the hot air to remove water from the surface. The improved drying rate is ascribed to the creation of a porous structure of the food material (puffing), which facilitates the transport of the water vapor. (2) By applying MW energy when the drying rate begins to fall. In this case the material surface is dry, and moisture is concentrated at the center. When applying MW at this moment, the generation of internal heat and, therefore, vapor pressures force the moisture to the surface to be readily removed by ambient environment. (3) By applying MW energy in the falling rate period(s) or at low moisture content to facilitate finish drying. When drying with hot air, food products suffer shrinkage of the structure which in turn restricts diffusion and causes a sharp reduction in drying rates. The outward flux of vapor and generated vapor pressure during MW-assisted drying, however, can help to prevent the shrinkage of tissue structure (Feng, Tang, Cavalieri, & Plumb, 2001). In some cases applying MW drying in the last stage of the dehydration process can also be very efficient in removing bound water from the product.

MW-assisted drying techniques are divided into general categories here, namely, MW-assisted drying in whole air drying process (MDWAD) and MW-assisted drying as final stage of air drying process (MDFSAD). To save energy and avoid risk of overheating, it is possible to apply MW field intermittently and such a scheme can be carried out with airflow or under vacuum conditions.

MW-assisted drying in whole air drying process (MDWAD)

A small-scale MDWAD dryer is shown in Fig. 1. This dryer has the capability of online measurement of sample weight and power adjustment. After setting the desired temperature in the controller the blower is started. The MW-convective dryer is run idle for 30 min to achieve a steady

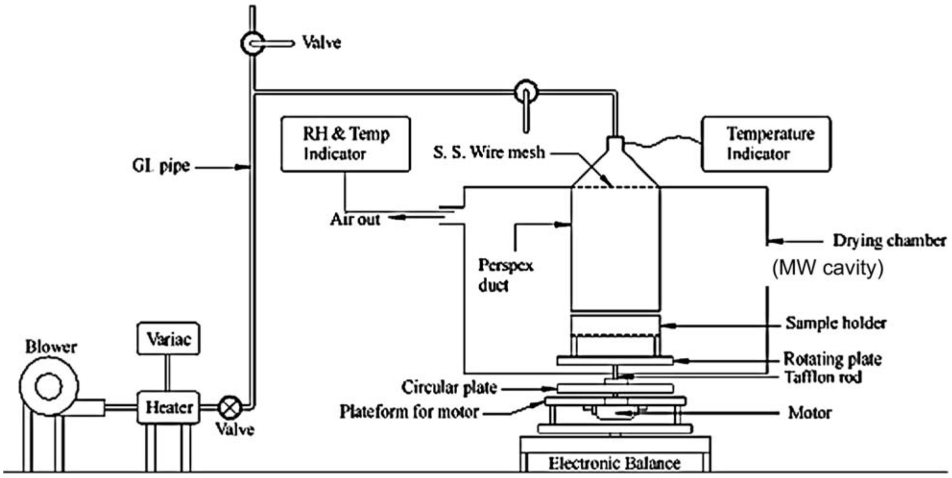

Fig. 1. Schematic of MW-convective testing dryer (Uprit & Mishra, 2003).

state with respect to desired drying conditions. For delivering specific power output, the ammeter current is adjusted.

Funebo and Ohlsson (1998) described MW-assisted air dehydration of apple and mushroom. The drying time for apple and mushroom was reduced with the use of MDWAD.

Jia *et al.* (2003) carried out a simulation study on combined convection and MW heating using potato and carrot as model materials. They found that up to a certain value of the moisture diffusivity, the drying rate increased with increment of moisture diffusivity. For a specific drying condition, the drying rate remains unchanged if the moisture diffusivity of a product is higher than this threshold value. However, moisture diffusivity of the product increases with volumetric heating using MW.

Andrés *et al.* (2004) studied the drying kinetics of apple cylinders under combined hot air–MW dehydration (MDWAD). They reported higher MW power effect than air temperature in reducing drying time. They developed an empirical model to estimate the drying kinetic constants as a function of the air temperature and the MW power level for fresh apples and impregnated apples. The tissue characteristics observed in the micrographics indicate that process variables not only affect the drying kinetics, but also lead to different macro- and microstructures of the final product.

Ruiz Diaz *et al.* (2003) modeled dehydration–rehydration of orange slices in combined MW/air drying. Despite the low levels of MW power used in their study, a sharp reduction in drying time of orange slices was obtained. No differences were observed in rehydration behavior as a function of the applied MW power.

MW-assisted drying as final stage of air drying (MDFSAD)

A typical apparatus for MDFPAD is shown in Fig. 2. The equipment can adjust power so that the field intensity in the cavity is changed continuously.

Much of drying time used for the dehydrating process of vegetables and fruits with high-moisture contents is in the final stage of drying. When applied to the final stage of drying, MW drying results in a high thermal efficiency, a shorter drying time and, sometimes, an improvement in product quality (Xu, Min, & Mujumdar, 2004).

Maskan (2001) investigated MDWAD drying of banana, a very difficult product to dry with traditional hot air drying method. MW finish drying of banana slices reduced the drying time by about 64%, the product had lighter color and higher rehydration value compared with that produced with the traditional airflow drying. MDWAD resulted in increased drying rates and substantial shortening of the drying time (by 89–40%). The author also studied the MDWAD of kiwifruits in terms of color change, shrinkage and rehydration. Shrinkage of kiwifruits which occurs during normal MW drying was not observed with MDFSAD. Interestingly, introduction of MW increased the rate of color deterioration and produced more brown products in kiwifruits. Some pretreatment prior to drying, e.g. osmotic dehydration in sucrose, may reduce the extent of discoloration.

MW-assisted vacuum drying (MWVD)

An experimental MWVD system is shown in Fig. 3. Applied MW power is controlled through the programmable logic controller interface.

In order to prevent significant quality degradation, vacuum drying is introduced to replace the conventional hot airflow drying. During vacuum drying, high-energy water molecules rapidly diffuse to the surface and evaporate into the vacuum chamber. The vacuum in the drying chamber sharply reduces water vapor concentration at the surface of the products. In addition, it lowers the boiling point of water in the interior of the products. These create large vapor pressure gradients between the food interior and surface, resulting in significantly rapid drying rates. Thus,

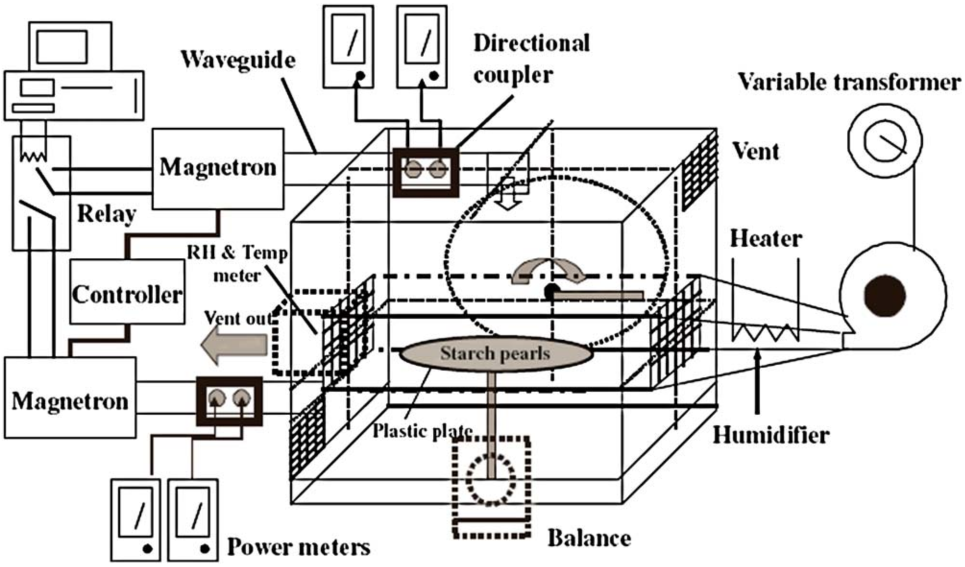

Fig. 2. A typical apparatus for convective and MW finish drying (Fu *et al.*, 2005).

for a given rate of drying, vacuum enables the products to be dried at a lower product temperature than that under atmospheric pressure. Moreover, the absence of air during dehydration reduces oxidation. Because of these advantages, the color, texture, and flavor of dried products are all improved (Gunasekaran, 1999). Vacuum drying is especially suitable for products that are heat sensitive such as fruits with high sugar contents and certain vegetables with high value.

External heat transfer by convection is, however, absent in vacuum. One must use MW or radiation or conduction in conjunction with vacuum to provide thermal energy needed for water evaporation. Vacuum drying has high operating costs due to the need to maintain vacuum over long periods of drying (Gunasekaran, 1999; Xu *et al.*, 2004).

To overcome the drawback of vacuum drying, MW-assisted combination drying with vacuum has been investigated to speed up the process. Most MWVD studies focus on the fruits and vegetables that need the ‘puffing’ quality in the final product. But the same method can also be applied to other food products, such as parboiled rice and shrimp (Lin, Durance, & Scaman, 1998). In particular, MWVD techniques are reported to be used successfully for the dehydration of grapes (Clary *et al*., 2005), cranberries (Yongsawatdigal & Gunasekaran, 1996), bananas (Drouzas & Schubert, 1996; Mousa & Farid, 2002), tomatoes (Durance & Wang, 2002), carrots (Cui, Xu, & Sun, 2005; Lin *et al*., 1998; Regier, Mayer-Miebach, Behsnilian, Neff, & Schuchmann, 2005), garlic (Cui *et al*., 2005), kiwifruit, apple and pear (Kiranoudis *et al*., 1997). These

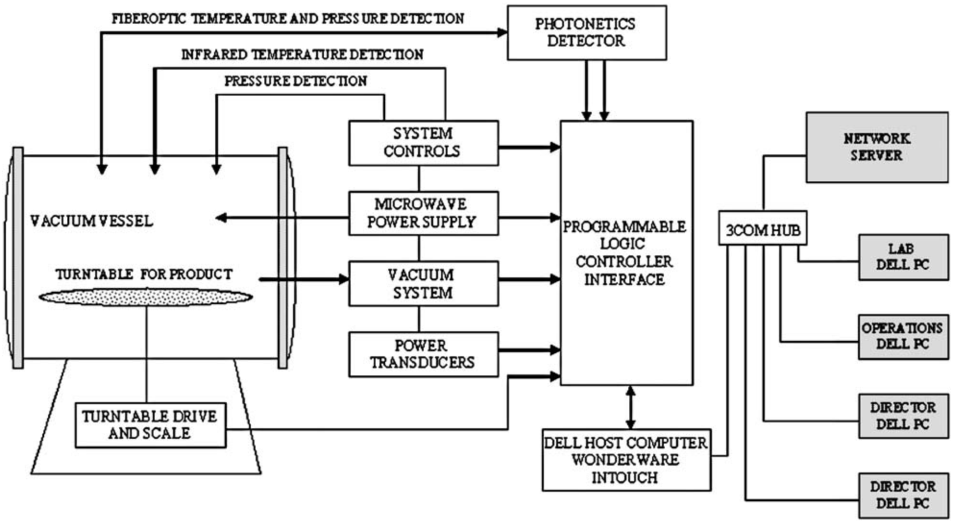

Fig. 3. Schematic diagram of the laboratory MW vacuum dehydration system (Clary *et al*., 2005).

products possess excellent quality in terms of taste, aroma, texture, and appearance.

Cui *et al.* (2005) investigated temperature changes during MW-assisted vacuum drying of sliced carrots and developed mathematical models for predicting the sliced sample temperature. Regier *et al.* (2005) compared the convectional drying of lycopene-rich carrots with MW vacuum drying and concluded that by MWVD the drying time was shortened to less than 2 h compared with 4.5–8.5 h in convection drying with similar carotenoid stability (50–70 °C).

Lin *et al.* (1998) compared MW-assisted vacuum drying of carrot slices with air drying and freeze-drying. MWVD sliced carrots had higher rehydration potential, higher α-carotene and vitamin C contents, lower density, and softer texture than those prepared by air drying. Although freeze-drying of carrot slices yielded a product with improved rehydration potential, appearance, and nutrient retention, the MWVD carrot slices were rated as equal to or better quality than freeze-dried samples by a sensory panel for color, texture, flavor and overall preference, in both the dry and rehydrated states. As noted earlier, energy savings and product quality enhancement are feasible when MW field is applied intermittently rather than continuously. It is also possible to lower the MW field strength as the material dries to avoid potential for overheating. Although not reported in the literature yet it is possible to apply MW field intermittently or continuously while the ambient pressure is cycled between atmospheric and vacuum levels.

Gunasekaran (1999) and Yongsawatdigal and Gunasekaran (1996) studied MW-vacuum drying of cranberries. Durance and Wang (2002) used 16 kW throughout a drying cycle to dry 13.7 kg of fresh tomatoes to a final moisture content of 18.7% (w.b.) in 0.81 h. Kiranoudis *et al.* (1997) studied the drying kinetics of apple, pear and kiwifruit in an MW-assisted vacuum drying system to develop a single parameter empirical mass transfer model.

MW-enhanced spouted bed drying (MWSD)

During MW drying processes, non-uniform heating may cause partial scorching in products with high sugar content. Various field-averaging methods have been developed to achieve heating uniformity. With such methods, a product is in constant movement within the MW cavity so that different parts of the product receive an MW radiation of about the average of the spatial electromagnetic field intensity over a period of time. The MW energy averaging can be accomplished by either mechanical means (Torringa *et al.*, 2001) or through pneumatic agitation (Feng & Tang, 1998). Fluidization provides pneumatic agitation for particles in the drying bed. It also facilitates heat and mass transfers due to a constantly renewed boundary layer at the particle surface. Therefore, combined fluidized or spouted bed drying is considered as an effective means of solving the uneven problem of the single MW drying.

Since coarse food particles such as diced or sliced materials are difficult to fluidize, especially when their moisture content is relatively high and surface is relatively sticky, spouted bed can be used for fluidizing coarse particles that are not suitable for a conventional fluidized bed. A reported MWSD at 2450 MHz is shown in Fig. 4. The system consisted of MW power source, cavity, hot-air source, spouted

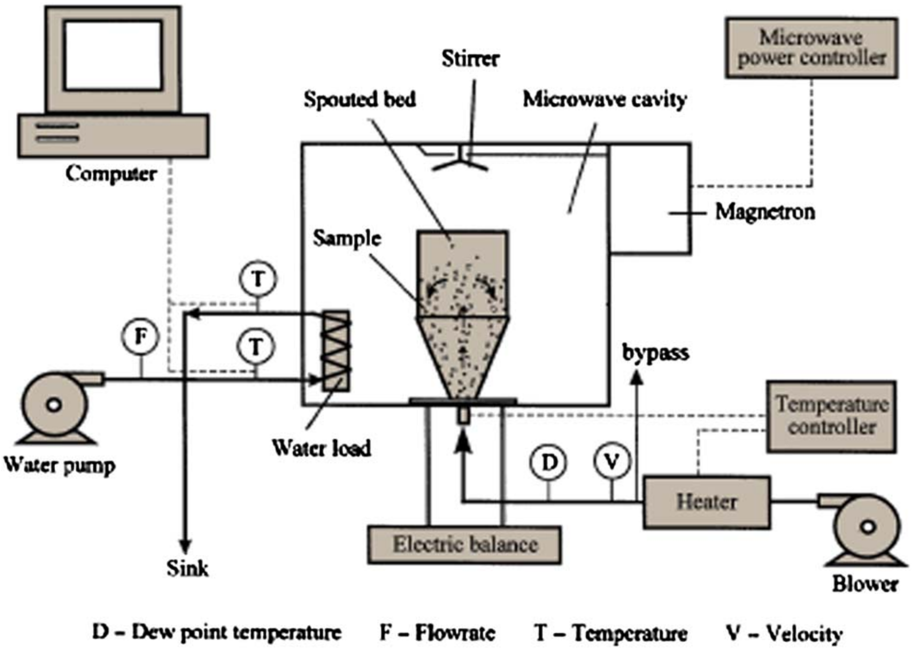

Fig. 4. Schematic of MW and spouted bed drying system (Feng & Tang, 1998).

bed, and water load. The water load was placed to protect the magnetron from overheating. In this area of research, almost all testing materials are granular or diced (or sliced) products of fruits such as blueberries and diced apple (Feng & Tang, 1998; Feng *et al.*, 2001) or vegetables such as sliced asparagus (Nindo *et al.*, 2003), though few reports on other kinds of granular materials, e.g., wheat by combined MW-enhanced fluidized bed drying, are available.

The MW-enhanced spouted bed (MWSB) drying method was used to dry diced apples and blueberries with high sugar contents (Feng & Tang, 1998). It is shown that MWSB sharply reduces the drying time and improves product quality, compared to conventional hot airflow drying methods. In the study on frozen blueberries, MWSB drying resulted in a lower bulk density, more acceptable color, and higher rehydration ratio compared with other drying methods (Feng & Tang, 1998). In the study on diced apples, with MWSB finish drying (from 24% moisture content to about 5%), drying temperature uniformity in diced apples was greatly improved, and the drying time was reduced by more than 80% as compared to that with a stationary bed. At the same time, products had less discoloration and higher rehydration rates. The effect of drying conditions on drying kinetics of MWSB was studied by Feng *et al.* (2001). The authors found under suitable drying conditions that, uniform MW heating was achieved as evidenced by uniform product color and temperature, and developed a heat- and mass transfer model to simulate MWSB drying process of diced apples.

Nindo *et al.* (2003) used MWSB to evaluate the retention of physical quality and antioxidants in sliced asparagus and found that MWSB drying produced asparagus particles with good rehydration and color characteristics. The suitable power level (2 W/g) and heated air temperature (60 °C) resulted in enhanced retention of total antioxidant activity of asparagus.

Chen, Wang and Mujumdar (2001) investigated, with numerical models, the effects of uniform, sinusoidal, and rectangular MW heat input patterns in fluidized bed drying of spherical particles by solving the coupled heat and mass transfer equations. Such a process can reduce potential for overheating while reducing the net energy consumption during drying.

MW-assisted freeze-drying (MWFD)

A simple MWFD apparatus is shown in Fig. 5, in which a conventional freeze dryer has the added capability of allowing MW to be introduced within the drying chamber. The initial capital costs of this equipment are clearly higher than those of conventional freeze-drying equipment, but are offset by more efficient use of the equipment afterwards with an increased drying rate.

Freeze-drying (FD) is used as a gentle dehydration method for heat-sensitive food, pharmaceutical and biological materials. It is well-known for its ability to keep the quality of products higher (color, shape, aroma, texture, biological activity, etc.) than any other drying methods due to its low processing temperature and almost no oxygen involved in the process. Other advantages of freeze-drying include its protection against chemical decomposition, easy rehydration, etc. (Tao, Wu, Chen, & Deng, 2005; Xu, Zhang, & Tu, 2005). However, freeze-drying is an expensive and lengthy dehydration process because of low drying rates, which lead to relatively small throughputs and high

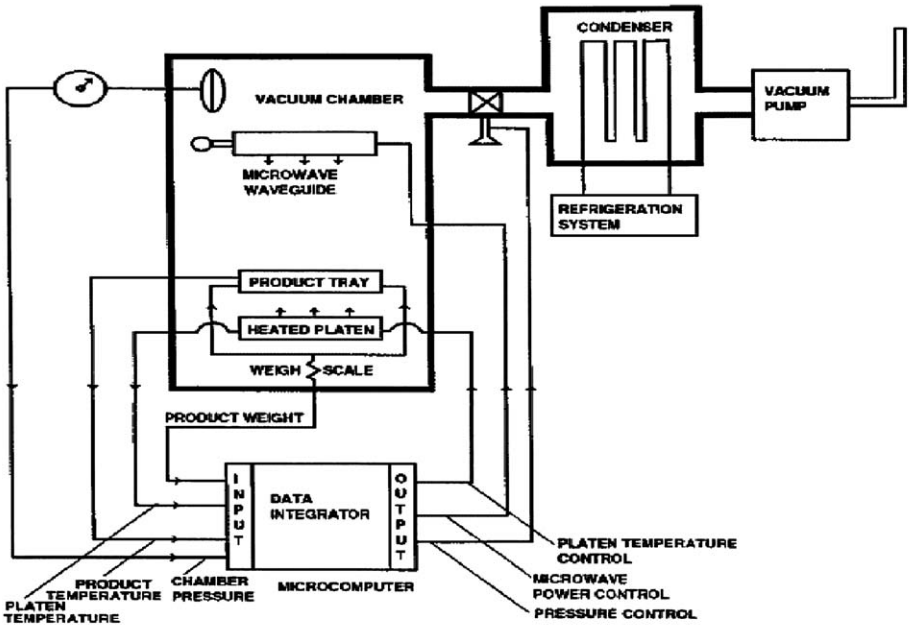

Fig. 5. A typical MW freeze-drying apparatus (Cohen & Yang, 1995).

capital and energy costs generated by refrigeration and vacuum systems (Liapis, Pikal, & Bruttini, 1996; Zhang & Xu, 2003). As such, the use of freeze-drying on the industrial scale is restricted to high-value products.

MWFD overcomes some of the above-mentioned disadvantages, as it has the characteristics of heating-up materials volumetrically. The difficulties found in heat transmission in FD disappear with MW heating. In the MWFD systems, energy is directly absorbed by the water molecules for sublimation within the food material, without being affected by the dry zone. As a result, the MW heating offers a good opportunity to increase the drying rate in FD. Experiments and numerical predictions all showed that the drying rate was significantly increased and the drying cost reduced with MW heating (Wu, Tao, Chen, & Deng, 2004).

Some researches have shown that MWFD is one of the most promising techniques to accelerate the drying process and to enhance overall quality (Sochanske, Goyette, Bose, Akyel, & Bosisio, 1990). This may be particularly helpful for intermediate value products, such as normal fruits and vegetables. Many experimental studies based on MWFD have demonstrated that MWFD provided a 50–75% reduction in drying time in comparison with conventional freeze-drying methods (Cohen & Yang, 1995). The MWFD products show higher volatile retention levels than the conventionally freeze-dried products. When peas were MW freeze-dried, the resulting product showed a higher rehydration capacity than by conventional methods. Other reported food materials using MWFD were ground meat (Cohen & Yang, 1995), beef (Wang & Shi, 1999), foamed milk (Sochanske *et al.*, 1990), skim milk (Wang, Chen, & Gao, 2005), and egg (Barrett *et al.*, 1997).

Since the first modeling on MWFD processes with pseudo steady state assumption, many reports on MWFD have been published on heat and mass transfer analyses of MWFD processes (Drouzas & Schubert, 1996; Tao *et al.*, 2005; Wang & Shi, 1999; Wu *et al.*, 2004). Tao *et al.* (2005) and Wu *et al.* (2004) studied conjugate heat and mass transfer processes within cylindrical porous media with cylindrical dielectric cores in MWFD and reported that the proper usage of cylindrical dielectric cores could dramatically reduce the drying time.

Wang and Chen (2003) studied MWFD of an aqueous mannitol solution. A coupled heat and mass transfer model was developed by considering distributions of the temperature, ice saturation, and vapor mass concentration inside the material being dried, as well as the vapor sublimation–desublimation in the frozen region. They found that the dielectric material (silicon carbide, SiC) significantly enhanced the MWFD process as applied to MWFD of skim milk (Wang *et al.*, 2005).

Wang and Shi (1999) studied the sublimation–condensation phenomena during MWFD over a wide range of different operating parameters, including electric field strength, sample thickness, and vacuum pressure. A sublimation–condensation model was developed for drying unsaturated porous media to evaluate the effects of sublimation–condensation region on heat and mass transfers during MWFD drying of unsaturated beef products. The results show that the effect of sublimation–condensation region on drying time is significant.

MWFD is, however, sometimes difficult to use in industrial applications due to plasma discharge problems. This happens when the electric field intensity in the vacuum chamber is above a threshold value. The ionization of the residual gases presented in the vacuum chamber leads to the appearance of a purple light, causing burning on the product surface. The occurrence of this phenomenon causes great energy losses and excessive heating on the dry zone of the material, seriously damaging the final product. The threshold value of the electric field is normally a function of chamber pressure. It happens to have the minimum value in the pressure range normally used in conventional freeze-drying operations. Thus, it is necessary to control the process parameters (vacuum pressure and MW power intensity) to avoid the appearance of this phenomenon. It is also very important to design a chamber with minimum localized concentration of electromagnetic field.

The electric field strength in a vacuum chamber is proportional to the power applied by the MW generator. To avoid the plasma discharge, the MW generator power should be controlled below the threshold value. Since the electric field experiences a transition period after turning on the generator until it reaches a steady stable condition, intermittent power levels can be used during this period to avoid possibility of arcing. According to Lombrana, Zuazo, and Ikara (2001), the MW application with the pressure cyclic strategy was equivalent to a power-directly regulated equipment. An MW on–off cycled strategy with simultaneous up–down modification of pressure was found as an acceptable power regulation method. In this case, chamber pressure becomes a convenient control parameter to avoid plasma discharge and subsequent melting of product.

In general, MWFD presents a complex control problem. The liquid water has a dielectric factor much higher than the one for the ice, and localized melting in the frozen zone of the food material may cause thermal-run away resulting in extremely uneven heating. Therefore, a suitable control system is needed for MWFD processes. Heat and mass transfer mathematical models have been developed to simulate the MWFD process with the aim of seeking the best operational conditions. A good knowledge of the product temperature is required as an indicator of final product quality (Lombrana *et al.*, 2001).

MW-assisted finish drying following osmotic dehydration (MDOD)

Osmotic dehydration has been widely studied in combination with MW drying (Prothon *et al.*, 2001). Osmotic dehydration involves immersing the materials for a given period of time in a hypertonic solution. It is a partial dehydration of materials through the process of osmosis. When sugar is used in the solution for osmotic dehydration, it has two main beneficial effects in helping produce a high-quality product: (1) inhibition of polyphenoloxidase and (2) preventing the loss of volatile compounds during dehydration, even under vacuum. A water loss of up to 50% of the initial material weight is attainable depending on several factors such as concentration, temperature, osmotic medium type, etc. After this initial osmotic step, a following drying method is necessary to produce shelf-stable dehydrated products.

Although air drying has been the main drying method following osmotic dehydration, MW or MW-convective drying of osmotically dehydrated products has been shown to improve the drying rate and retain product quality compared to air drying (Ahrne *et al.*, 2003; Contreras *et al.*, 2005; Funebo *et al.*, 2002; Piotrowski, Lenart, & Wardzynski, 2004; Prothon *et al.*, 2001; Raghavan & Silveira, 2001; Torringa *et al.*, 2001).

At present, almost all the tested materials for MDOD are fruits and vegetables, including apple (Contreras *et al.*, 2005; Funebo *et al.*, 2002; Prothon *et al.*, 2001), strawberries (Piotrowski *et al.*, 2004; Raghavan & Silveira, 2001), mushroom (Torringa *et al.*, 2001), and potato (Ahrne *et al.*, 2003). Piotrowski *et al.* (2004) studied the influence of osmotic dehydration on MW-convective drying of frozen strawberries and found that increasing MW doses in the range of 0–1.7 kW/kg in MW/air drying significantly shortened the drying time for initially osmotically dehydrated strawberries. Prothon *et al.* (2001) evaluated the effects of combined osmotic and MW/air drying of apple cubes on texture, microstructure, and rehydration characteristics and found that osmotic pretreatment before MW-assisted air drying increased the final overall quality of the product and firmness of the rehydrated samples. Although the drying time to reach the final moisture content (10%) was reduced, the presence of infused sucrose in the osmotically dehydrated tissue reduced the drying rate during the MW finish drying and the rehydration capacity in water for the pretreated samples.

Raghavan and Silveira (2001) investigated shrinkage characteristics of strawberries osmotically dehydrated in combination with MW drying (0.1 and 0.2 kW/kg power level). They reported that the shrinkage had a linear relation with moisture ratio, and affected by both osmotic dehydration process and power level of MW.

Feng *et al.* (2001) studied the effect of MW-improved drying and pretreatment on physical properties and retention of flavor volatiles of blueberries and investigated ethyl oleate and 0.2 M NaOH dipping solution followed by sucrose osmotic treatment. The drying kinetics of MWSD was compared with spouted bed drying and tray drying with dipping treatment.

Torringa *et al.* (2001) studied osmotic dehydration using NaCl solution as a pretreatment before combined MW-hot-air drying of mushrooms. The MW hot-air drying greatly improved the structure and bulk volume of dried mushroom. However, the geometry of whole mushrooms caused center heating. Slicing mushrooms into halves before MWSD improved heating uniformity, shortened drying time, improved rehydration properties, reduced shrinkage and increased open-pore porosity.

Contreras *et al.* (2005) studied the effect of vacuum impregnation with isotonic solution and MW heating (0.5 kW/kg) on structural changes during air drying of apple slices. MW heating resulted in an increased water-soluble pectin fraction, ranging from 0.313 to 0.390, and slightly increased (about 2 °C) glass transition temperature (Tg) in the MW-dried samples. The MW-dried slices had a harder texture when drying to final moisture content, but softer when rehydrated.

Funebo *et al.* (2002) studied MW and convective dryings of ethanol treated and frozen apple-physical properties and drying kinetics. The drying rate of apple in the combined drying was increased with freezing as a pretreatment. Ethanol as a pretreatment before drying improved the rehydration capacity and shrinkage of combining-dried apple.

Ahrne *et al.* (2003) compared drying kinetics and texture effects of two calcium pretreatments before MW-assisted drying of apple and potato cubes. Pretreatments with calcium influenced the strength of the plant tissue cell wall, and producing products of varying hardness after rehydration. The effect of two calcium pretreatments was quite different for apples and potatoes. For apples, calcium pretreatment at 20 °C increased the hardness of rehydrated apples compared with untreated apples, but calcium pretreatment at 70 °C had no effect on texture. For potatoes, calcium pretreatments both at 20 °C and at 70 °C significantly increased the hardness of rehydrated potatoes.

Conclusions and suggestions for future research

This review has shown that MW-related combination dryings provide unique opportunities in the development of advanced food drying technologies. Significant progresses and beneficial evidences have been reported on MW-assisted or MW-enhanced combination drying methods (MWAD, MWVD, MWSD, MWFD, MDOD, HMD, and three drying-stage combinations including MW drying). The main advantage of combining MW with other drying methods is to sharply reduce drying times. As long as the product temperature is controlled, the new drying methods can improve the product quality. However, most of the reported studies on technologies of MW-related combination drying were based on laboratory scale systems. There is a need for further studies to bridge the gap between laboratory research and industrial applications. Industrial implementation of those technologies relies on positive economic returns, considering the start-up and maintenance costs, need to use electricity, the complexity of operations, and added value to the final products. At present, the use of the new drying technologies is still limited to selected categories of high-value fruits and vegetables. Future research on MW-related drying should focus on the following areas.

Determination of combination order, type and conversion point of MW-related combination drying

As with other combination drying methods, the combination order, type and conversion point of MW-related combination drying that link the two different drying processes are very important. Since different vegetables and fruits have different physical and chemical characteristics, the microwave-related combination drying needs optimal combination order, type and conversion points (moisture content or drying time) from one drying method to another, which should be determined with experiments.

Process modeling and optimization of MW-related combination drying

Although several models of heat and mass transfers during MW-related combination drying processes such as MWVD and MWSD have been established for a selected number of materials, there is still a lack of theoretical analyses, modeling, and simulation for most MW-related combination drying processes on vegetables and fruits. Such studies are necessary for optimization of the complicated drying technologies. The general simulation models validated by experiments should predict the influence of the important parameters on the drying time and energy efficiency, and help to improve the operational performances for different combination drying processes.

Improving hardware and automatic control of MW-related combination dryers

As mentioned above, most previous researches used domestic MW ovens at 2450 MHz as the main MW sources. This leads to difficulties in scaling up the pilot-scale results to industrial-scale applications. Therefore, future studies should use larger MW systems that can simulate continuous processes based on industrial-level MW equipment. For two- or three-stage combinations, a study of continuous and automatic control is very important for further potential applications.

Study of special phenomena taking place in MW-related combination drying

Unique phenomena, such as plasma discharge during MWFD, can occur during MW-related combination drying. Studies on the mechanisms of these special phenomena are needed.

Acknowledgements

The authors are grateful to the China Scholarship Council for providing Senior Visiting Scientist Fellowship (No. 2003832025) to support this work done mainly by Dr Min Zhang at Washington State University, USA.

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