Chapter 19
Ultrasound-Assisted Hot Air Drying of Foods

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1 Introduction

This chapter deals with the application of power ultrasound, also named high-intensity ultrasound, in the hot air drying of foods. The aim of ultrasound-assisted drying is to overcome some of the limitations of traditional convective drying systems, especially by increasing drying rate without reducing quality attributes. The effects of ultrasound on drying rate are responsible for some of the phenomena produced in the internal and/or external resistance to mass transfer.

Ultrasonic energy transfer in gas media is more difficult than in liquid media, due to the poor impedance match between the radiating element systems and the air and between the air and the particle being dried. This chapter will show the different alternatives available for improving acoustic energy transfer in the gas media during drying. Stepped plate ultrasonic systems have shown high transfer efficiency working at direct contact between the samples and the radiating element. Despite their high efficiency, applying stepped plate ultrasonic devices to conventional drying systems is quite difficult. A vibrating cylinder constituting not only the drying chamber but also the acoustic radiating element represents an interesting alternative to stepped plate systems.

Using the vibrating cylinder ultrasonic application system, the influence of the main process variables which affect hot air drying has been addressed. This chapter shows the main results of the influence of the velocity and temperature of the air flow used during drying assisted by power ultrasound. It also addresses the influence of the acoustic energy level in the medium and the importance of the structure of the material being dried.

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2 The Food Drying Process

Although the preservation of food based on the partial removal of its water content dates back a long time, it is still one of the most relevant and challenging unit operations in food processing. The drive toward improved drying technologies is spurred by the need to produce better quality products (Chou and Chua, 2001) and to save energy. Because dehydration operations, in general, are very costly in terms of energy consumption, there is still a lot of room for improvement (Vega-Mercado et al., 2001). Drying is a notoriously energy-intensive operation that easily accounts for up to 15% of all industrial energy usage, often with relatively low thermal efficiency in the range of 25–50%. Thus, in order to reduce energy consumption per unit of product moisture, it is necessary to examine different methodologies to improve the energy efficiency of the drying equipment (Chua et al., 2001). The slowness of moisture transport is usually one of the main factors responsible for a long drying process that affects both the quality of the product and the energy consumption.

During the drying process, two types of resistance control water transport: internal resistance to the water movement inside the material and external resistance between the solid surface and the air (Rosselló et al., 1997; Simal et al., 2001). Internal resistance is a characteristic of the material, while external resistance depends on the thickness of the diffusion boundary layer.

Nowadays, several methods are applied to accelerate the loss of moisture and to minimize quality degradation in the final dried product. It is also very important to point out that the selection of the best drying technique is still determined by the type of product, its composition, and its physical properties (Vega-Mercado et al., 2001).

An increase in air velocity results in an increase of turbulence around the solid surface that reduces the thickness of the diffusion layer, thus attaining a higher drying rate (Cárcel et al., 2007a). An air velocity threshold is usually observed, above which an increase in the drying rate is no longer significant (Mulet et al., 1999). In this sense, fluidized bed drying is applied to reduce the external resistance of mass transfer in the drying of granular solid food. Infrared drying helps to reduce the drying time by providing additional sensible heat to expedite the drying process (Chou and Chua, 2001). For the drying of liquids, slurries, or purees, external resistance is overcome using spray driers (Vega-Mercado et al., 2001). In microwave drying techniques, the microwaves applied produce internal heating and a vapor pressure within the product that gently "pumps" the moisture to the surface (Turner and Jolly, 1991), thereby reducing the internal resistance of food to moisture transport. Another attempt to deal with the heat transport in conventional hot air drying combines radio frequency heating with conventional convective drying. The high processing costs of the superior quality products achieved by freeze drying are partially compensated by heat pump drying techniques (Strommen and Kramer, 1994). Other techniques to save energy and to improve the quality of products are based on the use of several air temperatures in stepwise drying (Chua et al., 2001).

The dehydration of food products can take place not only in gas–solid (or liquid) systems but also in liquid–solid systems such as osmotic dehydration (Mavroudis et al., 1998). This kind of process consists of immersing the solid in a hypertonic solution to dehydrate. Two main fluxes of matter take place, but moving in opposite directions: a moisture flux from the solid to the liquid and a solute flux from the solution to the solid. As a consequence, the changes in solid composition produce a decrease in the amount of water available for degradation reactions by enzymes and microorganisms (Cárcel et al., 2007b).

The use of high-intensity ultrasound may constitute a technique to accelerate the mass transfer in both liquid–solid systems (Cárcel et al., 2007c) and gas–solid systems (García-Pérez et al., 2006a).

3 Influence of Ultrasound on Mass Transfer

When ultrasound is applied in a solid–fluid system, it produces a series of effects that can affect both internal and external resistance to mass transfer between solid and fluid (Mulet et al., 2003). In liquid systems, the main mechanical effects of ultrasound are provided by cavitation. Cavitation consists of the appearance, growth, and collapse of bubbles inside the liquid which, for example, in water, generates temperature of about 40,000 K and pressure in excess of 1,000 atm in many localized points called "hot spots" (Mason et al., 2005). This bubble collapse, distributed through the medium, has a variety of effects. Thus, the collapse of bubbles is asymmetric near to the interfaces and produces a microjet that hits the solid surface (Mason, 1998). This is the main effect observed when using high-intensity ultrasound in cleaning operations. The microjets hitting the solid food surface may produce an injection of fluid inside the solid (Mason and Lorimer, 2002) and affect the mass transfer between the solid and the fluid. If cavitation is produced in the inner liquid phase of foods, it can facilitate moisture transport from the solid to the surrounding medium. Depending on the system characteristics, bubbles sometimes do not collapse and continue vibrating at the same frequency as the applied ultrasound (Leighton, 1998). This vibration also contributes to liquid agitation.

High-intensity ultrasound can generate a sound wind in the fluid produced by plane ultrasonic waves. This kind of agitation can reduce external resistance to mass transfer by increasing the bulk transport within the fluid (Mulet et al., 2003). The interaction of ultrasound in solid–fluid interfaces can produce a microstirring (Pugin and Turner, 1990). This microagitation is very important because it is formed in the immediate vicinity of the solid surface (Borisov and Gynkina, 1973) and exerts an important influence on the reduction of diffusion boundary layer thickness. All these effects influence external resistance and should affect mass transfer in the same way as mechanical stirring.

In the solid, ultrasonic waves produce a series of rapid compressions and expansions of the material that can be compared to a sponge squeezed and released repeatedly (Floros and Liang, 1994). This effect, known as the "sponge effect," helps the liquid to flow out of the samples (Gallego-Juárez et al., 1999). On the other hand, the compressions and expansions of the material can create microchannels which are suitable for fluid movement (Muralidhara et al., 1985).

The effects described can affect both internal and external resistances to mass or heat transport and are the reason why high-intensity ultrasounds are applied to improve some transport operations. In heat transfer processes, high-intensity ultrasound can be used to improve the convective heat transfer coefficient (Cárcel et al., 2002; Lima and Sastry, 1990; Sastry et al., 1989) in a similar way to mechanical agitation. The advantage of "ultrasonic agitation" is that it may increase the turbulence and the heat transfer in places where it is not possible to introduce a mechanical agitation device (for example, inside a hermetically closed recipient) (Riera et al., 2004). The cavitation and the microstirring generated by high-intensity ultrasound in freezing processes can not only accelerate heat transfer (Li and Sun, 2002) but can also promote ice nucleation and control crystal size distribution in the frozen product (Zheng and Sun, 2006).

In mass transfer processes, the use of high-intensity ultrasound has been considered because it enhances mass transfer in solid–liquid extraction processes (Li et al., 2007; Romdhane and Gourdon, 2002; Vinatoru et al., 1997). The yield and the quality of the extracts obtained with ultrasound are, in general, better than non-ultrasonic extracts (Jiménez et al., 2007; Xia et al., 2006). High-intensity ultrasound has also been used in solid–liquid systems to affect the mass transfer in processes such as the osmotic dehydration of apples (Cárcel et al., 2007c; Liang, 1993; Simal et al., 1998), the brining of meat (Cárcel et al., 2007b; Sajas and Gorbatow, 1978), cheese (Sánchez et al., 1999), and peppers (Gabaldón-Leiva et al., 2007). Fernández and Rodrigues (2007) applied high-intensity ultrasound in solid–liquid systems as a pre-treatment for air drying bananas. They observed an increase in moisture diffusion after the application of ultrasound and a decrease in the total process time, pre-treatment, and air drying, compared to pre-treatment in a hypertonic solution followed by air drying.

The application of high-intensity ultrasound in air drying processes has been known for more than five decades. However, its development has been very slow due to the technical problems of designing an efficient and powerful air-borne acoustic generator (Mason et al., 2005). Many of these problems have been solved in the last few years, and this has allowed research of the influence of ultrasound in air drying of some food products. Thus, acoustic drying has been applied in the drying of cereals (Muralidhara et al., 1985), vegetables (Da Mota and Palau, 1999; Gallego-Juárez et al., 1999; García-Pérez et al., 2006b; Riera et al., 2002), and fruits (Cárcel et al., 2007a; García-Pérez et al., 2006a).

It is interesting to be aware of the difficulties when applying high-intensity ultrasound in air drying processes and how some of these problems have been solved. The influence of the main process variables, such as air velocity, air temperature, and applied acoustic energy in the kinetic of dehydration, will be described below.

4 Main Systems for Ultrasonic Application in Hot Air Drying

A system for producing ultrasonic waves consists of three different main components: the generator, the transducer, and the application system. All of the methods used for producing ultrasonic fields convert another kind of energy (electric, magnetic, kinetic, etc.) into acoustic energy. The generator supplies the energy to the system, and the transducer is responsible for carrying out the conversion of the energy supplied by the generator into acoustic energy. A good transducer must achieve a good rate of energy conversion. Usually, the losses of energy are converted into heat that produces a temperature increase in the system. Finally, the application system must transmit the generated acoustic signal to the product.

The application system represents one of the main handicaps in the application of ultrasound. The transfer of acoustic energy generated from a transducer to a food material is relatively inefficient due to the mismatch between the acoustic impedances of the application system, the propagation medium, and the food (Mason et al., 2005).

In solid–liquid applications, there are lower differences in the acoustic impedances of media than in solid–gas applications. As a consequence, applications in solid–liquid systems are much more developed than in solid–gas media. For applications in solid–liquid systems, two main types of ultrasonic equipment are used for laboratory and the large-scale applications, i.e., bath and probe (sonotrode) systems. Bath systems consist of a metallic vessel with piezoelectric transducers attached to the bottom. When the transducers vibrate, they transmit their vibration to the whole vessel, and then the vessel transmits the vibration to the liquid medium contained in the tank. In the probe system, a horn is attached to the transducer. The horn transmits the ultrasonic signal to the medium. Its shape defines whether the signal is transmitted or amplified.

In solid–gas systems, the application of high-intensity ultrasound is more difficult than in solid–liquid systems due to the poor match between ultrasonic application systems and air. There are reflections in the interface with air of a high proportion of the acoustic signal generated, heating the transducer and not reaching the food. However, the efficiency of the energy transformation depends not only on the equipment itself but also on ultrasonication conditions (Raso et al., 1999). In this sense, air produces a greater attenuation (power loss) in the transmission of sound than liquids (Gallego-Juárez, 1998). Significant attempts have been made to alleviate these problems by developing a very powerful source of air-borne ultrasound that can achieve a more efficient energy transmission to the material.

4.1 Siren and Whistle Systems

Air-borne ultrasound systems convert the kinetic energy of a fluid into an acoustic wave. For that purpose, two main kinds of setups can be used: sirens and whistles. In sirens the fluid is forced to pass across a hole, thus generating turbulence that constitutes a mechanical wave. In whistles, the fluid is forced across a thin blade which causes the blade to vibrate. For each vibrational movement, the leading face of the blade produces a pressure wave (Mason, 1998). In liquid applications, the whistle constitutes a powerful tool for mixing and homogenization (Mason and Lorimer, 2002). The air applications is generally within human audible range, and this could be an obstacle to its use. Da Mota and Palau (1999) used a siren system to apply ultrasound during the drying process of onions. The results obtained showed that drying rates were increased by the acoustic vibration and that this increase depended on the sound frequency.

4.2 Stepped Plates

As previously mentioned, gas media present low specific acoustic impedance and high acoustic absorption. Therefore, in order to obtain an efficient transmission of energy, it is necessary to achieve the following requirements: a good impedance match between the transducer and the medium, large amplitude of vibration, and high-directional or focused beams for energy concentration. In addition, for large-scale industrial applications, a high power capacity and an extensive radiating area would be required in the transducers. Gallego-Juárez et al. (1999) developed a transducer with a flexural-vibrating plate radiator and an electronic unit for driving the transducer (Fig. 19.1). The extensive vibrating plate has a stepped profile driven by a piezoelectrically activated vibrator. The extensive surface of the plate increases radiation resistance, offering a better impedance match with air, thus increasing the power capacity of the system. The stepped surface avoids the phase cancellations produced in flat plate radiators. The system achieves high electroacoustic efficiency (75–80%) and produces a maximum intensity level of 175 dB working in the frequency range of 10–50 kHz .

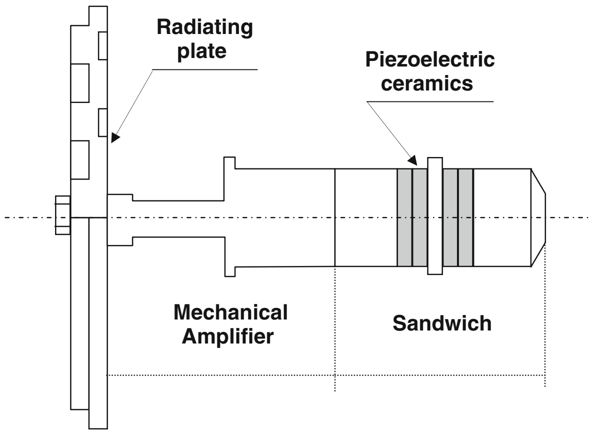


Fig. 19.1 Structure of the stepped plate transducer (Gallego-Juárez, 1998)

The stepped plate system has been used to apply air-borne power ultrasound in the drying of several vegetables (carrots, apples, and mushrooms), subsequently observing an increase in drying kinetics (Gallego-Juárez, 1998; Gallego-Juárez et al., 1999; Riera et al., 2002). If the stepped plate transducer is in direct contact with the samples, the dehydration rate is greater than in air-borne ultrasound drying. Riera et al. (2002) attributed this fact to the low penetration of ultrasonic energy in the vegetable material produced by the high mismatch between the acoustic impedance of media, the air, and the vegetables.

4.3 Vibrating Cylinders

The main disadvantage of the stepped plate transducer is its industrial scale application of conventional hot air drying, mainly the contact technique. A promising alternative technique, more adaptable to traditional hot air driers, has been developed (de la Fuente et al., 2005; García-Pérez et al., 2006a), allowing for the efficient application of high-intensity ultrasound during drying. This new ultrasonic application system was installed in a pilot-scale conventional hot air drier (Fig. 19.2), which was modified to install the new device. In the drying apparatus, two PID control algorithms allowed the temperature and the velocity of the air to be computer controlled. The drier is equipped with a pneumatic device, allowing samples to be weighed automatically at preset drying times (Sanjuán et al., 2003). The novelty concerns the drying chamber. The conventional container was replaced by an aluminum vibrating cylinder (internal diameter 100 mm, height 310 mm, and thickness 10 mm) driven by a piezoelectric composite transducer generating a high-intensity ultrasonic field inside the cylinder. The driving transducer consists of an extensional piezoelectric sandwich element together with a mechanical amplifier (Fig. 19.3). The ensemble has to be resonant at the frequency of the selected vibration mode

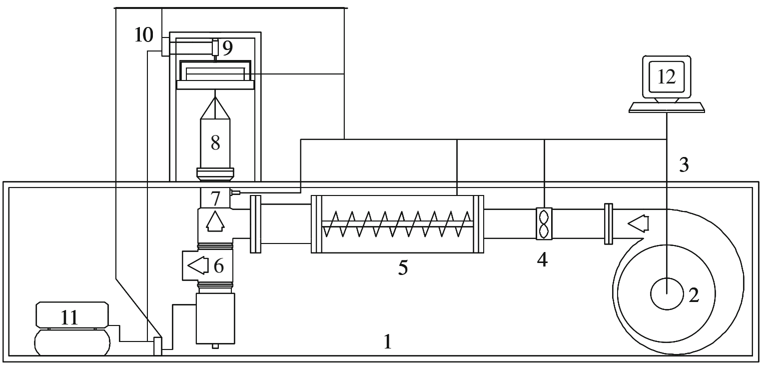


Fig. 19.2 Laboratory convective drier: 1 – metallic frame; 2 – fan; 3 – flux control; 4 – anemometer; 5 – heater element; 6 – pneumatic valve; 7 – measurement and control of temperature; 8 – drying chamber; 9 – balance; 11 – air compressor (Sanjuán et al., 2003)

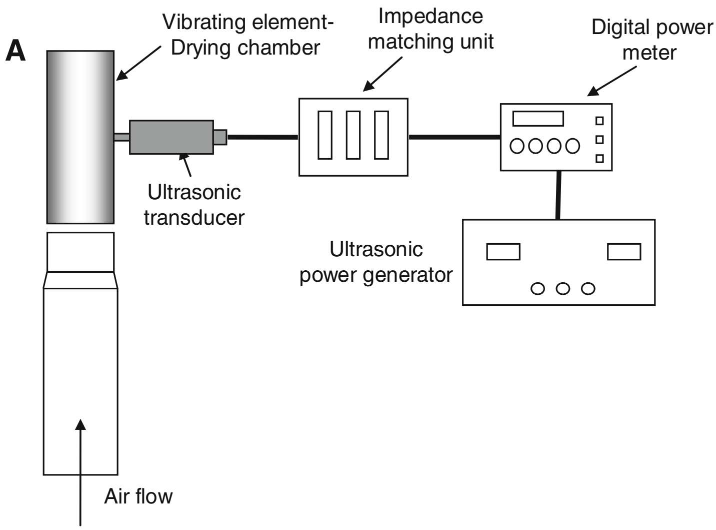


Fig. 19.3 Experimental setup for hot air ultrasound combined drier (Cárcel et al., 2007a)

of the chamber. For that purpose, the vibration modes of the cylindrical chamber were analyzed using finite element methods (FEM). The resonant frequency of the chamber at 21.8 kHz corresponds to a flexural mode of the tube with 12 nodal lines (Fig. 19.4). The acoustic field inside the chamber was calculated by FEM and it was found that for a displacement of 5 μm at the edge of the tube, an average sound pressure level of about 156 dB was obtained. The extensional transducer was screwed to the central part of the cylindrical chamber which corresponds to a point of maximum displacement. The vibration amplitudes along the tube were measured with a Polytec Scanning Vibrometer and fitted with numerical predictions calculated by FEM. The electrical characteristics of the transducer were measured (IZI = 365 Ω) by an impedance analyzer HP-4192 A in order to properly match the output impedance of the electronic generator. The acoustic field inside the chamber was measured, and raster scans were carried out with a 1/8″ GRAS microphone parallel to the tube axis (y-axis) and perpendicular to the radial distance to the walls (x-axis) to measure the sound pressure levels (SPL) in a plane of symmetry. An average SPL of about 154.3 dB was measured in the tube for an electrical power applied to the transducer of 75 W. Therefore, a high-intensity acoustic field inside the tube was obtained with relatively low applied power. Such a result confirms the FEM predictions for the acoustic field and the feasibility of using this type of system to ultrasonically assist a hot air drier. These measurements were carried out without air flow.

The vibrating cylinder setup described was used to study the effect of high-intensity ultrasound on hot air drying of food. This setup allowed the influence of high-intensity ultrasound on the effects of the main process variables during hot air drying to be addressed.

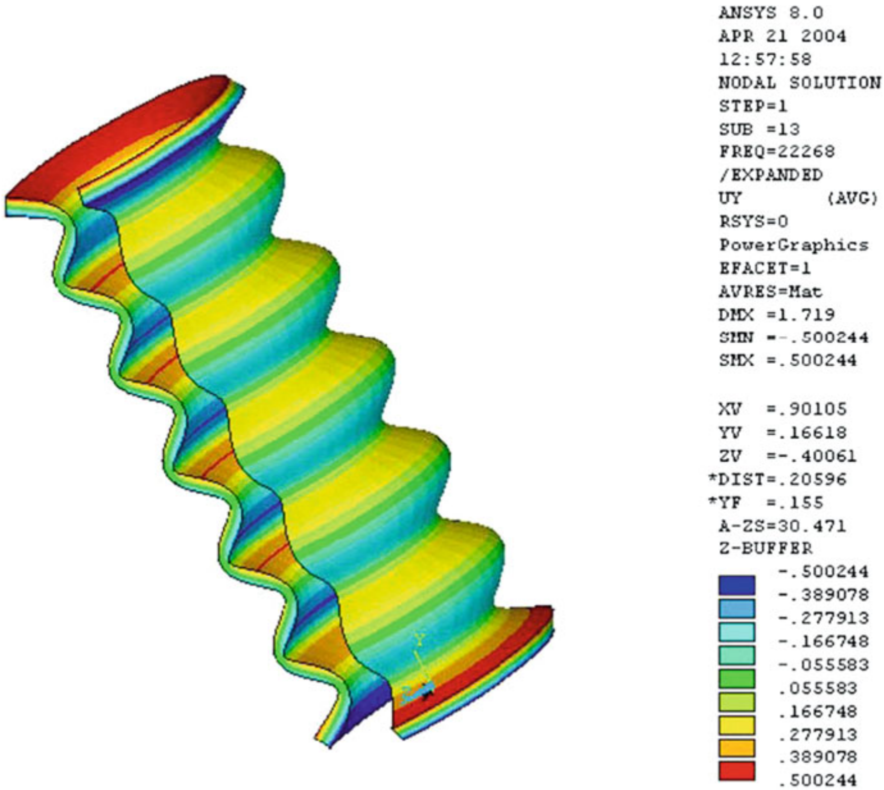


Fig. 19.4 Flexural mode of the ultrasonic drying chamber simulated by FEM (21.8 kHz) (García-Pérez et al., 2006a)

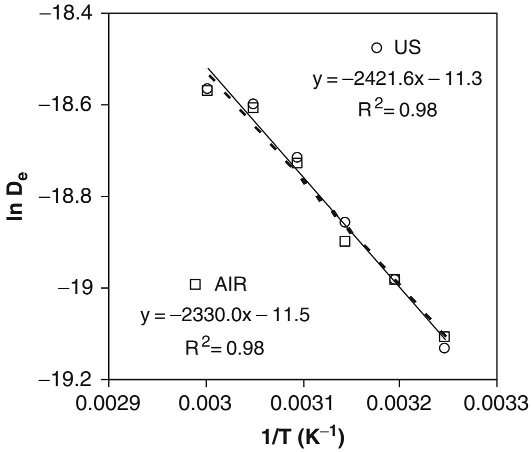
5 Influence of Some Process Variables on Hot Air Drying of Foods Assisted by High-Intensity Ultrasound

Although the literature provides scarce results, some preliminary conclusions can be reached. These conclusions about how the application of high-intensity ultrasound affects convective drying were obtained by analyzing experimental drying kinetics of several products (carrot, persimmon, apricot, and lemon peel) and quantified by using diffusion models to consider external resistance (ER model) or neglect it (NER model), which were developed for the different geometries being considered (cubes, cylinders, and slabs). It needs to be pointed out that a larger research effort is needed to apply ultrasound-assisted drying on a large scale. Although several systems have been used, there are two that seem particularly promising: stepped plates and vibrating cylinders. The most relevant results using vibrating cylinder ultrasonic systems will be noted in the next sections. The variables studied include variables related with air (temperature and velocity), with the raw matter being treated (some vegetables and fruits), and also with the characteristics of the applied acoustic field (applied energy).

5.1 Effect of Air Velocity

Using a vibrating cylinder, hot air drying experiments using eight portions of apricots were carried out under fluidized bed conditions (air velocity between 10 and 14 m/s) and different air temperatures (30, 35, 40, 45, 50, 55, and 60°C) without (AIR) and with power ultrasound application (US, 21.7 kHz, 75 W). A close fit of experimental drying data was obtained using an NER model for slabs (L=10 mm), which provided percentages of explained variance of greater than 99%. The effective moisture diffusivities (D_e) identified showed an Arrhenius-type relationship with temperature (Fig. 19.5), which was not affected by power ultrasound application. No effect of ultrasound was found under these experimental conditions characterized by a high air flow. This discovery pointed to the fact that high air velocity may affect the intensity of ultrasound, since previous results showed the influence of ultrasound on drying rate increase (Gallego-Juárez et al., 1999).

Fig. 19.5 Influence of air temperature (°C) on effective moisture diffusivity. AIR and US (21.7 kHz, 75 W) drying of apricots on fluidized bed



For that reason, new experiments without ultrasound (AIR) and with ultrasound (US) were considered. AIR and US (21.7 kHz, 75 W) drying kinetics of persimmon cylinders (diameter 13 mm and height 30 mm) were carried out at 50°C and at several air velocities: 0.5, 1, 2, 4, 6, 8, 10, and 12 m/s (Cárcel et al., 2007a). A different effect of power ultrasound was found at low and high air velocities (Fig. 19.6). In experiments carried out at 0.5 m/s, applying power ultrasound reduced the drying time required to reach a moisture content of 1 kg/kg of dry matter by 28%; however, no effect was found at 12 m/s. As can be observed in Fig. 19.7, the influence of power ultrasound on D_e values identified using an NER model was only found at air velocities lower than 6 m/s. For that reason, no effects of power ultrasound

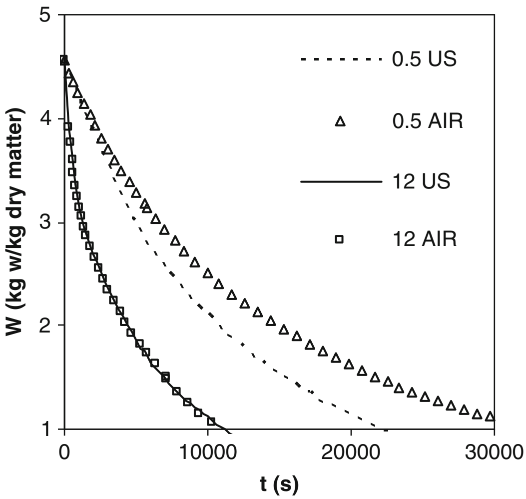


Fig. 19.6 AIR and US (21.7 kHz, 75 W) drying kinetics of persimmon cylinders at low (0.5 m/s) and high air velocities (12 m/s) (García-Pérez et al., 2007)

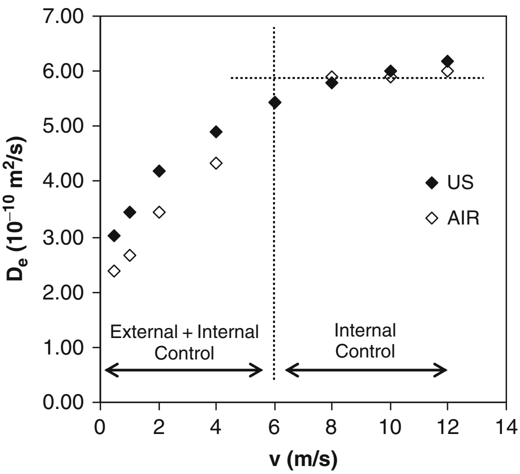


Fig. 19.7 Influence of air velocity (m/s) on effective moisture diffusivity. AIR and US (21.7 kHz, 75 W) drying experiments of persimmon cylinders (50°C) (García-Pérez et al., 2007)

application were found in previously reported fluidized bed drying experiments of apricots (air velocity range: 10–14 m/s).

There has been very little work conducted on the influence of air velocity on air-borne acoustic drying. The effects of power ultrasound application on carrot drying, using a stepped plate ultrasonic system, decreased when the air velocity changed from 1 to 3 m/s (Gallego-Juárez et al., 1999). The drying rate of surimi slices increased under power ultrasound application, using a probe-type ultrasonic system, in experiments carried out at air velocities between 1.6 and 2.8 m/s (Nakagawa et al., 1996). These experiments agree closely with the results obtained on persimmon drying, since the low air velocities used in these experiments (<6 m/s) may explain the effects observed when applying power ultrasound. However, no previous references have been found to confirm the results obtained at air velocities of over 6 m/s.

Below 6 m/s, D_e values were not only affected by power ultrasound but also by air velocity (Fig. 19.7), which showed that the external resistance to mass transfer cannot be neglected. Above this threshold, mass transfer seems to be controlled by internal resistance; consequently D_e is independent of air velocity. Furthermore, it is important to note that the NER model did not fit drying kinetics below 6 m/s adequately, since the behavior of the systems under these conditions, characterized by a significant external resistance, departs from boundary conditions assumed in the NER model (external resistance neglected).

The use of the ER model for cylinders allowed for an adequate fitting of the drying kinetics of persimmon samples carried out at below 6 m/s (Table 19.1). D_e values remained almost constant with the air velocity, and the overall effect of this variable was found on mass transfer coefficient (k). The ER model also permitted the influence of applying power ultrasound on D_e and k to be split (Table 19.1). Power ultrasound application significantly increased the identified D_e and k values when low air velocities were used (<6 m/s), which involves a significant reduction of internal and external resistance to mass transfer. The microstreaming and oscillating velocities produced by the ultrasound on interfaces are responsible for the effects on external resistance (Gallego-Juárez et al., 1999), while alternative expansions and compressions (sponge effect) in the material being dried reduced internal resistance (Arkhangel'skii and Stanikov, 1973; Borisov and Gynkina, 1973; Muralidhara et al., 1985).

Table 19.1 Effective moisture diffusivities (D_e, 10^{-10} m^2/s) and mass transfer coefficients (k, 10^{-3} kg w/m^2/s) identified using the ER model from experimental drying kinetics of persimmon cylinders carried out at low air velocities (v, m/s) (Cárcel et al., 2007a)

	AIR			US		
V	D_e	k	VAR	D_e	k	VAR
0.5	5.25±0.35	0.54±0.08	99.6	6.75±0.35	0.61±0.04	99.8
1	5.70±0.42	0.58±0.02	99.5	6.93±1.05	0.78±0.06	99.9
2	5.49±0.54	0.96±0.06	99.9	6.67±1.56	1.09±0.04	99.9
4	6.02±0.48	1.45±0.08	99.9	6.09±1.08	1.59±0.21	99.8

For a close examination of these effects, the sound pressure level generated by the vibrating cylinder inside the drying chamber was measured at different air velocities. The measurement was carried out using a microphone (1/8″, GRAS, Holte, Denmark) and followed a preset pathway; thus, the average sound pressure level was calculated integrating the values measured in the different points of the whole volume (García-Pérez et al., 2006a). It was found that the measurement was disturbed by the noise produced by the air flow on the protective hood of the microphone (Fig. 19.8). In fact, the sound pressure obtained without filtering increased as the

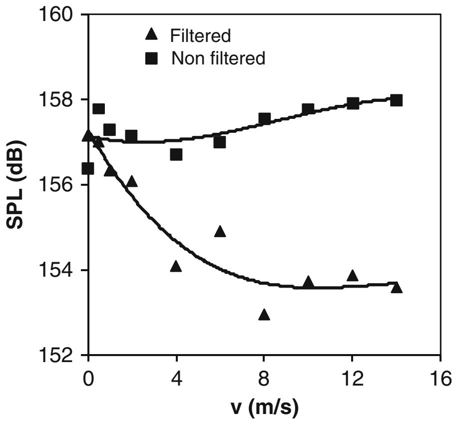


Fig. 19.8 Average sound pressure level measured in the drying chamber at different air velocities (m/s)

air velocity got higher, which is explained by the increase in noise intensity produced by the air. For that reason, it was necessary to filter the electric signal using a Heterodyne (Brüel & Kjær, Naerum, Denmark) around the resonance frequency of the transducer (21.7 kHz, widthband 100 kHz). In that case, the real average sound pressure (filtered) in the drying chamber decreased as the air velocity got higher, remaining almost constant at above 8 m/s (Fig. 19.8). This means that there was a reduction of the acoustic energy in the medium at high air flow rates. The effect of turbulence on the acoustic field has also been addressed in a liquid medium; thus, the acoustic energy produced by a probe system (20 kHz) decreased when a mechanical agitator was used, when compared with those found without agitation (Cárcel, 2003).

It may be concluded that the air flow produced a disruption of the acoustic field generated inside the drying chamber, which explains the lack of any effects caused by power ultrasound application in experiments carried out on persimmon at high air velocities and also those found on fluidized bed drying of apricots.

5.2 Air Temperature Effect

Vibrating cylinder AIR and US (75 W, 21.7 kHz) drying experiments on carrot cubes (8.5 mm side) were carried out at air temperatures ranging between 30 and 70°C (García-Pérez et al., 2006b). In order to ensure high acoustic energy levels in the medium, a low air velocity (1 m/s) was used. Different effects of power ultrasound were found at low and high air drying temperatures (Fig. 19.9). At low temperatures the drying time needed to reach a moisture content of 1 kg/kg of dry matter was reduced (28% at 30°C) by ultrasound application. Nevertheless, the effect of power ultrasound application disappeared at the highest air temperature tested (70°C). By modeling, the influence of power ultrasound at the different air velocities tested may be quantified.

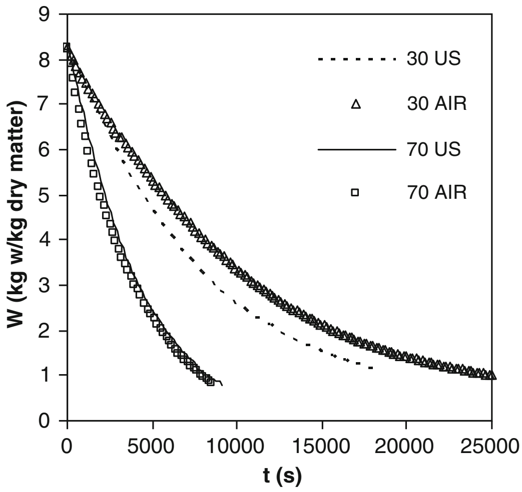


Fig. 19.9 AIR and US (21.7 kHz, 75 W) drying kinetics of carrot cubes at low (30°C) and high air temperatures (70°C) (García-Pérez et al., 2006b)

The ER model was used to fit the experimental drying kinetics due to the low air velocity used. As expected, the ER model contributed to fit the drying kinetics adequately (percentages of explained variance > 99%), showing the importance of external resistance at low air velocities (Table 19.2). Power ultrasound application significantly increased the mass transfer coefficients in the air temperature range tested. This finding points to significant effects of power ultrasound on the gas–solid interfaces reducing boundary layer thickness and thus diminishing external resistance to mass transfer (Gallego-Juárez et al., 1999).

Table 19.2 Effective moisture diffusivities (D_e, 10^{-10} m^2/s) and mass transfer coefficients (k, 10^{-4} kg $w/m^2/s$) identified using the ER model from experimental drying kinetics of carrot cubes carried out at different air temperatures (T, °C) (García-Pérez et al., 2006b)

	AIR			US		
T	D_e	k	VAR	D_e	k	VAR
30	1.38±0.25	2.87±0.40	99.9	2.14±0.60	3.06±0.36	99.9
40	1.93±0.22	4.13±0.21	99.9	2.71±0.51	5.86±0.48	99.9
50	2.87±0.70	6.17±0.86	99.9	3.91±0.33	8.80±0.50	99.9
60	3.83±0.61	6.77±0.23	99.9	4.69±0.40	9.07±1.27	99.9
70	4.57±0.07	8.83±0.38	99.9	4.88±0.41	9.40±0.70	99.9

A significant (p<0.05) influence of power ultrasound application on effective moisture diffusivity was only found at air temperatures of less than 60°C. The D_e value identified at 30°C increased by 53% when power ultrasound was applied (Table 19.2). However, the effects were almost negligible at 70°C (Table 19.2). This could be explained by assuming that ultrasound introduces a given amount of energy into the solid producing alternative expansions and contractions, thus improving water mobility (Muralidhara et al., 1985). As the temperature increases, water movement is faster and the relative importance of the acoustic energy effect on internal resistance diminishes. Nevertheless, more experimentation is needed to verify this assumption.

In AIR experiments, D_e values followed the Arrhenius-type relationship with temperature quite well (Fig. 19.10). An activation energy figure of 26.7 ± 5.3 kJ/mol was identified, which is similar to others reported in literature for convective drying of carrots (Reyes et al., 2002; Srikiatden and Roberts, 2006). However, this relationship could not be established in US experiments, since the D_e values identified at high air temperatures departed from the linearity found at low temperatures. The linear relationship found for D_e values identified at low temperatures in US experiments presented a similar slope to those found in AIR experiments; the effect of power ultrasound was only observed on the *y*-axis intercept.

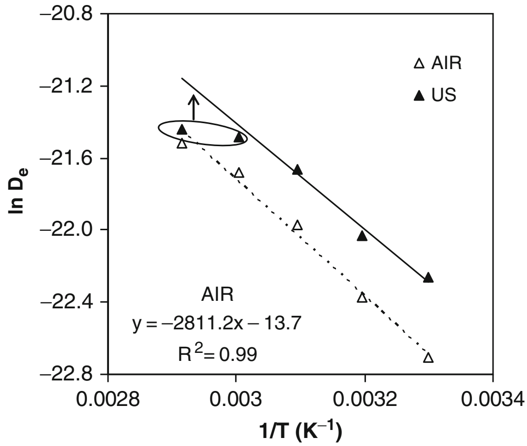


Fig. 19.10 Influence of air temperature (°C) on effective moisture diffusivity. AIR and US (21.7 kHz, 75 W) drying experiments of carrot cubes (1 m/s) (García-Pérez et al., 2006b)

The literature reports agree with these results on the influence of air temperature. Gallego-Juárez et al. (1999) found that the effects of high-intensity ultrasound application on carrot drying, using a stepped plate ultrasonic system, decreased from experiments carried out at 60°C to those found at 90°C and disappeared completely at 115°C.

Those authors also reported a similar temperature-related tendency of high-intensity ultrasound effects to those shown in Fig. 19.10, since the influence decreased as the air velocity got higher. Nevertheless, the effects were still significant at temperatures of over 60°C, which may be explained by the different ultrasonic application systems used. High-intensity ultrasound application, or using a probe-type system increased the drying rate at 20, 30, 40, and 50°C during the drying of surimi slices (Nakagawa et al., 1996), which confirms the effectiveness of ultrasound in a moderate temperature range (<60°C).

5.3 Applied Acoustic Energy

Carrot cube drying experiments (side 8.5 mm) were carried out in a vibrating cylinder ultrasonic system by applying several acoustic energy levels, which were set by applying different electric powers to the ultrasonic transducer: 0, 10, 20, 30, 40, 50, 60, 70, 80, and 90 W (García-Pérez et al., 2008, 2009). According to previously reported results, a low air velocity (1 m/s) and a moderate temperature (40°C) were used (García-Pérez et al., 2007) to highlight the effect of acoustic energy.

The level of acoustic energy applied was found to have a significant ($p < 0.05$) influence on drying kinetics; thus, the drying time needed to reach a moisture content of 1.5 kg/kg of dry matter was reduced by 32% when the electric power applied increased from 10 to 90 W (Fig. 19.11). Similar results about the influence of the amount of acoustic energy have been reported related to the convective drying of carrots, mushrooms, apples, and potatoes, assisted by power ultrasound (Riera et al., 2002; de la Fuente et al., 2004) using a stepped plate system.

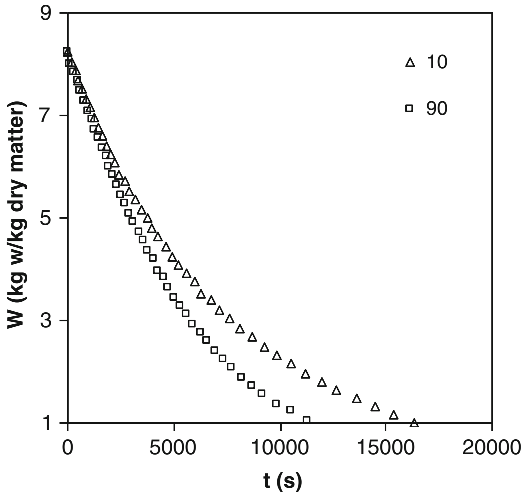


Fig. 19.11 US drying kinetics of carrot cubes (40°C, 1 m/s) applying low and high electric power (W) to the ultrasonic transducer (García-Pérez et al., 2009)

The literature has not pointed to results that quantify the effects produced by power ultrasound at different acoustic energy levels. For that reason, in order to quantify the influence of acoustic energy level on drying kinetics, the ER model was fitted to the drying kinetics of carrot cubes. The ER model fitted the experimental drying data well (Table 19.3), reaching percentages of explained variance (VAR) higher than 99% in all cases. Both effective moisture diffusivity and mass transfer coefficients values increased significantly as the electric power was raised, which means there were more intense effects of power ultrasound on internal and external resistance to mass transfer. Nevertheless, the effects were only observed when the acoustic energy level in the medium exceeded a minimum value, which, under these

Table 19.3 Effective moisture diffusivities (D_e, 10^{-10} m^2/s) and mass transfer coefficients (k, 10^{-4} kg $w/m^2/s$) identified using the ER model from experimental drying kinetics of carrot cubes carried out at different levels of electric power applied to the ultrasonic transducer (P, W) (García-Pérez et al., 2008)

P	D_e	k	VAR
0	2.03±0.04	4.60±0.09	99.9
10	2.05±0.33	4.66±0.41	99.9
20	2.01±0.36	4.58±0.15	99.9
30	2.24±0.22	4.40±0.54	99.9
40	2.33±0.17	4.98±0.32	99.9
50	2.48±0.20	5.55±0.01	99.8
60	2.53±0.01	5.45±0.49	99.9
70	2.63±0.03	5.60±0.25	99.9
80	2.57±0.31	6.03±0.66	99.9
90	2.82±0.27	6.60±0.48	99.9

experimental conditions, corresponded to applying an electric power of 30 W to the transducer (Table 19.3, Fig. 19.12). Below this threshold, no significant influence of the acoustic energy level was found (Fig. 19.12). Above 30 W, the influence the level of electric power applied had on the mass transfer coefficient was fitted well by a linear correlation. That means that the effects of power ultrasound application on the gas–solid interface were proportional to the acoustic energy level in the medium. A similar influence of acoustic energy level was found on the effective moisture diffusivities.

No reports have been found in the literature about the ultrasound intensity threshold necessary to affect air drying.

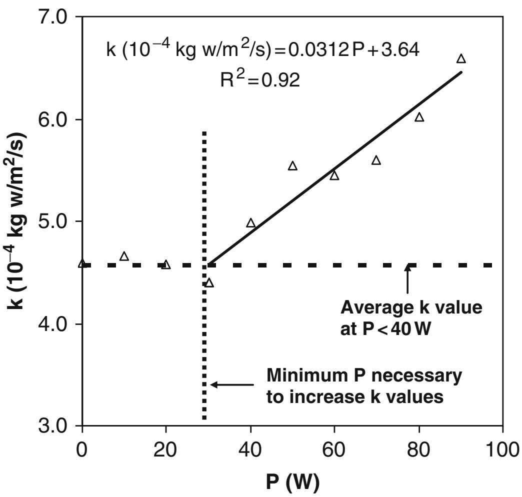


Fig. 19.12 Influence of electric power applied (W) on mass transfer coefficients. US (21.7 kHz) drying experiments of carrot cubes (40°C, 1 m/s) (García-Pérez et al., 2008)

5.4 Material Structure

Experiments with different products under the same experimental conditions were carried out to test the influence of the material being treated on hot air drying assisted by power ultrasound. For that reason, vibrating cylinder AIR and US (21.7 kHz, 75 W) drying experiments at air velocities of between 0.5 and 9 m/s and at constant temperature (40°C) were carried out on carrot cubes (8.5 mm side) and lemon peel slabs (thickness 10 mm) (García-Pérez, 2007; García-Pérez et al., 2007). According to previously shown results, the increase in air velocity reduces acoustic energy in the medium. Therefore, the planned US experiments permitted us not only to illustrate the behavior of both materials but also to compare with AIR experiments.

Although power ultrasound application reduced the drying rate of both lemon peel and carrots at low air velocity, the ultrasound effects were more intense in lemon peel (Fig. 19.13). However, whereas power ultrasound was found to have

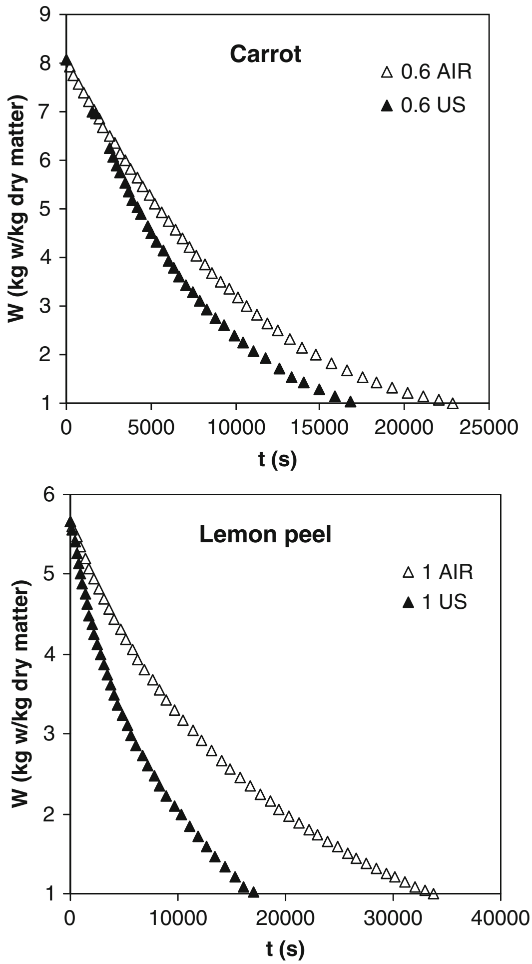


Fig. 19.13 AIR and US (21.7 kHz, 75 W) drying kinetics of carrot cubes and lemon peel slabs at low air velocities (García-Pérez et al., 2007)

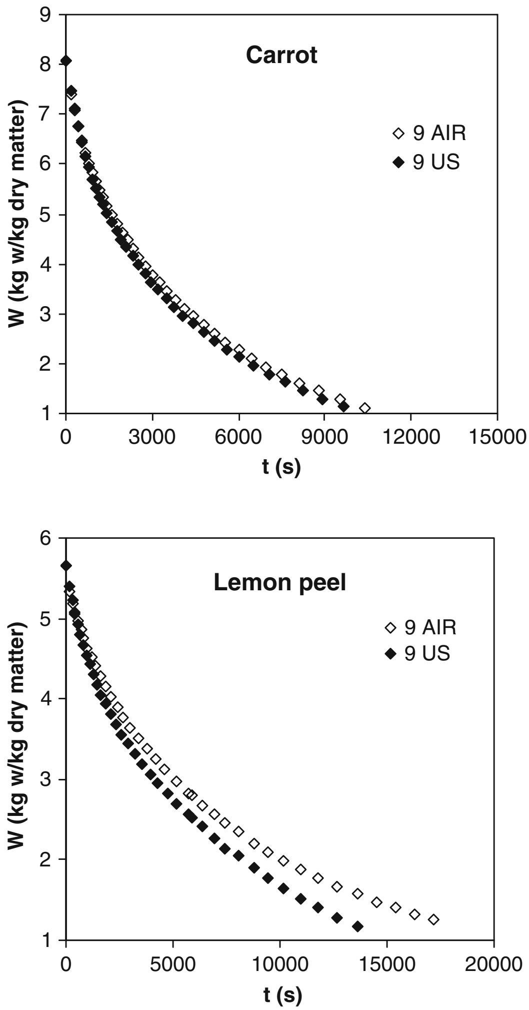


Fig. 19.14 AIR and US (21.7 kHz, 75 W) drying kinetics of carrot cubes and lemon peel slabs at high air velocities (García-Pérez et al., 2007)

no effect on carrot drying at high air velocities (Fig. 19.14), in the case of lemon peel, the drying rate was also reduced by ultrasound application at high air velocities. Through drying kinetics modeling, the influence of power ultrasound may be quantified and, furthermore, the different behavior of the materials may be clarified.

An NER model was used to identify the effective moisture diffusivities at different air velocities on carrot and lemon peel drying, as shown in Fig. 19.15. The influence of power ultrasound application on carrot drying was very similar to the results found for persimmon drying (Cárcel et al., 2007a). Effective moisture diffusivities were only improved by ultrasound at low air velocities, as the effect was negligible at air velocities higher than 5 m/s. At high air velocities, the amount of

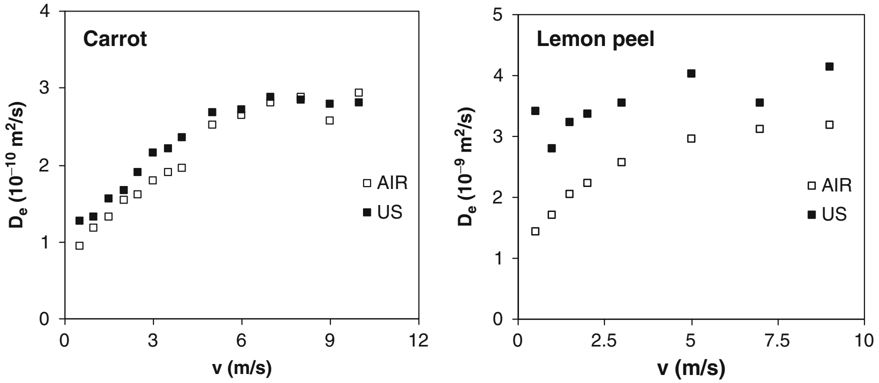


Fig. 19.15 Influence of the air velocity (m/s) on the effective moisture diffusivity. AIR and US (21.7 kHz, 75 W) drying experiments of carrot cubes and lemon peel slabs (García-Pérez et al., 2007)

acoustic energy remaining due to acoustic field disruption was not enough to affect the mass transfer process in carrot drying.

The behavior found in lemon peel drying was quite different than in carrot or persimmon drying, since a power ultrasound effect was found for the whole range of air velocity tested (Fig. 19.15). Despite reducing acoustic energy by increasing air velocity, the acoustic energy in the medium was able to effect a more sensitive product like lemon peel; consequently, acoustic effects on lemon peel were stronger.

An explanation for the fact that lemon peel behaves differently when compared to carrot and persimmon could be linked to its structure (García-Pérez et al., 2009). In fact, lemon peel is considered to be a more porous product than carrot or persimmon (Boukouvalas et al., 2006). Porosity may be considered as one of the most important structural variables for determining the acoustic effectiveness in foodstuffs. High porosity products may be considered to be more prone to alternating compression and expansion cycles produced by ultrasonic waves (sponge effect) (Gallego-Juárez, 1998), improving the water transfer rate in its large intercellular spaces. Small intercellular spaces are also found in low porosity products, which means a high internal resistance to water transfer. Thus, high acoustic energy levels are required to affect mass transfer in low porosity products (persimmon and carrot) (García-Pérez et al., 2007).

The influence of porosity may also be explained by taking the greater acoustic energy absorption of high porosity products into account. As a consequence, the internal energy available in the particles would increase, leading to more intense compressions and expansions (sponge effect), which could improve water removal and therefore reduce internal resistance. Furthermore, the acoustic effects on the solid–gas interfaces of intercellular spaces could increase in high porosity products due to a larger porous net. Indeed, this phenomenon also contributes to reduce internal resistance to mass transfer.

Raw material may be considered as one of the most important variables to be evaluated when considering the application of power ultrasound during the convective drying of foodstuffs. A sound knowledge of the material structure would contribute to determine its response to acoustic energy during hot air drying assisted by power ultrasound, since structure is important to determine how difficult it is for water molecules to leave the solid matrix.

6 Final Remarks

The use of high-intensity ultrasound in hot air drying seems to be a promising technology to improve quality and energy savings. As it appears to be more effective at low temperatures, the related quality effects of high temperatures can be avoided without compromising the kinetics of the process. Decreasing the drying air temperature also produces energy savings.

High-intensity ultrasound also appears to be more effective at low air velocities, which is very interesting to accelerate the drying kinetics of products with a tendency to suffer case hardening during drying. Drying at low air velocities also results in energy savings.

The existence of an intensity threshold for ultrasound affecting the process is an important point to be considered when planning experiments on either the laboratory or the industrial scale.

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