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FOOD PROCESS INNOVATION THROUGH NEW TECHNOLOGIES: USE OF ULTRASOUND

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Abstract

The use of new or non-conventional technologies widens the food processing innovation possibilities. Among technologies with a potential application, high intensity ultrasonics has emerged. Ultrasound is a mechanical wave that can affect transport phenomena. Accordingly, the effect associated to ultrasonic application will be dependent on the medium where ultrasound is travelling and on the material to be affected. In this work, ultrasonic applications in different media, such as liquid, gas and supercritical fluid, are addressed as innovative alternatives to enhance transport phenomena and highlight the main factors affecting the process.

1. Introduction

Food processing is in constant evolution in response to different challenges. The changes in consumer tastes and the need to produce safe and high quality foods are responsible for the evolution of the established food processes or the development of the new ones. In this sense, the introduction of new technologies could lead to a reduction of the processing time or an improvement in operating conditions. These aspects are closely linked to the search for high quality products that preserve the natural characteristics of foods. Another important aspect that must be taken into account is the reduction of the energy needs of the processes, thereby decreasing both environmental and financial costs. Ultrasound is an example of new technology and its application in food processing could lead to both these areas undergoing an improvement. On the one hand, ultrasound could be applied as a diagnosis technique to control aspects, food product or processes. On the other hand, ultrasound could be used to improve food processes by affecting the kinetics, the yield or the product quality. This work will focus on the latter.

Acoustic waves are mechanical waves that need a material medium to propagate. Usually, they are classified by taking the human audible frequency as reference. This range could be placed between 20 Hz to 20 kHz. Lower frequencies are referred to as infrasound and higher frequencies as ultrasound. The ultrasound waves suffer changes in their properties (velocity, attenuation, frequency spectrum,...) when travelling through a medium. The study of these variations is used in diagnosis applications to characterize the medium. In these applications, the frequency of the waves is in the range of MHz and the power applied is not higher than 1 W/cm^2 (Patist and Bates, 2008). When the applied power of ultrasound is higher, the acoustic waves could affect the medium generating interesting effects for industrial applications. This use of ultrasonic technology is known as "power ultrasound" or "high intensity ultrasound" and the main objective is to induce changes in products or processes. In this case, the frequency is in the range of 20-100 kHz (Mason and Lorimer, 2002).

The aim of this work was to address different power ultrasound applications in order to highlight factors affecting some innovative approaches to food processing.

1.1. Effects of ultrasound

The effects produced by high power ultrasound when travelling across a medium are diverse and their relative importance depends on the characteristics of the medium. In general, ultrasound produces alternating compression and decompression of the media. In liquids, when ultrasonic power attains a threshold, the rarefaction cycle may exceed the attractive forces and, from existing gas nuclei, cavitation bubbles could appear (Soria and Villamiel, 2010). These bubbles could maintain a stable increasing and decreasing size giving rise to the so-called "stable cavitation" generating a micro-agitation of the medium. However, the bubbles can also grow and collapse generating very high local temperatures (5000 K) and pressures (1000 atm), which produce, in turn, high energy shear waves and turbulence in the cavitation zone. This last effect is known as "transient cavitation" (Leighton, 1998). The implosions are asymmetric if produced near a solid surface generating a microjet that hits the solid (Mason, 1998). This is the main effect observed in the use of high intensity ultrasound in cleaning operations. Moreover, the microjets hitting the solid food surface may produce an injection of fluid inside the solid (Mason and Cordemans, 1996). The intensity of cavitation and its effects depend on the characteristics of the medium, such as viscosity, and/or process variables, like ultrasonic intensity, ultrasonic frequency or pressure.

In gas media, the main challenge of the application of ultrasound is attaining an efficient transmission of the acoustic waves at high frequencies due to the acoustic impedance mismatch between transducers and gas as well as the high ultrasonic attenuation in gas media. However, when ultrasound is applied in an efficient way, it can produce intense effects on the interfaces, such as pressure variations or microstirring, which can affect the mass transfer phenomena (Carcel et al., 2007a) by reducing the boundary layer thickness.

In solid materials, alternative compressions and expansions generated by the ultrasonic waves produce a similar effect to that observed when a sponge is squeezed and released repeatedly (De la Fuente et al., 2006). This “sponge effect” produces the release of liquid from the inner part of the particle to the solid surface and the entry of fluid from outside. The forces involved in this mechanism can be higher than the surface tension which maintains the water molecules inside the capillaries of the material, creating microscopic channels (Muralidhara et al., 1985) and making the interchanges of matter easier. Other effects to be considered are the variation of viscosity, surface tension or the deformation/degradation of the solid structure.

From a general point of view, all the effects produced by ultrasound could influence mass and/or heat transfer phenomena. In treatments with a solid immersed in a fluid, ultrasound could accelerate the internal transport making the entry of fluids in the solid matrix and/or their exit easier and also facilitating the exchanges between the solid surface and the surrounding fluid. Then, the use of ultrasound, when applied in an efficient way, could be interesting in applications involving heat or mass transport, decreasing both the external and internal resistance to transport.

1.2. Applications of high intensity ultrasound in food processing

The main applications of ultrasound in food processes are linked to the effects it has on heat or mass transfer operations. Most of the ultrasonic applications reported in literature are found in liquid-liquid and liquid-solid systems (Mulet et al., 2003) due to the relative ease with which ultrasonic waves are transmitted in liquids. There is a wide offer of commercial equipment available on the market, including ultrasonic baths and different probe systems, which may be adapted for different operations. Thus, ultrasound has been applied in osmotic dehydration (Cárcel et al., 2007b; Fernandes and Rodrigues, 2007; Jambrak et al., 2007), brining, (Cárcel et al., 2007c; Gabaldon-Leiva et al., 2007; Siró et al., 2009), freezing (Delgado et al., 2009), extraction (Vilkhu et al., 2008; Soria and Villamiel, 2010) or enhancement of heat transfer in heat exchangers (Gondrexon et al., 2010). Emulsions are also a field of interest, for example in the production of mayonnaise (Mason, 1998) or traditional products like Xixona turron (Mulet et al. 1999).

The applications in gas-solid systems are less common, because, as mentioned before, the high impedance mismatch and the high ultrasonic energy attenuation in air makes the transmission of ultrasound from the transducer to the air and from the air to the solid difficult (Garcia-Perez et al., 2009). Nevertheless, some applications have been developed in the convective drying field to overcome these challenges. This is the case of the stepped plate ultrasonic transducers developed by Gallego-Juárez et al. (1999). These prototypes have been used in the convective drying of several food products, applying airborne ultrasound or with direct contact between the transducer and the solid (De la Fuente et al., 2006; Gallego-Juárez et al., 2007). Another alternative consists of the development of vibrating drying chambers to apply air borne ultrasonic energy (García-Pérez et al., 2006a). The promising results of this system will be addressed in the following sections.

Ultrasonic applications in supercritical media are also scarce (Riera et al., 2004). The use of a supercritical fluid as solvent in the extraction operation has been receiving increasing attention due to its advantages when compared to the conventional extraction processes, such as the product quality or the use of a non-toxic, recyclable, cheap, relatively inert and non-flammable solvent. The main disadvantage of the process is the slow kinetics. Due to the high pressure needed to achieve and maintain the supercritical phase of the solvent, it appears to be difficult to introduce some agitation system inside the extractor. The effects produced by ultrasound (compression and decompressions, radiation pressure, high turbulence, etc.) could increase the extraction kinetics. In the literature, some works have approached this problem by locating the ultrasound application system outside the extractor (Balachandran et al., 2006) and others have succeeded in introducing the transducer inside the extractor (Riera et al., 2002)

However, the potential applications mentioned should be examined case by case, because it is not only the medium, solid, liquid, gas or supercritical, but also the process variables (temperature, flow regime, intensity, etc.) and the product structure which could affect the magnitude of the changes induced by ultrasound. These aspects, deriving from applications of ultrasound in different media (liquid-solid, gas-solid and supercritical-solid), will be illustrated.

2. Solid-liquid systems

2.1. Equipment

The application of ultrasound requires a system capable of producing a stable and reliable ultrasonic field from another type of energy, usually electrical. The transducers are the devices used to convert the energy, coming from a power generator, into mechanical energy in the form of ultrasonic vibrations. There are two main types of transducer: magnetostrictive and piezoelectric. The first, constructed from high-strength metallic alloys, has the advantage of being able to reach high levels of acoustic power intensity, over 150 W/cm^2, is very stable, reliable and does not age (Peshkovsky and Peshovsky, 2010). However, the relatively low efficiency (below 50%) when compared to piezoelectric systems (up to 95 %), the other type of transducer, is probably the main reason why the latter is more widely used, regardless of the relatively low levels of acoustic power intensity and the short life-span.

The transducers are attached to the vibrating system whose function consists of transmitting the vibration from the transducer to the medium. In liquid applications, the most commonly used systems are baths and probe-type systems. In the ultrasonic baths, several transducers, vibrating in phase, are attached to the bottom of a metallic tank transmitting the vibration to the contained liquid. Due to the reflection of ultrasonic waves in the air-liquid interface, a stationary field, with maximum and minimum acoustic intensity zones, is created inside it (**Figure 1**). Then, the applied ultrasonic treatment can change depending on the location of the samples.

In the probe systems, ultrasound is directly applied by a vibrating "horn". Depending on the geometry of the probe, it could be used simply to transmit the ultrasonic energy or to concentrate it on a lower surface in order to amplify the intensity and, therefore, their effects (Mason, 1998). In applications with this type of systems, the distance between the sound tip and the treated sample is an important parameter to be controlled due to the attenuation of the ultrasonic field with the distance.

2.2. Influence of ultrasound on the transport resistance

The effects produced by ultrasound in solid-liquid systems could affect the transport process reducing the external transport resistance. Carcel et al. (2004) addressed the influence of ultrasound on convective heat transport by introducing an aluminum cylinder in one ultrasonic cleaning bath (Fungsonics mod. 28 L, 20 kHz, Fungilab S.A., Barcelona, Spain) containing hot distilled water (28 L). The dimensions of the cylinder were chosen in order to neglect the internal resistance to heat transfer. The evolution of the temperature inside the cylinder was logged until there was less than 1 ºC difference when compared with the bath temperature. Four types of heating tests were carried out: without any agitation of the bath water, with (USWAG) and without ultrasound application (WAG), and agitating the bath water, with (USAG) and without ultrasound application (AG). The experimental results were modelled considering Newton's law of heating and the convective heat transfer coefficient (h) was identified. This model was adequate for describing the heating process, as confirmed by the close agreement between the experimental and calculated temperatures (**Figure 2A**). The h coefficient was significantly different ($p<0.05$) for the four kinds of experiments carried out and the identified values varied according to: WAG<USWAG<USAG<AG (**Figure 2B**). Therefore, the ultrasound treatment (USWAG) resulted in an h coefficient lower than that of a well-stirred medium (AG) but higher than that of the static condition experiments (WAG). That means that the application of ultrasound reduced the external resistance to heat transfer compared to natural convection. The limited effects on the h values compared to the mechanical stirring of the medium, could be explained by the low acoustic power provided by the ultrasonic bath systems, in order to avoid cavitation damage to the tank walls, and the low power density applied, because there is generally a large volume of liquid in the tanks (Mason, 1998).

It must be highlighted that the h coefficient identified in experiments with the simultaneous application of agitation and ultrasound (USAG) presented an intermediate figure between USWAG and AG treatments. This fact could indicate the existence of an interaction between ultrasonic and mechanical agitation resulting in a reduction of the turbulences in the medium. As **Figure 1** shows, the agitation of the medium affected the ultrasonic field decreasing both the average acoustic pressure and the difference between maximum and minimum pressure zones. In this sense, the h value of USAG experiments will indicate that the ultrasonic field could also affect the agitation of the medium, decreasing the turbulence level created.

The level of acoustic intensity applied and the type of material treated could influence the magnitude of the ultrasound effects in the transport process. In this sense, it is important to take into account that the treated medium could affect the transmitted acoustic field. As can be observed in **Table 1**, the same ultrasonic system, working under the same conditions, produces different acoustic pressure when in brine than when in sucrose solution and, therefore, the ultrasonic effects can be different. On the other hand, the effects of ultrasound on the mass transport kinetics might not appear until an acoustic intensity threshold is attained. Studying the mass transport of moisture and solutes during the osmotic treatment of apple in a sucrose solution (30 ºBrix; 30 ºC), Carcel et al. (2007b) found an intensity threshold of 10 W/cm^2, below which no influence of ultrasound was observed. When the applied ultrasonic intensity was 11.5 W/cm^2, the identified effective diffusivity increased by 117% for moisture transport and 137% for the dry matter transport, compared to the treatments without ultrasound application. This ultrasonic intensity threshold could vary for different products or transport processes. Carcel et al. (2007c) reported that intensity thresholds of 39 and 51 W/cm^2 were needed in order to observe some effects on the moisture or salt transport respectively during pork meat brining (saturated NaCl brine, 2 ºC). Above this threshold, the higher the level of applied ultrasonic intensity, the more the ultrasound was observed to affect mass transport.

However, the level of acoustic intensity can also affect the type of influence on the mass transport. The levels of acoustic intensity used by Carcel et al. (2007b) (11.5 W/cm^2) in the osmotic dehydration of apples increased the two main mass transport processes that took place in these treatments: moisture loss and solute gain, but the higher levels used by Carcel et al. (2007c) in meat brining (> 51 W/cm^2) not only affected the kinetics of transport but, in the case of moisture, the transport direction. The samples treated ultrasonically at the higher acoustic intensities tested (75.8 W/cm^2) did not undergo a dehydration process like the conventionally brined meat, but had a higher moisture content than fresh meat. Moreover, the NaCl content of the ultrasonically brined samples after 45 min of treatment was 115% higher than conventionally brined samples. That means that the conventional brining process produced a water loss and a NaCl gain while, at these intensity levels, the application of ultrasound, induced the gain of both water and NaCl. The influence of ultrasound on apple treatments can be explained by ultrasonic effects such as the "sponge effect" or the creation of microchannels, which can affect the internal mass transport resistance, and the generation of microstirring or cavitation, which affect the external resistance by reducing the boundary layer of diffusion. In the case of meat brining, the highest applied acoustic intensity generates a more intense cavitation in brine. The asymmetric implosion of cavitation bubbles near the meat surface produces the formation of microjets that hit the solid (Mason & Lorimer, 2002) and could produce the microinjection of brine into the meat samples. This fact could not only explain the increase in NaCl content but also the increase in sample water content.

3. Solid-gas systems

3.1. Equipment

As already mentioned, the main drawback of the application of ultrasound in gas media is the transmission of the acoustic wave from the emitter’s surface to the samples. The air is a high attenuating medium that absorbs the acoustic energy preventing its transfer to the solids to be treated. On the other hand, the high impedance difference between the solid surface of emitters and the air, and between the air and the solid samples, produces the reflection of a high proportion of the generated acoustic signal (García-Pérez et al. 2006a). This is the reason why there are very few research groups working on the application of ultrasound in food drying. The applications of ultrasound during osmotic pre-treatments prior to the air drying process may be mentioned (Fernandes & Rodrigues, 2007), but these processes are applications in solid-liquid systems. Therefore, it is of great importance to gain further a more thorough knowledge of the mechanisms of the ultrasonic wave transmission in gas media in order to optimize the application systems (de la Fuente et al., 2006). Significant attempts have been made to alleviate these problems by developing a powerful source of airborne ultrasound that can achieve a more efficient transmission of energy to the material.

The systems of sirens and whistles convert the kinetic energy of a fluid into an acoustic wave. 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 application, the whistle constitutes a powerful tool for mixing and homogenization (Mason & Lorimer, 2002). Da Mota and Palau (1999) used a siren system to improve onion drying. A low frequency (1.6 and 3.2 kHz) was used in these experiments to partially avoid the acoustic energy attenuation; this action, however, may involve an intense noise that could be an obstacle to its use.

Another group of ultrasonic systems includes the use of a piezoelectric transducer attached to different types of emitters trying to adapt the signal in order to achieve a good transmission to the air. One of the main types is the stepped plate emitters, characterized by a surface emission with a stepped profile that is responsible for the best impedance match with air, the increase in the power capacity of the system and which avoids the phase cancellations produced in flat plate radiators (Gallego-Juárez et al., 1999; Gallego-Juárez, 2010). Circular and rectangular prototypes have been developed for the 10-40 kHz frequency range and power capacities of about 100 W and have been applied in forced air dehydration assisted by airborne ultrasound and also in the direct coupling of the ultrasonic vibrator and the solid matrix. Drying experiments have been carried out on different vegetables such as carrots, potatoes, and mushrooms (De la Fuente et al., 2006; Gallego-Juárez et al., 2007). The drying process which involved direct contact between the vibrating elements and the materials being dried showed a very intense effect which can increase when a low static pressure is applied. The effect that power ultrasound had on drying was reduced when the application was carried out using an airborne technique. The better transmission of vibrations to the sample in direct contact experiments is what is mainly responsible for this fact. Nevertheless, it is very difficult to adapt the direct contact systems to work on an industrial scale. An alternative consists of considering the drying chamber itself as the vibrating element to transmit the acoustic waves to the samples. To apply this concept, García-Pérez et al. (2006a) replaced the drying chamber of a conventional laboratory hot air drier (Sanjuan et al., 2003) by an aluminium vibrating cylinder (internal diameter 100 mm, height 310 mm, thickness 10 mm) driven by a piezoelectric composite transducer capable of generating a high-intensity ultrasonic field inside the cylinder. The driving transducer consists of an extensional piezoelectric sandwich element together with a mechanical amplifier (**Figure 3**). The whole has to be resonant at the frequency of the selected vibration mode of the chamber, 21.8 kHz. The average sound pressure level inside the chamber in stagnant air conditions was 154.3 dB, measured for an electrical power applied to the transducer of 75 W. Therefore, a high intensity acoustic field inside the chamber is obtained with relatively low applied electric power. This system has been used in the drying of different products, such as carrot (García-Pérez et al. 2008), persimmon (Cárcel et al, 2007a), lemon peel (García-Pérez et al., 2009) or olive leaves (Cárcel et al. 2010) and, despite the fact that the vibration transmission transducer-sample is not as good as the direct contact application, the results of the increase in the drying rate have been promising.

3.2. Influence of process variables.

The use of sonication to improve the dehydration process dates from the middle of the 20th century, promoted by the interest in the drying of heat-sensitive materials (Boucher, 1953) due to the limited heating effect of ultrasound on gas systems. Borisov and Ginkina (1973) reported a series of experiments carried out in the Academy of Science of the USSR to determine the influence of the main process variables using fluid driven transducers. Due to the development of more efficient devices with which to apply ultrasound in gas systems, especially the aforementioned vibrating drying chamber, studies into several food materials considering different process variables have been carried out in order to address their influence on the drying rate.

In general, the application of ultrasound during drying increases the kinetics of dehydration, affecting both the internal and the external resistance. As can be observed in **Figure 4**, the application of ultrasound in the drying of carrot and lemon peel increased the effective diffusivity and the mass transfer coefficient. The influence on the effective diffusivity could be attributed to the "sponge effect" or the creation of internal microchannels that make it easier for the water to be released from the solid samples. In cryo-SEM observations, Ortuño et al. (2010) found that ultrasonically dried orange peel albedo showed a more compressed cellular structure with larger intercellular air spaces than conventionally dried samples. The alternating expansions and compressions produced by ultrasound created a highly porous material that facilitated the water movement. These authors also found that ultrasound affected the flavedo structure. The conventional air drying process scattered the waxy components, closing the pores and creating a waterproof barrier. Nevertheless, the original ring-shaped waxy accumulations in the pores continued to be well defined. On the contrary, in the samples dried using ultrasound application, these ring-shaped accumulations disappeared revealing the very intense effect that ultrasound had in the interface. The influence of ultrasound on the external resistance to mass transfer could be linked to the generation of differential pressures and the microstirring at the interfaces and these effects should also affect the surface of the treated solid.

The magnitude of the effects of ultrasound depends on the process variables, such as air temperature, air velocity, mass load density, applied acoustic energy or the raw material processed. The air velocity has been found to be one of the most important variables involved in power ultrasound assisted air drying (Cárcel et al., 2007a; García-Pérez et al., 2007). From experimental measurements, Riera et al. (2011) found that the increase of the air velocity produced the reduction of the sound pressure level in the drying chamber. As a consequence, the energy available for the samples at high air velocities could not be enough to affect the mass transfer process.

The magnitude of the effects of ultrasound on the drying rate also depends on the ultrasonic power level applied. As can be seen in **Figure 4**, an ultrasonic intensity threshold can be achieved to find some evidence of the effect of ultrasound on the kinetic parameters of the process. Above this threshold, the more power is applied, the higher the values of diffusivity and mass transfer coefficient that can be obtained and, therefore, the faster the drying process (García-Pérez et al. 2009). Above the threshold, the relationship between the kinetic parameters and the applied ultrasonic power was linear for the whole range tested.

The influence of the power ultrasound also depends on the material to be processed. The structure of the material could be an important factor in the extension of the effects of ultrasound. This fact is also illustrated in **Figure 4.** The influence of ultrasound on diffusivity and mass transfer coefficient appeared in the case of carrots when over 20-30 W power was applied, whereas when drying lemon peel, it can even be observed at the lowest power level tested. Moreover, the slope of the linear relationship between kinetic parameters and the applied power was nearly one order of magnitude higher for lemon peel than for carrot. Lemon peel is more porous than carrot (García-Pérez et al., 2007) and so the expansions and contractions (sponge effect) produced by ultrasound may be more intense due to its low mechanical resistance; in addition, the effects on the interfaces would be more intense because of the large porous volume. Furthermore, a greater absorption of acoustic energy would be expected in high porosity products, thus increasing the energy available in the particle to affect mass transfer processes.

The relative effect of ultrasound depends on the transfer resistance affected. If the resistance is low, the effect of ultrasound application is also low. For that reason, the effect of ultrasound application is more evident when drying is carried out at moderate temperatures. For example, when carrying out experiments of the drying of carrot samples at different air temperatures García-Pérez et al. (2006b) found that the influence of ultrasound on the diffusivity was different depending on the temperature. The application of power ultrasound significantly increased ($p<0.05$) the effective moisture diffusivity at temperatures lower than 60 ºC but was almost negligible at 70 ºC. A similar influence of the temperature on the effects of ultrasound was found by Gallego-Juárez et al. (1999).

The effect of mass load density can be observed in **Figure 5** for drying experiments performed on carrot cubes. In conventional air drying processes, it appears that, the increase of mass load density, in the range tested, does not affect the effective moisture diffusivity although it does produce a reduction of the mass transfer coefficient. This could be linked to perturbations in the air flow through the drying chamber, thus creating preferential pathways and, as a consequence, increasing external mass transfer resistance (Cárcel et al., 2011). When high intensity ultrasound was applied, the mass transfer coefficient and the effective moisture diffusivity increased when the mass load density used was moderate, although the acoustic influence on mass transfer coefficient became negligible at high mass load densities.

Therefore, from previous results, for a specific ultrasonic application it appears to be important to carry out a study into the influence of different process variables in order to find the optimum drying conditions. The innovation of the process could fail if not properly addressed.

4. Solid-supercritical systems

Ultrasound has been used extensively in the last two decades as an efficient extraction tool for food engineering purposes and nowadays it has even become the reference for other extractive technologies under development. Ultrasound assisted extraction has been applied in the extraction of valuable compounds, like different herbal extracts, polyphenols, anthocyanins, aroma compounds, polysaccharides or proteins (Vilkhu et al., 2008). The sonication in solid-liquid systems could improve the extraction efficiency and rate, reduce the temperature needed and save solvents thus favouring the solubilisation of the interesting compounds. However, ultrasound assisted extraction is not only related to pure diffusion processes, in fact, the cavitation of bubbles generated by the application of ultrasound in an elastic medium can implode at the surface of the plant and destroy the plant cells (Veillet et al, 2010). However, it frequently presents similar drawbacks to the conventional extraction processes: the use of toxic solvents dangerous both for the environment and for the final quality of the product. Supercritical fluid extraction has become a promising technique with which to solve these problems due to the fact that the solvent commonly used, CO_2, is non-toxic, recyclable, cheap, relatively inert and the process improves the product quality and product recovery (Lang & Wai, 2001). However, supercritical fluid extraction presents slow extraction kinetics even when solute free solvent is recirculated and, therefore, improvements in mass transfer are required (Berna et al., 2000). The use of high-intensity ultrasound represents a potentially efficient way of enhancing mass transfer processes (Riera et al., 2004) and, consequently, innovating the supercritical fluid extraction techniques.

4.1. Equipment

Supercritical CO_2 fluid extraction takes place inside a reactor under high pressure conditions (pressure above 72 bar). This fact makes it difficult to introduce a mechanical agitation system in the reactor, as well as an ultrasonic transducer, which represents the main obstacle to the application of ultrasound in this kind of process. To address it, two different set-ups may be mentioned. One of them consists of the use of a commercial sound probe joined to the wall of the extractor. As the transducer is fitted externally, it is expected that there will be a power attenuation as the ultrasound passes through the stainless steel vessel walls (Balachandran et al., 2006).

The other set-up consists of the introduction of the transducer inside the reactor. This solution, proposed by Riera et al. (2002), is based on a piezoelectric sandwich transducer designed and built for this application and inserted in the upper part of the vessel with a 100 W power capacity. The transducer is driven by an electronic generator, which incorporates a system to follow the resonance frequency (**Figure 6**). This is an essential device due to the changes that different process conditions may provoke in the characteristic impedance of the supercritical fluid (Riera et al. 2004). In fact, these authors achieved stable operation conditions when the values of density, pressure and temperature were kept at the operational values. Moreover, any change in the flow rate or density was immediately detected and followed by the control system of the transducer. Therefore, it is possible to use this control system to monitor the extraction process.

4.2. Influence of ultrasound on supercritical fluid extraction

The application of ultrasound during supercritical fluid extraction affects both the kinetics and the yield. Balachandran et al. (2006) studied the application of ultrasound in the supercritical extraction of pungent compounds from ginger using a commercial probe system externally attached to the extractor. The nominal power used was 300 W but, due to the ultrasonic transducer being outside the extractor, the reflection and adsorption of the acoustic wave decreased the actual intensity received by the samples. However, they found an important increase in yield when ultrasound was applied. The particle size could be an important factor to take into account, in fact, the effects of ultrasound increased when the particles were smaller. Thus, for a particle size of 4 mm, the yield was 30 % higher in experiments carried out with ultrasound application compared to non-ultrasonic experiments. Similar behavior was found by Riera et al. (2004) working on almond oil extraction. They used a system where the ultrasonic transducer was inside the reactor and found that ultrasound had a greater influence on the yield at the lowest particle size tested (3-4 mm compared to 9-10 mm), achieving an increase of 20 % in oil recovery. It is likely that the highest surface area to volume ratio favors the action of ultrasound, pointing to an influence of ultrasound on the external resistance. From microscopic pictures (field emission scanning electron microscopy, FESEM), Balachandran et al. (2006) observed that the structure of the material treated with ultrasound showed cellular damage that could favor the removal of the cell contents. This fact could indicate that the effect of ultrasound could also be located in the internal resistance to mass transfer.

The influence of ultrasound may also be important in the extraction kinetics. Riera et al. (2004) report a 30 % reduction of the extraction time for a similar extraction yield and found that the influence of ultrasound was more evident in the second period of extraction, after the period when the solubility of the solute in the solvent controls the extraction. On the contrary, Balanchandran et al. (2006) found that ultrasound had the greatest influence on the extraction kinetics in the first phase of extraction, doubling the effective diffusivity identified for a conventional process. The ultrasound enhancement in the second stage of extraction, although significant, was lower than in the first extraction phase. These results show that, the magnitude of the influence of ultrasound on extraction could be different for each specific application.

The effects of ultrasound could be related to the compressions and decompressions, the radiation pressure or the streaming (Riera et al., 2004). No clear evidence of cavitation was found under the conditions used for supercritical fluids (Balachandran et al., 2006). The high pressure needed to achieve supercritical conditions, above 72 bar, makes the appearance of cavitation bubbles difficult.

5. Conclusions

The application of ultrasound affects the heat and mass transport processes. The effects linked to ultrasound include cavitation, compressions and expansions, microstirring, etc. and affect both the external and the internal heat and mass transfer resistance. The importance of each effect in the global influence of ultrasound on transport is different for the system considered: solid-liquid, solid-gas or solid-supercritical, since, for example, cavitation does not take place in a gas or supercritical medium. The process variables influence the magnitude of the ultrasound effects and it is necessary to establish the optimum value for each specific application. This offers new possibilities for food process innovation, ranging from energy savings to process yield or product quality. The use of ultrasound is opening up a field of activity in food processing.

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TABLE CAPTION

Table 1. Acoustic pressure measurements (bar) carried out using a hydrophone in 800 mL of a saturated brine and a sucrose solution (30 ºBrix). Ultrasound applied with a probe system (probe diameter of 13 mm and at 1.5 cm distance from the emitter's surface) supplying different percentages of the total electric power of the equipment (100 W).

FIGURE CAPTIONS

Figure 1. Variation of acoustic pressure inside an ultrasonic bath (Fungsonics mod. 28 L, 20 kHz, Fungilab S.A., Barcelona, Spain) containing distilled water (28 L) with the distance from the bottom. Measurements carried out with and without water agitation.

Figure 2. A. Evolution of experimental and calculated temperature on an aluminum cylinder during the heating in a bath with ultrasound application. **B.** Identified heat transfer coefficient, h, for heating treatments with agitation (USAG with ultrasound application and AG without) and without agitation (USWAG with ultrasound application and WAG without) of heating medium.

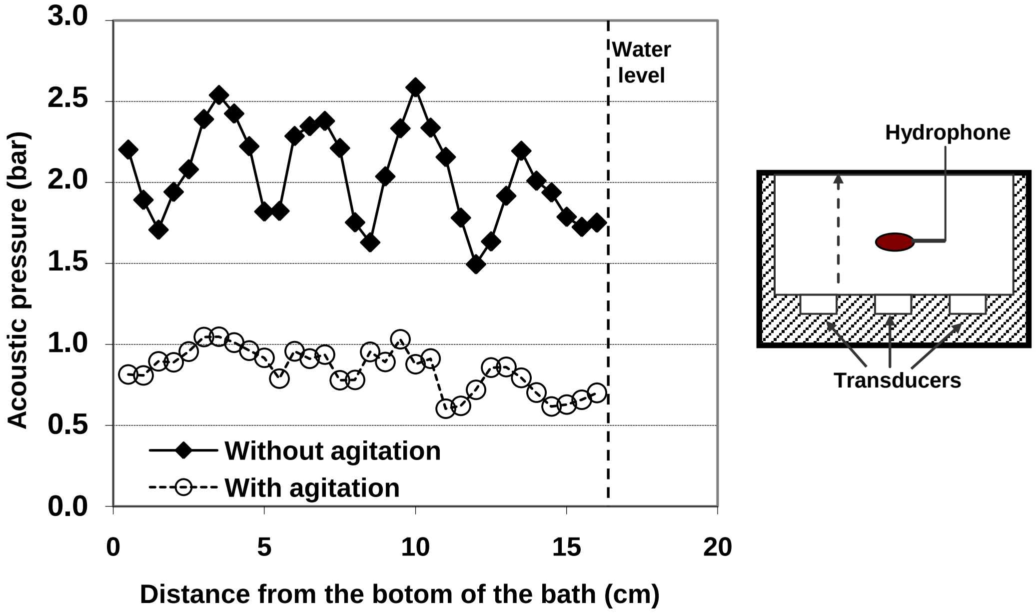
Figure 3. Detail of the ultrasonic application system of an ultrasonically assisted convective drier (Cárcel et al., 2007a).

Figure 4. Identified effective diffusivity (D_e) and mass transfer coefficient (k) for the drying of carrot and lemon peel with ultrasound application at different acoustic powers. Air temperature of 40 ºC and air velocity 1 m/s (García-Pérez et al. 2009).

Figure 5. Mass transfer coefficient (k) and effective moisture diffusivity (D_e), identified during the drying of carrot cubes at 40 ºC and 1 m/s with (US; 75 W, 21.7 kHz) and without (AIR) ultrasound application (Cárcel et al., 2011).

Figure 6. Scheme of the supercritical fluid extractor provided with an ultrasonic system to assist the extraction (Riera et al., 2004).

Figure



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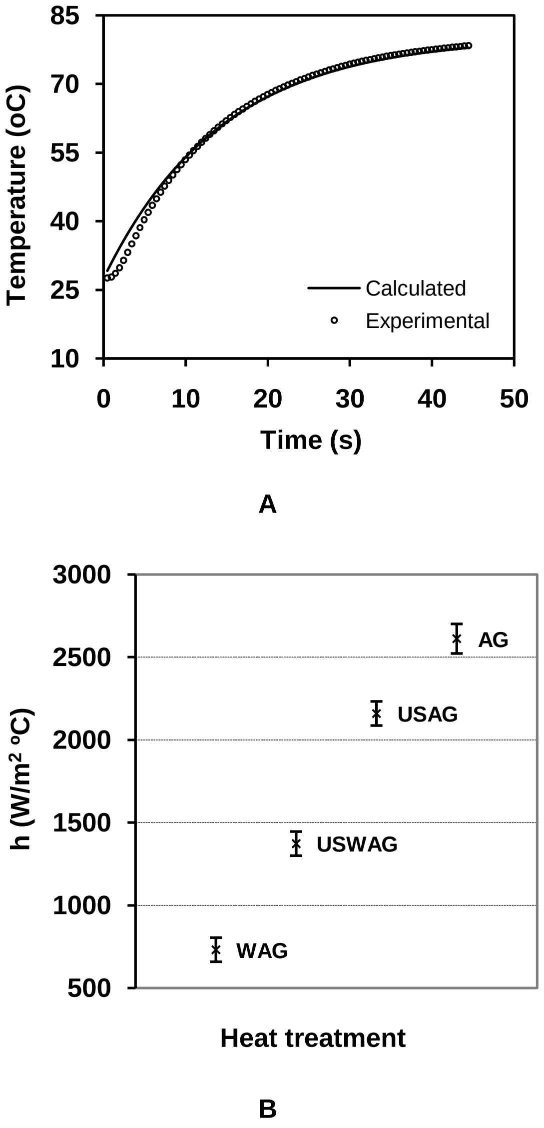

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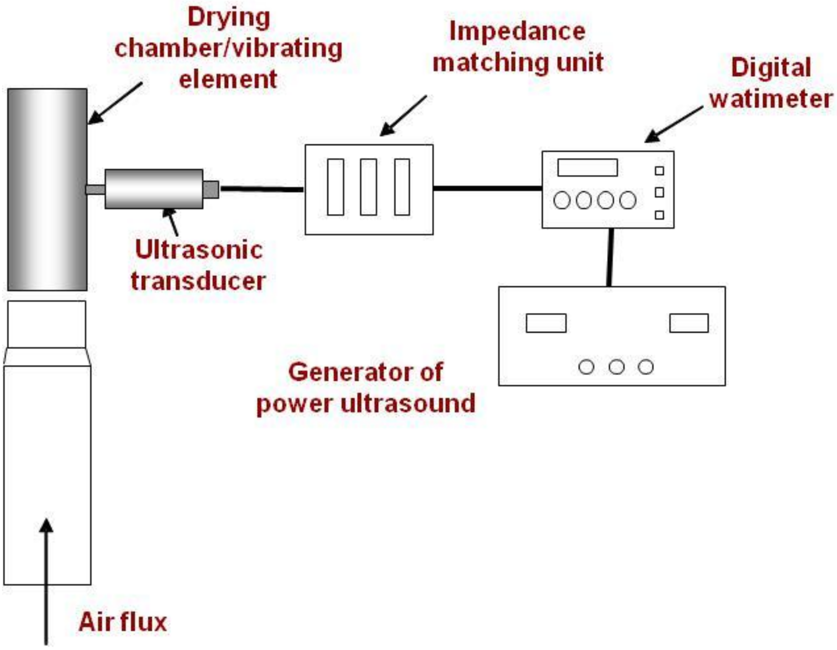

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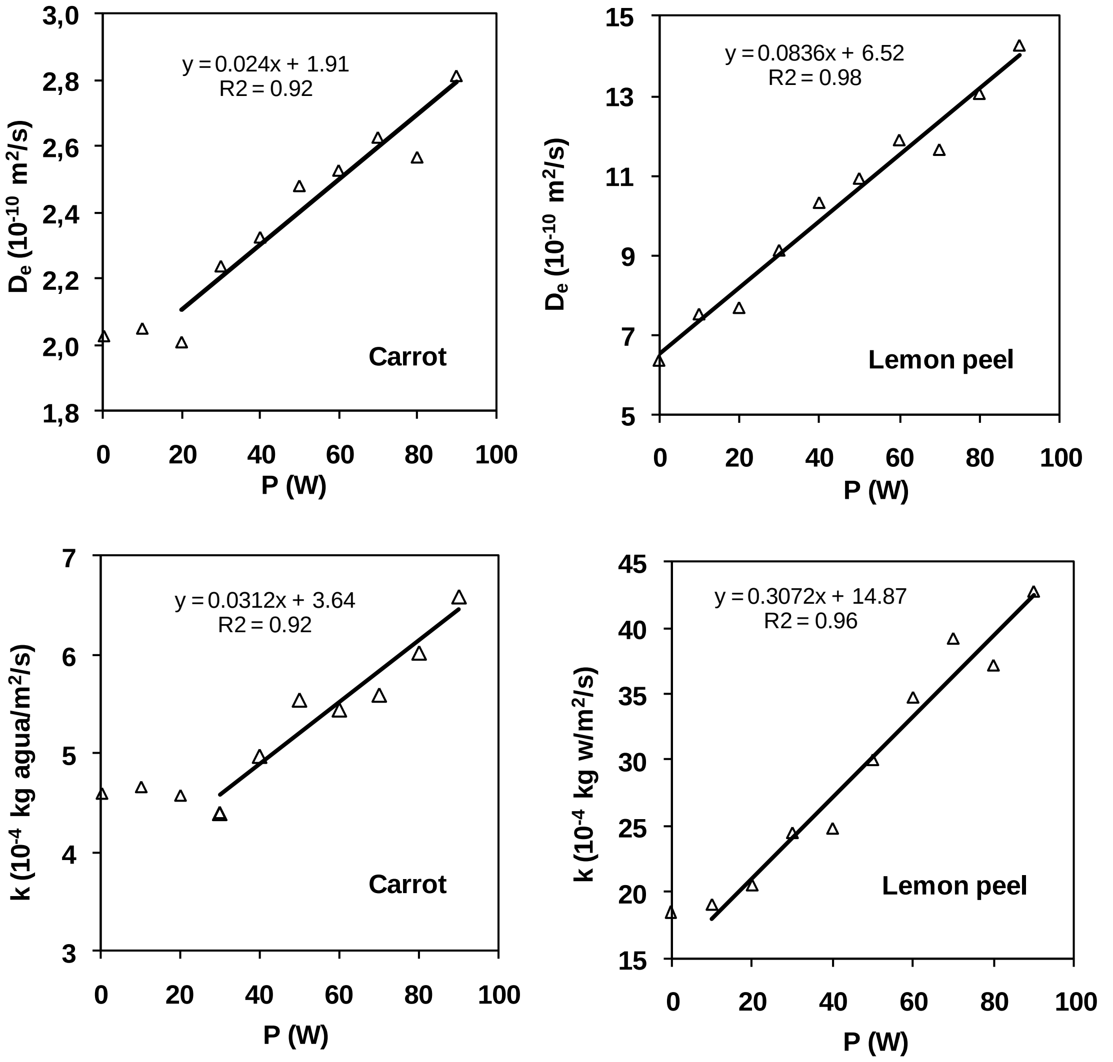

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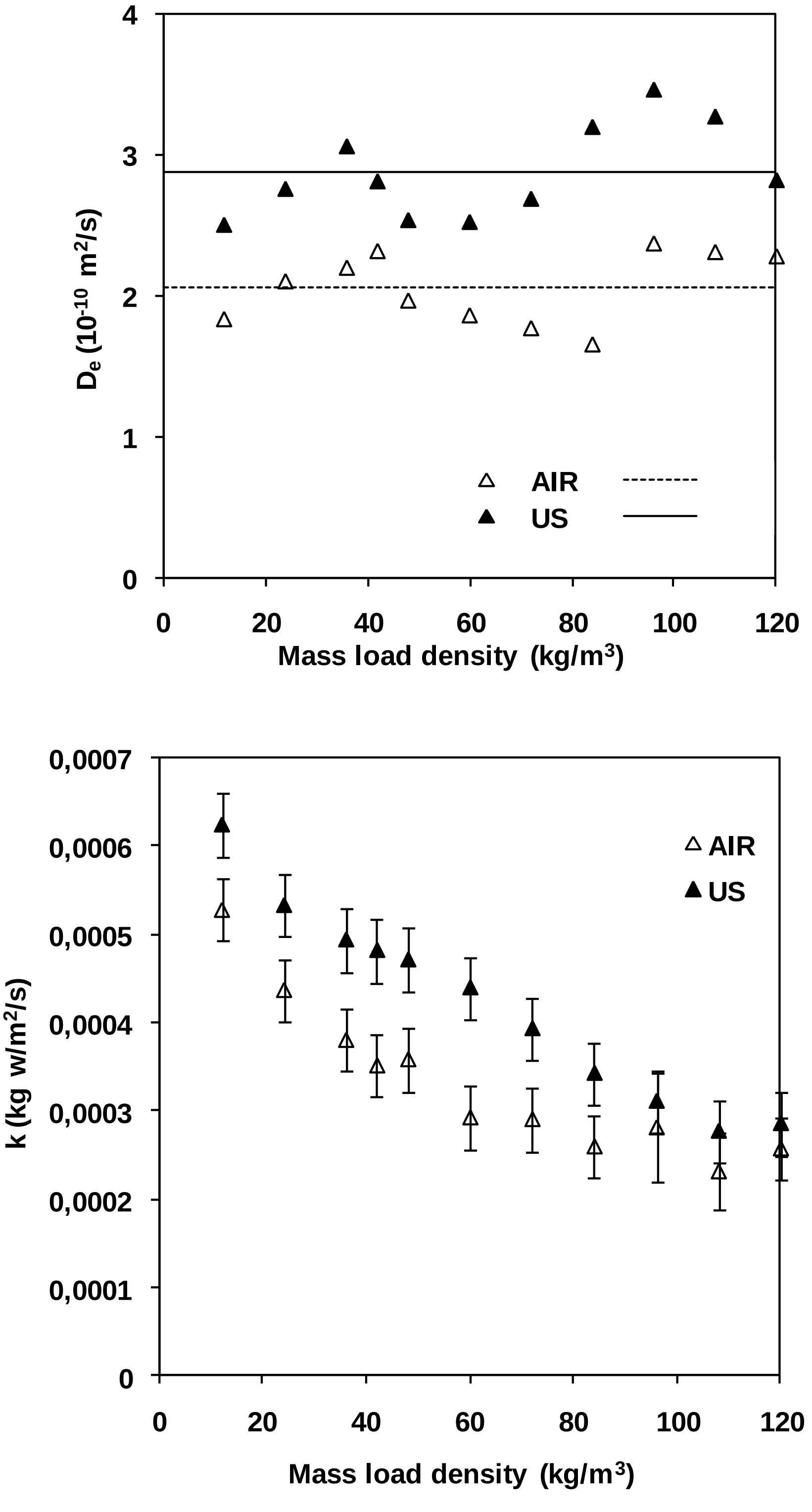

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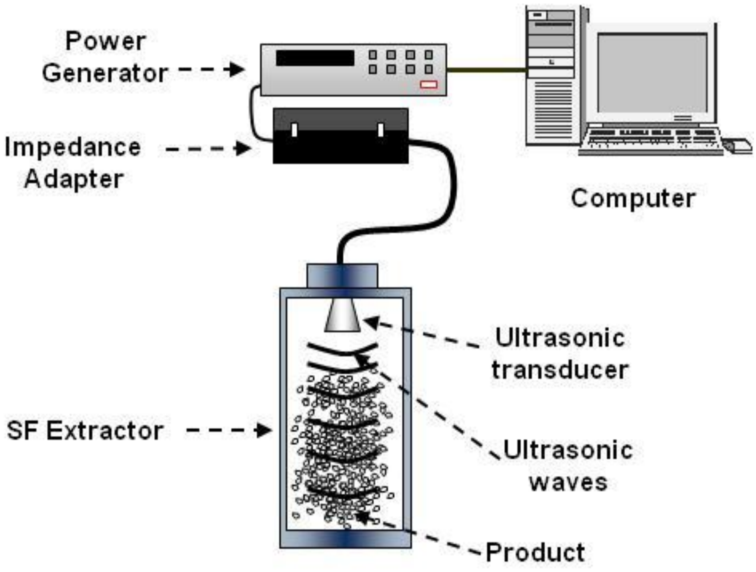

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	Percentage of the applied electric power				
	20	**40**	**60**	**80**	**100**
Brine	0.63 ± 0.07	0.68 ± 0.02	0.73 ± 0.05	0.88 ± 0.01	0.92 ± 0.09
Sucrose solution	0.56 ± 0.05	0.60 ± 0.04	0.66 ± 0.03	0.77 ± 0.06	0.86 ± 0.05