DRYING TECHNOLOGY
2021, VOL. 39, NO. 2, 245–258
https://doi.org/10.1080/07373937.2019.1677704

Airborne power ultrasound for drying process intensification at low temperatures: Use of a stepped-grooved plate transducer

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ABSTRACT

The recent development of a novel family of power ultrasonic transducers with extensive radiating surfaces represents a step forward in the implementation of new airborne power ultrasonic (APU) technologies for drying process intensification at low temperature. These systems have been successfully used to assist drying of different products at laboratory level. This work deals with the development, integration, and testing of a new APU transducer with a stepped-grooved circular radiator as an initial step in scaling up the process and the results achieved in experiments of airborne atmospheric freeze-drying (AFD) of apples. The results confirm that ultrasound application leads to a significant intensification of the processes. The modeling shows that the increase of kinetic parameters was lower than those obtained with cylindrical transducers having the same electrical input. This fact is attributed to the treatment of greater volume.

ARTICLE HISTORY
Received 1 April 2019
Revised 2 October 2019
Accepted 3 October 2019

KEYWORDS
Power ultrasound; ultrasonic processing; mass transport; atmospheric freeze-drying

Introduction

Reducing water content is one of the main ways to achieve food preservation. This is the case in convective drying of solids, where food product moisture is transferred to a gas media such as air. The matter transfer process in these solid-gas systems is influenced by both internal and external resistance. Internal resistance results from the characteristics of the solid matrix and the temperature, while external resistance mainly depends on the boundary layer thickness.[1] Currently, convective hot-air dying (CHAD) is one of the most common and widely used drying techniques employed to extend the shelf life of food products. However, it is a highly time and energy consuming thermal process,[2] which can also have negative effects on the final quality of the dehydrated product, as shown in properties such as color, texture, flavor, rehydration capacity, content of vitamins or other nutrients.[1]

The application of airborne power ultrasound (APU) in drying systems may overcome some of the limitations of CHAD by increasing the drying rate without significantly affecting the product quality. Ultrasound wave propagation mainly produces mechanical effects in the treated medium which can intensify the water removal without producing a significant heating of samples.[3–6] In fact, APU has been widely investigated in food processing applications[3,5–17] with the goal of increasing the drying rate of materials. Specifically, ultrasonically assisted CHAD process permits the use of lower temperatures and may be useful for drying heat sensitive materials.[3]

In 2017 Cárcel et al., among others, published a very interesting work on ultrasonically assisted CHAD that shows how the properties of the material structure being drying affect APU application. For this purpose, a quantitative analysis of the drying kinetics of orange peel, lemon peel, eggplant, apple, cassava, potato, and carrot samples were carried out at 40 °C and 1 m/s with different ultrasonic powers from 0 to 75 W[16,18–22] in Valencia by the ASPA Group. It was observed that the slope of the linear relationship, between the effective diffusivity and the level of APU application, depended on the product being dried. Thus, the structure not only determine porosity and textural properties (softness and hardness), but also

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the acoustic transmission coefficient in the product sample.[16] In other words, it controls acoustic propagation, the energy losses at the interface gas-solid, and consequently, the energy available in the solid matrix of the sample for water removal. Cárcel says that porosity can be used to estimate the feasibility of applying APU in a CHAD processes.

Generally, ultrasonic energy is used to produce permanents changes in the treated medium. Its use is based on the adequate exploitation of a series of mechanisms activated by the high-intensity ultrasonic waves, such as radiation pressure, acoustic streaming, agitation, instability at the interfaces, and structural diffusion.[11] When a high-intensity ultrasonic wave propagates in a medium in the presence of obstacles, continuous radiation forces that act on the obstacles give rise to what is known as radiation pressure. The radiation pressure is linked to any wave process and has its origin in the change of momentum that the wave experiences when acting on an obstacle. These forces are intense enough to give rise to processes of drag and interaction.[3,10,23,24] As the ultrasonic absorption processes on the high-intensity waves, radiation forces are generated inducing movements in the irradiated fluid, which improve the transfer of matter and heat.[10,24–26]

In addition, high-intensity ultrasound produces pressure variations in the solid-gas and liquid-gas interfaces that may influence the rate of evaporation/sublimation (as a function of temperature) of the solvent molecules retained in the matrix. During the negative phase of the pressure cycle, the pressure of the solvent at the solid surface decreases, enhancing its transport to the surrounding fluid. The high intensity ultrasonic energy also causes oscillating and microcurrent velocities at the interface, which may contribute to decrease the thickness of the diffusion boundary layer.[24,25,27,28] This reduces the external resistance to the matter transfer and increases the matter transfer coefficient.

The effects of ultrasound at the interfaces can also influence the internal resistance to matter transport when they affect the intercellular spaces inside the matrix. These phenomena will be more intense in materials with a wide network of intercellular spaces.[10,24,26,29] When the ultrasonic energy propagates through the solid, semi-solid or liquid matrix, it causes a rapid series of alternative contractions and expansions. This process could be compared to what happens when a sponge is squeezed and relaxed, so it is usually known as microsponge effect.[3,30,31] These alternate stresses facilitate the movement and elimination of the solvents (like water) through the microscopic channels created by the propagation of the wave, increasing the diffusion coefficients. Therefore, the mechanical effects produced by ultrasound can induce an improvement in the mass transfer phenomena, which can both shorten drying time and energy costs. A relevant characteristic of high-intensity ultrasonic waves is their capacity to work synergistically with other forms of energy in order to promote, accelerate, or improve many processes. For this reason many practical applications of high power ultrasound are not exclusively ultrasonic processes, but ultrasonically assisted processes.

Bantle et al. investigated AFD of apple, peas, and clipfish assisted by APU.[32–34] They performed a parametric study to identify the influence of the drying temperature, drying time and ultrasonic power in the acceleration of the dying rate of peas. For this purpose, the samples were dried in a cylindrical fluidize bed with and without APU. The experimental layout, developed at laboratory scale with a capacity for processing 1 kg of product, is described in detail in Refs.[32,34] In this study, a commercial ultrasonic transducer working at 20 kHz was placed below the tray where samples were placed. Different test series were carried out to investigate the influence of temperature (from −6 to 20 °C), drying time (3 and 24 h), and ultrasonic power (0, 15, 45, 70 W). AFD assisted by APU showed an increase of the order of 14.8% of the effective diffusion coefficient (De). Similar results were achieved with apple samples.[34] In this case, the improvement obtained in the sublimation rate in ADF assisted by APU was of the order of 9.9%. The authors confirmed that for higher temperatures (10 and 20 °C) the effect of APU decreases, while a higher mass transfer rate at the solid-gas interface is reached owing to the effect of APU on the thickness of the boundary layer as a result of acoustic streaming.

Some years late, in a different laboratory scale pilot plant, these authors investigated the effect of APU in LDT of clipfish, using the same APU system working at 20 kHz, and placing it on a tray inside the tunnel dryer[33] at a distance of 2 cm from clipfish samples. The tests showed that the drying kinetics at 20 °C was reduced by 43% when a power ultrasound was applied. Although the effect of APU clearly demonstrated a faster dehydration process, the APU energy consumption was too high to be competitive.

Schössler et al. investigated power ultrasound application as a non-thermal intensification procedure for LTD (low temperature drying) of red bell pepper, finding a drying time 11.5% shorter than in

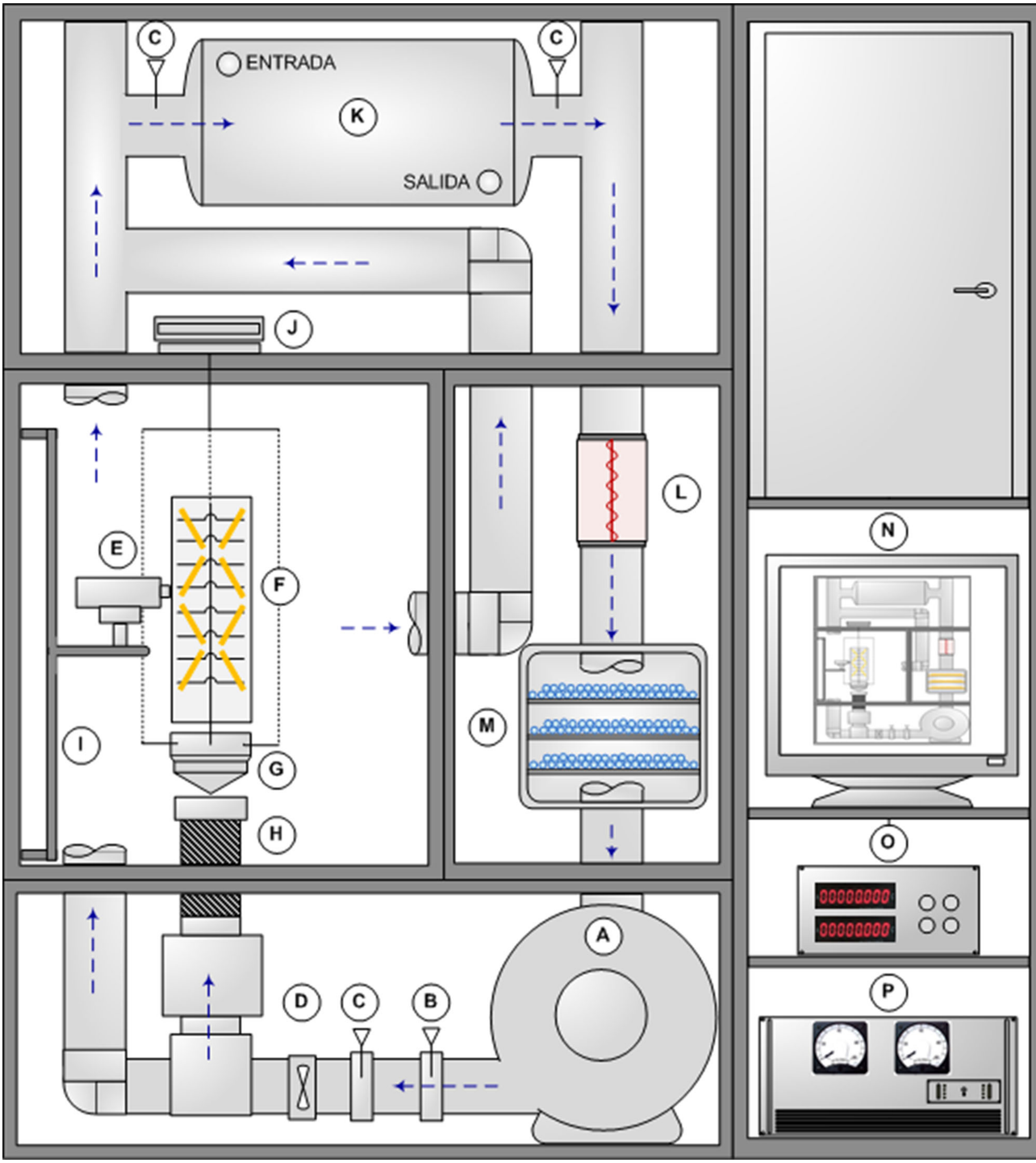

Figure 1. Diagram of the ultrasonically assisted low temperature dryer: A, fan; B, Pt-100; C, temperature and relative humidity sensor; D, anemometer; E, ultrasonic transducer; F, vibrating cylinder; G, sample load device; H, retreating pipe; I, slide actuator; J, weighing module; K, heat exchanger; L, heating elements; M, desiccant tray chamber; N, computer; O, amplifier; P, resonance dynamic controller. Reprinted from [57].

conventional experiments.[35] A different type of ultrasonic system was built for this research, working as a shaker/vibrator inside a freeze drying equipment[35,36] where ultrasonic energy cannot propagate through the air under vacuum operational conditions. Drying was carried out with laboratory scale freeze drying equipment. The ultrasonic system consisted of a ring sonotrode, driven by a power ultrasonic vibrator at 24 kHz.[35] A laboratory drying screen mounted on the ring sonotrode worked simultaneously to both hold the sample and transmit the ultrasonic wave. The ultrasonic vibration generated by the ring

Table 1. Ultrasonic assisted drying. Compendium of previous works carried out by UPV and CSIC groups addressing the application of airborne power ultrasound (APU) on low temperature drying (LTD) and atmospheric freeze-drying (AFD).

Reference	Ultrasonic device	Drying Method	US transfer mode	Process variable under study	Material being tested	Modeled and quality parameters
Spanish Patent[17]	CR	LTD	CL	Ultrasonic power	Apple cubes	DK
Santacatalina et al. (2012)[25]	CR	AFD	CL	Ultrasonic power	Carrot cubes	DK, RK, Hardness
García-Pérez et al. (2012)[24]	CR	AFD	CL	Ultrasonic power and hardness of material	carrot cubes, Eggplant cubes, apple cubes	DK, De, k
García-Pérez et al. (2013)[26]	CR	CHAD LTD	CL	Air velocity and ultrasonic power	Carrot and Apple cubes	DK, De, k,
Santacatalina et al. (2014)[27]	CR	LTD	CL	Air temperature and ultrasonic power	Apple cubes	DK, De, k, antioxidant potential
Santacatalina et al. (2015)[28]	CR	AFD	CL	Air velocity and temperature, and ultrasonic power	Apple cubes	DK, De,
Brines et al. (2015)[29]	CR	AFD	CL	Ultrasonic power	Apple cubes	DK, De
Santacatalina et al. (2016)[31]	CR	LTD	CL	Air velocity and temperature, and ultrasonic power	Eggplant cubes	DK, De, k, RK
Santacatalina et al. (2016)[30]	CR	LTD	CL	Air temperature and ultrasonic power	Apple cubes	DK, De, k, RK, microstructure
Cárcel et al. (2016)[32]	CR	LTD	CL	Air temperature and ultrasonic power	Apple and eggplant cubes, and desalted cod	DK, De, k, RK, microstructure, color
Rodríguez et al. (2017)[15]	CR	LTD	CL	Air temperature and ultrasonic power	Carrot and apple cubes,	
Cárcel et al. (2017)[14]	CR	LTD	CL	Ultrasonic power,	Apple cubes and cylinders, and dried-salted cod	DK antioxidant potential, microstructure Cryo-SEM
Colucci et al. (2017)[33]	CR	AFD	CL	Air velocity and temperature, ultrasonic power and sample thickness	Eggplant cubes	DK, De,
Charoux et al. (2017)[34]	CR	LTD	CL	Air temperature and ultrasonic power	Apple cubes	
Moreno et al. (2017)[35]	CR	AFD	CL	Samples geometry, ultrasonic power	Apple slabs and cylinders	DK, De, k, antioxidant potential,
Carrión et al. (2018)[36]	CR	AFD	CL	Ultrasonic power	Mushroom slices	DK, color, hardness, RK, cell damage
Vallespir et al. (2018)[37]	CR	CV	DK	Ultrasonic power	Beetroots	DK, De, k
Colucci et al. (2018)[38]	CR	AFD	CL	Air temperature, ultrasonic power and sample size	Eggplant cubes	Antioxidant potential

CR: Cylindrical radiator; SCPR: Stepped circular plate radiator; AFD: Atmospheric Freeze Dying; LTD: Low Temperature Drying; CHAD: Convective Hot-air Drying; DK: Drying Kinetics; RK: Rehydration Kinetics.

sonotrode was transmitted as compressional stress waves in the material being dried. A parametric study was performed by the authors to analyze the effect of drying time (from 4 up to 24 h) and vibration amplitude (4.9, 6.0, and 6.7 μm referred to power ultrasound of 76, 90, and 110 W, respectively) in the drying process of red bell pepper samples and apple cubes. High-temperature problems, in this case an increase over 50 °C, appeared in the system when it was working under continuous wave operation. For this reason, in order to minimize the temperature increase, the authors studied the effect of intermittent contact-vibration, reducing the ultrasound radiation time by 50% by alternating 10 s ultrasound-on and then 10 s ultrasound-off. As a result, the temperature increase in the system was kept constant at 5 °C.[36] In this context, systems with contact between transducers and samples are quite difficult to implement on an industrial scale.[16]

During the last two decades, the Ultrasonic Systems and Technologies Group (USTG) of the CSIC and ASPA Group of the UPV, from Spain, have been working together to introduce new systems and methods in food drying technology, specifically in convective hot-air drying (CHAD) and more recently in low temperature drying (LTD) including atmospheric freeze-drying (AFD) processes. From the beginning, APU proved to be an effective, nontoxic and environmentally friendly way to speed up not only the CHAD process[3,6,7,11,25,37–41] but LTD and AFD processes as well.[16,17,24,31,42–55] These APU systems have been successfully used to assist drying of different kind of products at laboratory level. This work deals with the development, integration and testing of the latest ultrasonic technologies developed by the USTG group-CSIC and commercialized by PUSONICS SL and the experimental results of their implementation in a pilot scale drier in the ASPA group-UPV facilities. This initiative is a first attempt to scale-up the ultrasonically assisted drying system, moving from a cylindrical transducer with small volume drying chambers to a stepped-grooved plate transducer more appropriate for a belt transport drying system.

Low temperature drying assisted by ultrasound: APU application with cylindrical radiator (CR)

Based on the expertise acquired by the ASPA group in the application of ultrasound in CHAD,[6,56] the UPV and CSIC groups developed[42] an ultrasonic-assisted dryer plant at laboratory scale to extend the application of APU in intensifying low temperature drying (LTD) processes including atmospheric freeze-drying (AFD) conditions. Figure 1 shows the design of this experimental dryer system.[57] The APU application, carried out using a cylindrical radiator, is able to produce a high intensity acoustic field inside the drying chamber. This allows the evaluation of the efficiency of ultrasonic devices at low temperature conditions, as well as to assessing the influence of the most relevant process variables. Table 1 shows a selection of feasibility studies of APU applications on LTD and AFD processes carried out during last decade by UPV and CSIC in their convective low temperature drying facilities with different fruits and vegetables These facilities have been used by different authors to investigate the effect of: (i) ultrasonic power[13,16,17,24,42–55]; (ii) air velocity[13,16,44,46–48,51]; (iii) air temperature[13,16,17,45,46,48–51]; (iv) hardness of the material[42]; (v) sample thickness and size.[51,55]

Effect of combined ultrasound and LTD/AFD on the kinetics

In general, the application of APU increased the dying rate and reduced drying time: the more power applied, the faster the process. Santacatalina et al.,[45] demonstrated the feasibility of applying APU to enhance the mass transfer rate during LTD of apple cubes. The samples were dried at five different low temperatures from $-10\,°C$ up to $10\,°C$, with an air velocity of 2 m/s, a and relative humidity less than 10%, both without and with ultrasound (20.5 kW/m^3, corresponding to 50 W of electric excitation power) application. The maximum reduction of the drying time achieved with APU application was of the order of 72%, and occurred when drying was carried out at sublimation conditions. Two years later, Santacatalina et al.[48] continued his studies of drying apple cubes of the same dimensions, at two different temperatures (-10 and $10\,°C$) and at four different ultrasonic powers (0, 25, 50, and 75 W). In this case, the maximum drying time reduction reached was 80.3% at the maximum power applied. Next, Santacatalina et al.[46] extended these previous studies to analyzed the contribution percentages of the process variables, air temperature (–5, –10, and –15 °C), air velocity (1, 2, 4, and 6 m/s) and ultrasound application (0, 25, 50, and 75 W) to the duration of the AFD of apple samples. The authors found that the effect produced by APU application on drying kinetics was more relevant than the effect produced by air temperature and velocity. Hence, this was considered as the key parameter of the drying process.

The enhancement of LTD by using ultrasound was also studied with products other than apples. Thus, Colucci et al.[51] observed in AFD experiments performed with eggplant cubes, that when an ultrasonic power of 25 W was applied, the average diffusivity coefficient increased by 380% compared to results obtained without PU. This result shows the ability of APU application to accelerate the kinetics. On the contrary, variations of air velocity and temperature showed no relevant effects on drying kinetics.

Sample geometry was another process variable studied. Moreno et al.[52] studied the influence of surface/volume ratio of two apple sample geometries (slabs and cylinders) on APU effects on the kinetics. In the case of cylindrical samples, drying time was reduced by 69% and 88% when APU was applied at 25 and 75 W, respectively. In the case of slab-shaped samples, the application of the same power levels reduced the drying time by 82% and 92%, respectively. The greater decrease in the drying time in the

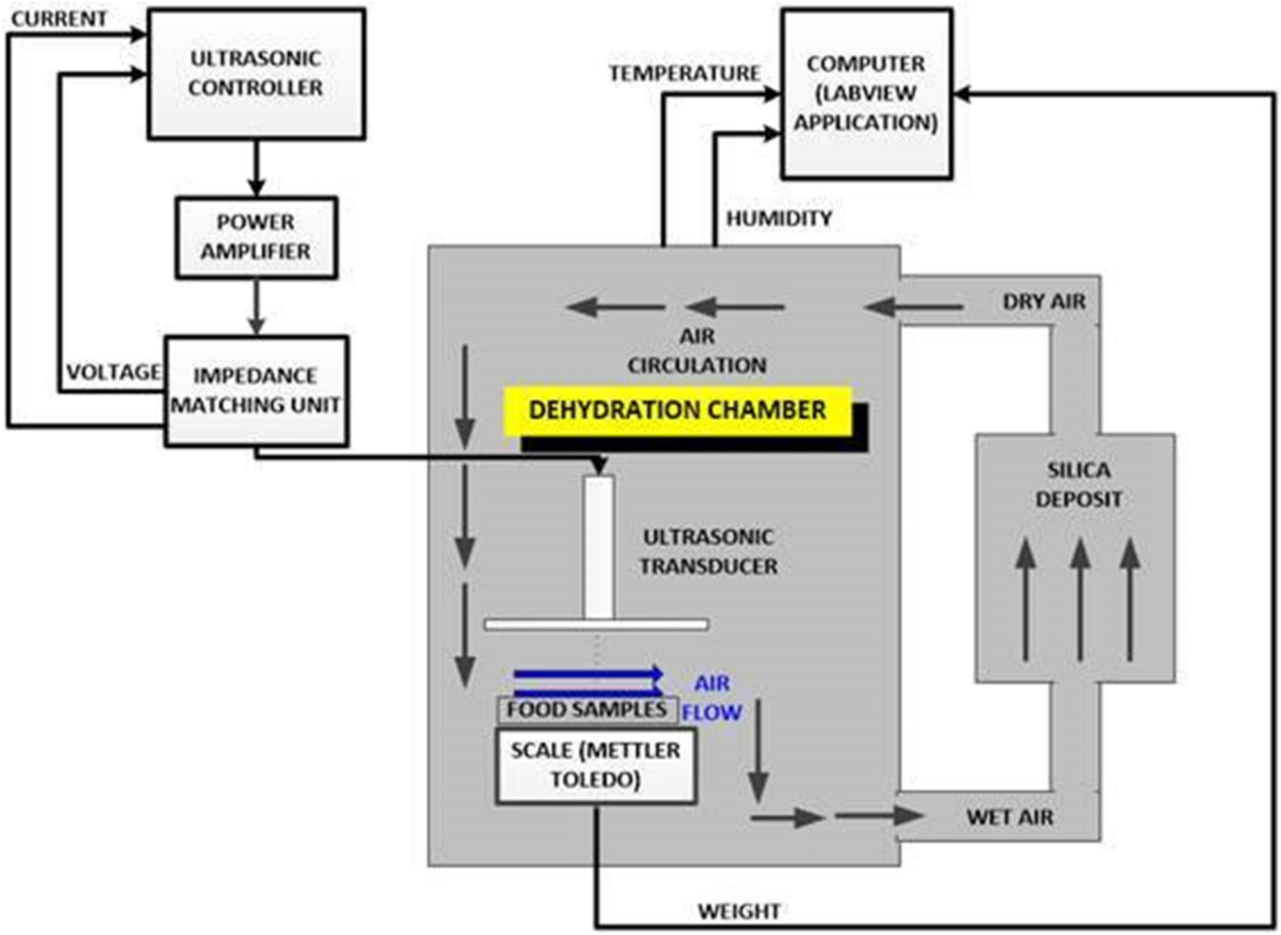

Figure 2. Scheme of the new ultrasonically assisted LTD system.

slabs was probably due to the lower surface/mass ratio of the slab samples used compared with the cylindrical ones.

Vallespir et al.[54] focused their interest on improving mass transfer by applying freezing pretreatment and ultrasound application on the convective drying of beetroot cubes. The drying time of the sample cubes decreased (36–43%) when ultrasonic power was applied and decreased (55–58%) when samples were frozen before drying with APU application. In addition, APU application during drying induced relevant increases in both effective diffusivity (60–73%) and mass transfer (24–49%) coefficients. Therefore, ultrasound application was suitable for the intensification of the drying kinetics of beetroot.

Carrión et al.[53] studied the ultrasound application to enhance the AFD of mushroom slices. The drying experiments, carried out at a constant temperature of $-10\,^{\circ}$C and an air velocity of 2 m/s, showed that the values for the effective diffusivity increase significantly up to 280% as the applied ultrasonic power was increased up to 60 W. This implies a reduction of the drying time up to 74%. Generally, we can conclude that the low influence of the air velocity on the drying rate and the porous structures that are generated in dried products by sublimation means that APU application represents an interesting technique to significantly increase the drying rate in LTD processes.[16]

Effect of combined US and LTD/AFD on product quality

In 2018, Rodriguez et al.[17] published a very interesting review that summarizes the effects of the APU application on the quality of different products, dried under different operational conditions. These authors state that the APU at LTD and AFD conditions produced an intensification of the drying process, limiting oxidation reactions and maintaining most of the bio-compounds intact. Santacatalina et al.[48] studied the influence of LTD conditions on quality parameters of apple cubes. They carried out drying experiments with an air flow of 2 m/s, at two different temperatures (10 and $-10\,^{\circ}$C), without (0 W) and with (25, 50, and 75 W) APU application. Their results showed that APU only had a mild impact on the quality attributes

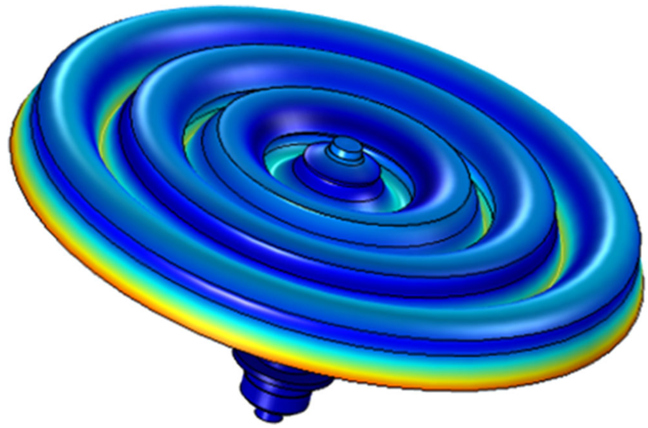

Figure 3. Representation of the stepped circular plate transducer vibrating at its operational mode with 7NC.

studied (rehydration capacity, hardness, total phenolic content, antioxidant capacity and microstructure). Similar results were obtained in the case of eggplant by these authors.[49] In this case, the cubic samples were dried at different air velocities (1, 2, 4, and 6 m/s) and temperatures (10, 0 and −10 °C) without (0 W) and with (50 W) APU application. These processing variables did not result in a relevant influence on the hardness of the rehydrated samples. In addition, they observed that the rehydration capacity was only affected by air temperature. Similar results were obtained by Colucci et al.,[55] during ultrasound-assisted AFD on the antioxidant properties of eggplant samples. The authors evaluated the effect of air velocity (2, 5 m/s), drying temperature (−5, −7.5, −10 °C), sample size (cubic samples of 8.8 and 17.6 mm side) and APU power applied (0, 25, and 50 W). Although the degradation was greater when processing larger samples, the APU application did not significantly affect the antioxidant content of the product.

Therefore, the results obtained at laboratory scale shows that APU may be considered a promising technology for enhancing the AFD process. It is necessary to study whether or not this influence can be scaled-up to an industrial process. In this regard, it is very difficult to achieve big vibrating chambers with the same acoustic behavior as the small cylindrical transducers used in laboratory scale driers. An alternative could be the use of stepped-plate transducers, which can be easily implemented in a convective drier. In this work, a new freeze-drying system is introduced. This system is composed of a convective drier and an airborne power ultrasonic transducer with a stepped circular radiator for the generation of a coherent field. The performance of this new system was evaluated by a study of drying kinetics of apple samples, dehydrated under different operational conditions.

Materials and methods

LTD drier with APU application by stepped circular plate radiator (SCPR)

A new convective drier was designed and developed by ASPA group to carry out ultrasonically assisted LTD experiments with a stepped plate transducer. The aim of this new drier was to scale up an ultrasonically assisted drier. The drier consists of a semi-industrial freezing chamber (Figure 2) divided in two sections, a pre-chamber and the drying chamber. The pre-chamber allows constant temperature and relative humidity in the drying chamber. This constant relative humidity is achieved by recirculating air from the drying chamber through a bed of desiccant material. The drying temperature was maintained at the desired level by a combination of the evaporating system of the freezing chamber and an electrical resistance. Temperature and relative humidity sensors (Rotronic iroflex, mod. HYGROFLX HF520DB1) allowed monitoring both parameters. A fan provided a flat air flux whose velocity was measured with an anemometer. The air flux is directly focused towards the sample holder. A scale registered changes in the weight of samples during drying. A Labview application was developed to control the process conditions (temperature, air velocity) inside the drying chamber.

Ultrasonic system for freeze-drying

The APU transducer, developed by CSIC and Pusonics, consists of a Langevin transducer, a mechanical amplifier and a stepped circular plate radiator (SCPR) to ensure a coherent ultrasonic radiation. The ultrasonic system operates at working mode with an extensional vibration for the Langevin sandwich and the horn, and a flexural vibration with seven nodal circles (7NC) for the circular radiator at a frequency around 26 kHz. The APU transducer is described in detail by Andrés et al.[58,59] The operational mode of the transducer, determined numerically by FEM, with a flexural mode with 7NC, is shown in Figure 3. The transducer needs an electric supply and guidelines to vibrate at the required frequency with the desired amplitude. The generation system is placed outside the cabinet and is composed of a dynamic resonance frequency control unit (ultrasonic controller), which provides adjustable continuous power output at the resonance frequency of the transducer by keeping the voltage (V) and current (I) signals in phase, and tracking the resonance when the frequency shifts during operation.[60,61] The controller operates as a finely tuned electronic signal generator which sends the excitation signal to the transducer through an embedded impedance matching unit. This allows maximum energy transfer between the electronics and the transducer, by adapting the output impedance to the impedance of the transducer (about 500 ohm under resonance). To keep the system in resonance, samples of the voltage and current signals are taken at the output of the ultrasonic controller to measure the electrical response of the transducer.

The APU transducer with stepped-grooved circular radiator (radius of 20 cm) was placed inside the dehydration chamber, 19 cm above the sample holder. As a result, the volume covered by the transducer in terms of acoustic efficiency was 0.0239 m^3 and the surface, 0.126 m^2. The experimental acoustic characterization indicates that for an electric excitation of 50 W to the APU transducer, the sound pressure level (SPL) achieved in the volume of interest is 147 dB (547 W/m^2).[58] More specifically, the SPL obtained in the area where the food samples were placed was 148 dB (582 W/m^2). The acoustic energy is concentrated at the axis of the transducer, obtaining a SPL of 152 dB (1421 W/m^2) in this area.

Raw material and moisture content

Apples (Granny Smith var.), similar in size (approximate weight of 250 g), color (light green), and ripeness (10.5–12°Brix), were purchased from a local market (Valencia, Spain). This variety of apple was chosen because of its homogeneity. With the help of a mandolin, slices 3 mm thick were taken from the fleshy part of the apples, avoiding the area of the apple core. The samples were placed in a waterproof bag to prevent moisture content changes and were frozen in a blast freezing system (Hiber, mod. 051S) at a temperature of −35 °C for 1 h. After that, drying experiments were carried out.

The initial moisture content of the samples was determined following the AOAC standard method no. 934.06.[62] For this determination, fresh apple samples (5 g approximately) were placed in a vacuum oven at 70 °C and 200 mm Hg and dried until a constant weight was achieved.

Atmospheric freeze-drying experiments

The AFD experiments were conducted at a constant velocity of air flow (1 m/s), a constant temperature (−12 °C) and relative humidity below 7%, both without and with ultrasound application at 3 different levels of electric power (50, 100, 200 W) applied to the transducer. Each run was conducted with 15 samples, having an initial mass load ranging between 80 and 100 g. The different drying conditions were tested at least in three times and drying was extended until samples lost at least 80% of the initial weight.

Modeling

The resulting drying kinetics was modeled to quantify the influence of the conditions tested using a model based on the Fick's law. Because of the geometry of samples used (slices), the mass transport was assumed as unidimensional (Equation (1)):

$$\frac{\partial W_p(x,t)}{\partial t} = D_e\left(\frac{\partial^2 W_p(x,t)}{\partial x^2}\right) \tag{1}$$

where W_p is the local water content ($kg_{water}/kg_{dry\ matter}$), x represents the water transport characteristic direction (m), t is drying time (s), and D_e represents the effective diffusivity of moisture (m^2/s), meaning a measurement of the inverse of the internal mass transfer resistance. It was assumed that this effective moisture diffusivity was constant, no shrinkage occurred and the solid samples were homogeneous. This last fact, homogeneousness of solid samples, is not correct in AFD conditions because during drying two distinct parts can be distinguished in the samples: an external dried layer, which increases during the process, and an internal frozen core, which decreases. Nonetheless, this model has been previously used[45,46] to quantify the influence of process variables on drying kinetics. Equation (1) is a second order partial derivatives equation with respect to the mass transport direction (x) and first order with respect to drying time (t). According to this, an initial condition and two boundary conditions have are required to solve the equation. These conditions were the following:

Table 2. Parameters used for the drying kinetics modeling.

Parameter	Value
Thickness	3 mm
L	1.5 mm
Drying temperature (T)	−12 °C
φ_{air}	0.05
W_m	0.18 $kg_{water}/kg_{dry\ matter}$
C_G	8.9
K_G	0.89
ρ_{ss}	800 kg/m^3

- The initial moisture content (W_0) is the same in all points of the solid (Equation (2)):

$$W_p(x, 0) = W_0 \tag{2}$$

- No net moisture transport occurs at the symmetry plan of the solid (Equation (3)).

$$\frac{\partial W_p(0, t)}{\partial x} = 0 \tag{3}$$

- The moisture transported to from the inner to the sample surface by diffusion is transferred to the drying air by convection (Equation (4)).

$$-D_e\rho_{ss}\frac{\partial W_p(L, t)}{\partial x} = k\big((L, t) - \varphi_{air}\big) \tag{4}$$

Here, ρ_{ss} is the dry solid density ($kg_{dry\ matter}/m^3$), k is the mass transfer coefficient (kg_{water}/m^2 s), a_w is the water activity at the sample surface, and φ_{air} is the relative humidity of the airflow. The a_w (L,t) was estimated from the sorption isotherm reported by Vega-Galvez et al.,[63] whose model GAB parameters (W_m, C_G, and K_G) are shown in Table 2.

This model was numerically solved by a finite difference method using MATLAB 7.11.0. For this, the identified values of D_e and k minimize the square differences between experimental and calculated moisture content of samples.[25]

Results and discussion

Drying kinetics

The initial moisture content of apple was 6.14 ± 0.13 $kg_{water}/kg_{dry\ matter}$. The experimental results showed that AFD of the apple samples was a slow process. The samples dried without ultrasound application needed 23.6 ± 0.5 h to reach an 80% initial weight loss (a moisture content of 1.23 $kg_{water}/kg_{dry\ matter}$). The application of ultrasound significantly accelerated the dehydration process being faster the process when the electric power applied to the ultrasonic transducer was higher. For example the amount of time needed to reach an 80% weight loss decreased 22% using 50 W and 44% using 200 W of electric power compared to AFD drying time (see Table 3). It is important to highlight that the influence of ultrasound applications was important even at the low ultrasonic power applied 50 W. The apple samples before and after the dehydration process can be observed in Figures 4 and 5, respectively.

Table 3. Effective diffusivity coefficient (D_e) and mass transfer coefficient (k) identified by modeling experimental AFD kinetics (−12 °C and 1 m/s) of apple assisted by APU with different power (0, 50, 100, and 200 W).

	Ultrasonic Power Applied						
	0 W	50 W	Δ%	100 W	Δ%	200 W	Δ%
D_e (10^{-11} m^2/s)	2.60 ± 0.4	3.35 ± 1.1	29	3.46 ± 0.9	33	4.31 ± 1.3	66
k (10^{-4} kg_{water}/m^2 s)	1.12 ± 0.1	1.76 ± 0.2	57	1.58 ± 0.6	41	2.29 ± 0.1	104
Drying time (h)	23.6 ± 0.5	18.3 ± 0.5	22	16.1 ± 1.3	32	13.3 ± 0.8	44
Correlation coefficient (%)	99.4	99.8		99.9		99.9	
Explained variance (%)	99.3	99.8		99.9		99.9	
Mean relative error. (%)	14.5	7.6		2.7		2.2	

Note. Δ% represents the percentage of increase of each parameter compared to non-ultrasonically assisted experiments (0 W).

Modeling drying kinetics

The effect of airborne power ultrasound application was quantified numerically by modeling. The effective diffusivity coefficient (D_e) and the mass transfer coefficient (k) were identified by fitting the proposed model (Equation (1)) to the experimental data (Table 3). As stated before, the partially frozen state during drying invalidates the condition of homogeneity of the samples required in the model. This fact converts this theoretical model into an experimental one. However, the inverse of D_e and k parameters identified provide a measurement of the influence of drying condition tested on both, internal and external mass transfer resistance, respectively.

The representation of the drying kinetics under the four operational conditions analyzed (Figure 6) permits the comparison between the experimental and modeled curves. It can be observed that the modeled drying kinetics fitted adequately the experimental results obtained, and both experimental and calculated curves follow the same trend. Experimental results clearly confirm that this trend was greater in experiments carried out with ultrasound application (50, 100, and 200 W) than in non-ultrasonically assisted ones (0 W).

The accuracy of the model fitting was quantified by three parameters: the correlation coefficient, the explained variance and the relative mean error (Table 3). As indicated previously, the highest relative error (around 14.5%) was obtained for the case of drying kinetics without the use of ultrasound. In the case of

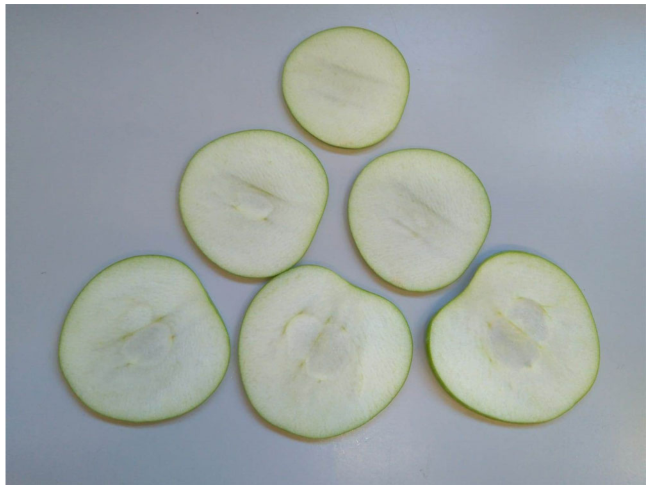

Figure 4. Fresh apple samples.

Figure 5. Dried apple samples.

ultrasonically assisted experiments, the higher the electric power applied to the transducer, the lower the relative mean error. It seems that ultrasound application during AFD reduced the variability of results. This fact was observed earlier by García-Perez et al.[42] in ultrasonically assisted AFD by using cylindrical transducer. Even so, the correlation coefficient and the explained variance were higher than 99% in all the drying conditions tested.

The values identified for D_e and k (Table 3) confirm the influence of the application of APU in enhancing AFD processes. Ultrasound application increased both parameters achieving greater increases when higher electric power was supplied to the ultrasonic system. Compared to 0 W experiments, the D_e increased 29% in 50 W experiments and 66% in 200 W experiments. These results indicate that the ultrasonic power applied was sufficient to induce significant effects in the internal moisture transport resistance of apples, even when the lowest electrical power was applied.

Similar influence of ultrasound application was observed for the k parameter. The value identified in 50 W experiments was 57% higher that the value identified in experiments carried out without ultrasound application (0 W) while the value reached 104% in the case of 200 W experiments (Table 3).

It is important to mention that these results correspond to initial experiments using the new prototype drier equipped with a power ultrasonic transducer with stepped circular radiator. The D_e and k values obtained in 0 W experiments were slightly lower, but in the same range, as those reported by Santacatalina et al.,[45] when drying cubic apple samples (Granny Smith, var.) at $-10\,°C$ without ultrasound application ($3.5 \pm 0.4 \times 10^{-11}$ m^2/s and $1.6 \pm 0.2 \times 10^{-4}$ $kg_{water}/m^2\,s$, respectively) fitting the same model. When ultrasound was applied with a cylindrical transducer

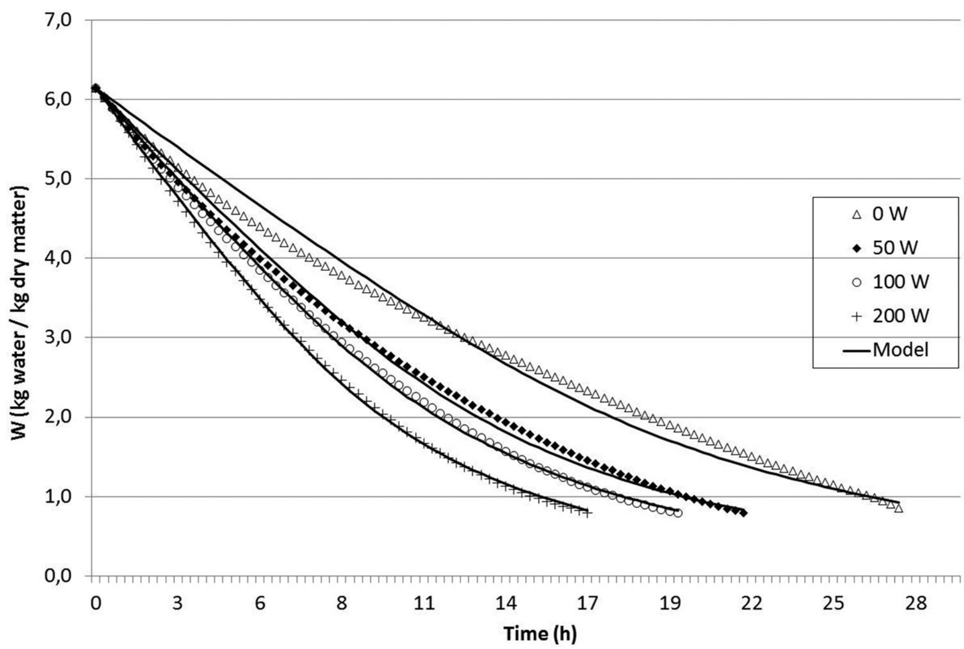

Figure 6. Experimental (dots) and calculated (lines) moisture evolution of apple slices during drying at −12 °C, 2 m/s without (0 W) and with ultrasound (50, 100, 200 W) application at 21.7 kHz.

(50 W of electrical input) a 500% increase in the D_e identified was observed, a value 66% greater than one observed in 200 W experiments of the present study. In the case of k, the increase produced by ultrasound application observed by Santacatalina et al.[45] was 148% while in the present 200 W experiments was 102%.

This comparison indicates that the cylindrical radiator appears to be more efficient than the stepped circular radiator. Higher values for D_e and k were achieved, applying less electric power to the ultrasonic transducer.

This fact is consistent because the acoustic energy generated by the cylindrical radiator is confined inside. The small volume of the cylinder keeps the acoustic energy concentrated in cells,[6] as shown in the acoustic distribution measurements. In the case of the stepped circular radiator, the acoustic energy generated presents a more or less coherent distribution in free field[64] inside the dehydration chamber, where the energy is concentrated along the axis of the radiator.[58] Moreover, the acoustic energy in this case is not confined, and the volume covered by the transducer is much higher. Therefore, this system is not as efficient as the cylindrical radiator. However, the experimental results obtained demonstrate that this new system may significantly improve the drying rate and can be used in an industrial scale.

Therefore, with the double objective of improving the applied acoustic field and scaling up the technology to an industrial level, CSIC and UPV groups are developing a new prototype of APU transducer equipped with reflectors to generate a more intense acoustic field in the drying chamber.

Conclusions

The feasibility of applying ultrasound to accelerate low temperature drying (LTD) and atmospheric freeze drying (AFD processes has been confirmed.

Works reviewed in this publication used an APU transducer with a cylindrical radiator, offering a good performance in terms of reduction of the drying time. Nevertheless, its physical configuration accommodates only a small amount of food samples inside the cylindrical radiator, making it unsuitable for use on the industrial scale. This work is a first attempt to scale-up the process by considering a drying chamber with a new APU transducer with stepped-grooved circular radiator, capable of accommodating a larger amount of food samples. The APU application with this new system during AFD kinetics of apple slices resulted in an increased drying rate and a reduced drying time. The ultrasonic system with stepped-grooved circular radiator is not as efficient as the system with cylindrical radiator because the first covers a larger drying chamber. Nevertheless, it seems to be a more suitable system for industrial application. Furthermore, the diffusion model proposed was demonstrated to be adequate for describing the ADF kinetics.

The results obtained confirm that APU application leads to a significant intensification in LTD and AFD processes. Thus, the ultrasonically assisted LTD and AFD can be interesting alternatives to an expensive and high-demand energy process such as vacuum freeze-drying (VFD). What is now required is to increase efforts directed toward scaling-up APU application taking into consideration issues such as drying chamber configuration which will improve the ultrasonic efficiency as well as procedures for the mass production of ultrasonic transducers.

Funding

This work has been supported by the project DPI2012-37466-C03-01 funded by the Spanish Ministry of Economy and Competiveness and by the project RTA2015-00060-C04-02 funded by INIA-ERDF.

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References

[1] Mulet, A.; Cárcel, J. A.; Sanjuan, N.; García-Pérez, J. V. Food Dehydration Under Forced Convection Conditions. In *Current Trends in Chemical Engineering*, Houston, TX: Studium Press LLC, **2010**; pp 153–177.

[2] Motevali, A.; Minaei, S.; Khoshtagaza, M. H. Evaluation of Energy Consumption in Different Drying Methods. *Energy Convers. Manage.* **2011**, *52*, 1192–1199. DOI: 10.1016/j.enconman.2010.09.014.

[3] Gallego-Juarez, J. A.; Rodriguez, G.; Gálvez, J. C.; Yang, T. S. A New High-Intensity Ultrasonic Technology for Food Dehydration. *Dry. Technol.* **1999**, *17*, 597–608. DOI: 10.1080/07373939908917555.

[4] Riera, E.; Gallego-Juárez, J. A.; Rodríguez, G.; Acosta, V. M.; Andrés, E. Application of High-Power Ultrasound for Drying Vegetables. In *Forum Acusticum*; Sevilla, **2002**.

[5] Mulet, A.; Cárcel, J. A.; Sanjuán, N.; Bon, J. New Food Drying Technologies – Use of Ultrasound. *Food Sci. Technol. Int.* **2003**, *9*, 215–221. DOI: 10.1177/1082013203034641.

[6] Riera, E.; García-Pérez, J. V.; Cárcel, J. A.; Acosta, V. M.; Gallego-Juárez, J. A. Computational study of ultrasound-assisted drying of food materials. In *Innovative Food Processing Technologies: Advances in Multiphysics Simulation*, Knoerzer, K., Juliano, P., Roupas, P., Versteeg, C., Eds.; Chichester, UK: Blackwell Publishing Ltd., **2011**; pp 265–301.

[7] Gallego-Juárez, J. A.; Riera, E.; De la Fuente, S.; Rodríguez, G.; Acosta, V. M.; Blanco, A. Application of High-Power Ultrasound for Dehydration of Vegetables: Processes and Devices. *Dry. Technol.* **2007**, *25*, 1893–1901. DOI: 10.1080/07373930701677371.

[8] Gallego-Juárez, J. A.; Rodriguez, G.; Acosta, V. M.; Riera, E. Power Ultrasonic Transducers with Extensive Radiators for Industrial Processing. *Ultrason. Sonochem.* **2010**, *17*, 953–964. DOI: 10.1016/j.ultsonch.2009.11.006.

[9] Mulet, A.; Cárcel, J. A.; García-Pérez, J. V.; Riera, E. Ultrasound-Assisted Hot Air Drying of Foods. In *Ultrasound Technologies for Food and Bioprocessing*, Feng, H., Barbosa-Canovas, G., Weiss, J., Eds.; New York, NY: Springer New York, **2011**; pp 511–534.

[10] Cárcel, J. A.; García-Pérez, J. V.; Riera, E.; Rosselló, C.; Mulet, A. Drying Assisted by Power Ultrasound. *Mod. Dry. Technol.* **2014**, *8*, 237–276.

[11] Gallego-Juárez, J. A.; Rodríguez, G.; Acosta, V. M.; Riera, E.; Cardoni, A. Power Ultrasonic Transducers With Vibrating Plate Radiators. In *Power Ultrasonics*, Gallego-Juárez, J. A., Graff, K. F., Eds.; Oxford: Woodhead Publishing, **2015**; pp 159–193.

[12] García-Pérez, J. V.; Carcel, J. A.; Mulet, A.; Riera, E.; Gallego-Juarez, J. A. Ultrasonic drying for food preservation. In *Power Ultrasonics*; Oxford: Woodhead Publishing, **2015**; pp 875–910.

[13] Musielak, G.; Mierzwa, D.; Kroehnke, J. Food Drying Enhancement by Ultrasound – A Review. *Trends Food Sci. Technol.* **2016**, *56*, 126–141. DOI: 10.1016/j.tifs.2016.08.003.

[14] Onwude, D. I.; Hashim, N.; Janius, R.; Abdan, K.; Chen, G.; Oladejo, A. O. Non-Thermal Hybrid Drying of Fruits and Vegetables: A Review of Current Technologies. *Innov. Food Sci. Emerg. Technol.* **2017**, *43*, 223–238. DOI: 10.1016/j.ifset.2017.08.010.

[15] Fan, K.; Zhang, M.; Mujumdar, A. S. Application of Airborne Ultrasound in the Convective Drying of Fruits and Vegetables: A Review. *Ultrason. Sonochem.* **2017**, *39*, 47–57. DOI: 10.1016/j.ultsonch.2017.04.001.

[16] Cárcel, J. A.; García-Pérez, J. V.; Riera, E.; Rosselló, C.; Mulet, A. Ultrasonically Assisted Drying. In *Ultrasound in Food Processing: Recent Advances*, Villamiel, M., García-Pérez, J. V., Montilla, A., Cárcel, J. A., Benedito, J., Eds.; Chichester, UK: John Wiley and Sons, **2017**; pp 371–391.

[17] Rodríguez, O.; Eim, V.; Rosselló, C.; Femenia, A.; Cárcel, J. A.; Simal, S. Application of Power Ultrasound on the Convective Drying of Fruits and Vegetables: Effects on Quality. *J. Sci. Food Agric.* **2018**, *98*, 1660–1673. DOI: 10.1002/jsfa.8673.

[18] Ozuna, C.; Cárcel, J. A.; García-Pérez, J. V.; Mulet, A. Improvement of Water Transport Mechanisms during Potato Drying by Applying Ultrasound. *J. Sci. Food Agric.* **2011**, *91*, 2511–2517. DOI: 10.1002/jsfa.4344.

[19] Ozuna, C.; Gómez Álvarez-Arenas, T.; Riera, E.; Cárcel, J. A.; Garcia-Pérez, J. V. Influence of Material Structure on Air-Borne Ultrasonic Application in Drying. *Ultrason. Sonochem.* **2014**, *21*, 1235–1243. DOI: 10.1016/j.ultsonch.2013.12.015.

[20] García-Pérez, J. V.; Cárcel, J. A.; Riera, E.; Mulet, A. Influence of the Applied Acoustic Energy on the

Drying of Carrots and Lemon Peel. *Dry. Technol.* **2009**, *27*, 281–287. DOI: 10.1080/07373930802606428.

[21] García-Pérez, J. V.; Ozuna, C.; Ortuño, C.; Cárcel, J. A.; Mulet, A. Modeling Ultrasonically Assisted Convective Drying of Eggplant. *Dry. Technol.* **2011**, *29*, 1499–1509. DOI: 10.1080/07373937.2011.576321.

[22] García-Pérez, J. V.; Ortuño, C.; Puig, A.; Cárcel, J. A.; Pérez-Munuera, I. Enhancement of Water Transport and Microstructural Changes Induced by High-Intensity Ultrasound Application on Orange Peel Drying. *Food Bioprocess. Technol.* **2012**, *5*, 2256–2265. DOI: 10.1007/s11947-011-0645-0.

[23] Gallego-Juárez, J. A. Basic Principles of Ultrasound. *Ultrasound Food Process.* **2017**, *1*, 1–26.

[24] Charoux, C. M. G.; Ojha, K. S.; O'Donnell, C. P.; Cardoni, A.; Tiwari, B. K. Applications of Airborne Ultrasonic Technology in the Food Industry. *J. Food Eng.* **2017**, *208*, 28–36. DOI: 10.1016/j.jfoodeng.2017.03.030.

[25] García-Pérez, J. V. Contribución al Estudio de la Aplicación de Ultrasonidos de Potencia en el Secado Convectivo de Alimentos. *Univ. Politècnica Valèn.* **2007**; pp 1–27.

[26] Gallego-Juárez, J. A.; Riera, E. Technologies and Applications of Airborne Power Ultrasound in Food Processing. In *Ultrasound Technologies for Food and Bioprocessing*; New York, NY: Springer, **2011**; pp 617–641.

[27] Chemat, F.; Khan, M. K. Applications of Ultrasound in Food Technology: Processing, Preservation and Extraction. *Ultrason. Sonochem.* **2011**, *18*, 813–835.

[28] Riera, E.; Acosta, V. M.; Blanco, A.; Gallego-Juárez, J. A.; Cardoni, A. New Trends in Air Coupled Power Ultrasound Applications. In *Forum Acusticum*, Krakow: European Acoustics Association, **2014**.

[29] Gallego-Juárez, J. A. High-Power Ultrasonic Processing: Recent Developments and Prospective Advances. *Phys. Procedia* **2010**, *3*, 35–47.

[30] Muralidhara, H.; Ensminger, S. D.; Putnam, A. Acoustic Dewatering and Drying (Low and High Frequency): State of the Art Review. *Dry. Technol.* **1985**, *3*, 529–566. DOI: 10.1080/07373938508916296.

[31] Acosta-Aparicio, V. M.; Cárcel, J. A.; Gallego-Juárez, J. A.; García-Pérez, J. V.; Mulet, A.; Peña, R.; Riera, E. Method and Device for Improving Material Transfer in Low-Temperature Processes Using High-Intensity Ultrasound. Patent WO 2013/041750 A1, **2013**.

[32] Bantle, M.; Eikevik, T. M. Parametric Study of High-Intensity Ultrasound in the Atmospheric Freeze Drying of Peas. *Dry. Technol.* **2011**, *29*, 1230–1239. DOI: 10.1080/07373937.2011.584256.

[33] Bantle, M.; Eikevik, T. M. A Study of the Energy Efficiency of Convective Drying Systems Assisted by Ultrasound in the Production of Clipfish. *J. Cleaner Prod.* **2014**, *65*, 217–223. DOI: 10.1016/j.jclepro.2013.07.016.

[34] Bantle, M.; Eikevik, T. M.; Grüttner, A. Mass transfer in ultrasonic assisted atmospheric freeze drying. In 17th International Drying Symposium, Magdeburg, Germany, **2010**.

[35] Schössler, K.; Jäger, H.; Knorr, D. Novel Contact Ultrasound System for the Accelerated Freeze-Drying of Vegetables. *Innov. Food Sci. Emerg. Technol.* **2012**, *16*, 113–120. DOI: 10.1016/j.ifset.2012.05.010.

[36] Schössler, K.; Jäger, H.; Knorr, D. Effect of Continuous and Intermittent Ultrasound on Drying Time and Effective Diffusivity during Convective Drying of Apple and Red Bell Pepper. *J. Food Eng.* **2012**, *108*, 103–110. DOI: 10.1016/j.jfoodeng.2011.07.018.

[37] de la Fuente, S.; Riera, E.; Acosta, V. M.; Blanco, A.; Gallego-Juárez, J. A. Food Drying Process by Power Ultrasound. *Ultrasonics.* **2006**, *44*, e523–e527. DOI: 10.1016/j.ultras.2006.05.181.

[38] García-Pérez, J. V.; Cárcel, J. A.; de la Fuente, S.; Riera, E. Ultrasonic Drying of Foodstuff in a Fluidized Bed: Parametric Study. *Ultrasonics.* **2006**, *44*, e539–e543. DOI: 10.1016/j.ultras.2006.06.059.

[39] García-Pérez, J. V.; Rosselló, C.; Cárcel, J. A.; De la Fuente, S.; Mulet, A. Effect of Air Temperature on Convective Drying Assisted by High Power Ultrasound. In *Defect and Diffusion Forum*, Switzerland: Trans Tech Publications, **2006**; pp 563–574.

[40] Puig, A.; Perez-Munuera, I.; Carcel, J. A.; Hernando, I.; Garcia-Perez, J. V. Moisture Loss Kinetics and Microstructural Changes in Eggplant (*Solanum melongena* L.) during Conventional and Ultrasonically Assisted Convective Drying. *Food Bioprod. Process.* **2012**, *90*, 624–632. DOI: 10.1016/j.fbp.2012.07.001.

[41] do Nascimento, E.; Mulet, A.; Ramírez, J. L.; Piler de Carvalho, C. W.; Cárcel, J. A. Effects of High-Intensity Ultrasound on Drying Kinetics and Antioxidant Properties of Passion Fruit Peel. *J. Food Eng.* **2016**, *170*, 108–118. DOI: 10.1016/j.jfoodeng.2015.09.015.

[42] García-Pérez, J. V.; Cárcel, J. A.; Riera, E.; Rosselló, C.; Mulet, A. Intensification of Low-Temperature Drying by Using Ultrasound. *Dry. Technol.* **2012**, *30*, 1199–1208. DOI: 10.1080/07373937.2012.675533.

[43] Santacatalina, J. V.; Cárcel, J. A.; Simal, S.; Garcia-Perez, J. V.; Mulet, A. Atmospheric Freeze Drying Assisted by Power Ultrasound. *IOP Conf. Ser: Mater. Sci. Eng.* **2012**, *42*, 012021. DOI: 10.1088/1757-899X/42/1/012021.

[44] García-Pérez, J. V.; Bon, J.; Mulet, A.; Gallego Juárez, J. A.; Riera, E. Convective Drying of Foodstuffs Under the Action of High Power Ultrasound. In 2013 International Congress on Ultrasonics (ICU2013), Singapore, **2013**. pp 179–184.

[45] Santacatalina, J. V.; Rodríguez, O.; Simal, S.; Cárcel, J. A.; Mulet, A.; García-Pérez, J. V. Ultrasonically Enhanced Low-Temperature Drying of Apple: Influence on Drying Kinetics and Antioxidant Potential. *J. Food Eng.* **2014**, *138*, 35–44. DOI: 10.1016/j.jfoodeng.2014.04.003.

[46] Santacatalina, J. V.; Fissore, D.; Cárcel, J. A.; Mulet, A.; García-Pérez, J. V. Model-Based Investigation into Atmospheric Freeze Drying Assisted by Power Ultrasound. *J. Food Eng.* **2015**, *151*, 7–15. DOI: 10.1016/j.jfoodeng.2014.11.013.

[47] Brines, C.; Mulet, A.; García-Pérez, J. V.; Riera, E.; Cárcel, J. A. Influence of the Ultrasonic Power

Applied on Freeze Drying Kinetics. *Phys. Proc.* **2015**, *70*, 850–853. DOI: 10.1016/j.phpro.2015.08.174.

[48] Santacatalina, J. V.; Contreras, M.; Simal, S.; Cárcel, J. A.; García-Pérez, J. V. Impact of Applied Ultrasonic Power on the Low Temperature Drying of Apple. *Ultrason. Sonochem.* **2016**, *28*, 100–109. DOI: 10.1016/j.ultsonch.2015.06.027.

[49] Santacatalina, J. V.; Soriano, J. R.; Cárcel, J. A.; Garcia-Perez, J. V. Influence of Air Velocity and Temperature on Ultrasonically Assisted Low Temperature Drying of Eggplant. *Food Bioprod. Process.* **2016**, *100*, 282–291. DOI: 10.1016/j.fbp.2016.07.010.

[50] Cárcel, J. A.; Garcia Perez, J. V.; Santacatalina, J. V.; Riera, E.; Rosselló, C.; Mulet, A. Low Temperature Drying Enhancement Using Ultrasound. In the 20th International Drying Symposium (IDS2016), Gifu, Japan, **2016**; pp C-4-1.

[51] Colucci, D.; Fissore, D.; Mulet, A.; Cárcel, J. A. On the Investigation into the Kinetics of the Ultrasound-Assisted Atmospheric Freeze Drying of Eggplant. *Dry. Technol.* **2017**, *35*, 1818–1831. DOI: 10.1080/07373937.2016.1277738.

[52] Moreno, C.; Brines, C.; Mulet, A.; Rosselló, C.; Cárcel, J. A. Antioxidant Potential of Atmospheric Freeze-Dried Apples as Affected by Ultrasound Application and Sample Surface. *Dry. Technol.* **2017**, *35*, 957–968. DOI: 10.1080/07373937.2016.1256890.

[53] Carrión, C.; Mulet, A.; García-Pérez, J. V.; Cárcel, J. A. Ultrasonically Assisted Atmospheric Freeze-Drying of Button Mushroom. Drying Kinetics and Product Quality. *Dry. Technol.* **2018**, *36*, 1814–1823. DOI: 10.1080/07373937.2017.1417870.

[54] Vallespir, F.; Cárcel, J. A.; Marra, F.; Eim, V. S.; Simal, S. Improvement of Mass Transfer by Freezing Pre-Treatment and Ultrasound Application on the Convective Drying of Beetroot (*Beta vulgaris* L.). *Food Bioprocess. Technol.* **2018**, *11*, 72–83. DOI: 10.1007/s11947-017-1999-8.

[55] Colucci, D.; Fissore, D.; Rossello, C.; Carcel, J. A. On the Effect of Ultrasound-Assisted Atmospheric Freeze-Drying on the Antioxidant Properties of Eggplant. *Food Res. Int.* **2018**, *106*, 580–588. DOI: 10.1016/j.foodres.2018.01.022.

[56] Cárcel, J. A.; García-Perez, J. V.; Riera, E.; Mulet, A. Improvement of Convective Drying of Carrot by Applying Power Ultrasound—Influence of Mass Load Density. *Dry. Technol.* **2011**, *29*, 174–182. DOI: 10.1080/07373937.2010.483032.

[57] Ozuna, C. Estudio de la aplicación de ultrasonidos de alta intensidad en sistemas sólido-líquido y sólido-gas. Influencia en la cinética de transporte de materia y en la estructura de los productos. Editorial Universitat Politècnica de València; **2014**.

[58] Andrés, R. R.; Acosta, V. M.; Pinto, A.; Riera, E. Airborne Power Ultrasonic Systems for Food Dehydration Processes Intensification. Presented at the 25th International Congress on Sound and Vibration ICSV25, Hiroshima (Japan); **2018**.

[59] Andrés, R. R.; Blanco, A.; Riera, E.; Guinot, A. Description of an Ultrasonic Technology for Food Dehydration Process Intensification. *Proc. Meet. Acoust.* **2016**, *28*, 045003.

[60] Ramos, A.; Gallego-Juárez, J. A.; Montoya, F. Automatic System for Dynamic Control of Resonance in High Power and High Q Ultrasonic Transducers. *Ultrasonics.* **1985**, *23*, 151–156.

[61] Kuang, Y.; Jin, Y.; Cochran, S.; Huang, Z. Resonance Tracking and Vibration Stablilization for High Power Ultrasonic Transducers. *Ultrasonics.* **2014**, *54*, 187–194. DOI: 10.1016/j.ultras.2013.07.001.

[62] AOAC standard method no. 934.06 EEUU. *Association of Official Analytical Chemist.* Official Methods of Analysis. Arlington: AOAC, **1997**.

[63] Vega-Gálvez, A.; Miranda, M.; Bilbao-Sáinz, C.; Uribe, E.; Lemus-Mondaca, R. Empirical Modeling of Drying Process for Apple (cv. Granny Smith) Slices at Different Air Temperatures. *J. of Food Process. Preserv.* **2008**, *32*, 972–986. DOI: 10.1111/j.1745-4549.2008.00227.x.

[64] Andrés, R. R.; Acosta, V. M.; Riera, E. Ultrasonic Field Generated by Different Airborne Power Ultrasonic Transducers with Extensive Radiators. In Tecniacústica 2017: 48° Congreso Español de Acústica; Encuentro Ibérico de Acústica; European Symposium on Underwater Acoustics Applications; European Symposium on Sustainable Building Acoustics: A Coruña 3-6 Octubre 2017; **2017**; pp 1299–1312.