Modeling Ultrasonically Assisted Convective Drying of Eggplant

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ABSTRACT

In order to analyze the influence of ultrasound in mass transfer phenomena during drying, modeling constitutes a fundamental tool. In this work, the study of the effect of power ultrasound application on drying kinetics of eggplant was addressed by using different models based on theoretical (diffusion) or empirical approaches. Drying kinetics of eggplant cylinders (height 20 mm and diameter 24 mm) were carried at 40 ºC and 1 m/s applying different ultrasonic power levels: 0, 6, 12, 19, 25, 31 and 37 kW/m^3. Experiments were carried out, at least, in triplicate for the different powers. Furthermore, shrinkage and sorption isotherms were also addressed in order to reach an optimal description of eggplant drying.

Drying kinetics were sped up by the ultrasonic application, moreover, the higher the applied ultrasonic power the higher drying rate. A significant ($p<0.05$) influence of the ultrasonic power in both effective moisture diffusivity and mass transfer coefficient was identified; which was well explained by linear relationships. The most complex model, which considered external resistance, as well as shrinkage, as significant phenomena, showed the best agreement with experimental data, providing percentages of explained variance higher than 99.9% and mean relative errors lower than 1.2% in all the cases. According to these results, ultrasound could be considered a potential technology to improve the convective drying of eggplant.

Keywords: dehydration, ultrasound, mass transfer, diffusion, shrinkage.

INTRODUCTION

The energy consumption in food processing industries represents one of the largest costs in the production, provoking the increase of the product price and a negative environment impact. In developed countries, around of 12-25 % of the overall industrial energy consumption is attributed to the drying industry (Mujumdar, 2007). At industrial scale, the air-forced or convective drying is the most common way for dehydration. The low kinetics during the falling rate period, which results in high energy consumption (Chou and Chua, 2001), and the quality loss of the final product due to the high temperatures employed (Lewicki et al., 2006) constitute the main limitations of convective drying. Convective drying affects the biochemical properties of foodstuffs, such as the deterioration of aroma compounds (Timoumi et al., 2006), the degradation of nutritional substances (Santos and Silva, 2009), the browning reaction and the color loss (Suvarnakuta et al., 2005). Other effects are linked to the variation of the volume or shrinkage that is related with the volume of removed water, the mobility of the solid matrix and the drying rate (Mayor and Sereno, 2004), it is responsible for the main changes on mechanical properties of the product such as texture and rehydration capability (Abasi et al., 2009).

As a consequence, the food industry has been seeking for new technologies not only to improve the energy efficiency but also the quality of the dry products (Chou and Chua, 2001). In this sense, combining traditional methods with non-conventional energy sources seems to be a sound way to improve drying processes. Power ultrasound has the advantage over other technologies, such as microwave, infrared radiation and radio frequency, of increasing the drying rate with a small heating effect, thus the influence on mass transfer is related with mechanical and not heating mechanisms (Gallego-Juárez, 2010; De la Fuente et al., 2006). Literature reports that the application of power ultrasound during convective drying influences on external and/or internal resistance to mass transfer (García-Perez et al., 2009). Ultrasound brings about the reduction of boundary layer by mechanical effects, such as pressure variations, oscillating velocities and microstreaming that the ultrasonic waves introduce in the solid-gas interfaces. In addition, ultrasound may also affect internal water transfer by the well-known "sponge effect" (Mulet et al., 2010; Gallego-Juárez, 2010), the alternating expansions and compressions waves induced in the material creates micro-channels suitable for liquid movement (Mulet et al., 2010). In addition, the effects linked to the ultrasonic waves like the cavitation (Gallego-Juárez, 2010; De la Fuente et al., 2006), may facilitate of the removal of water molecules strongly attached in the solid matrix.

The application of power ultrasound in solid-gas processes is less frequent than in solid-liquid due to the high impedance mismatch between the application systems and air, and the high acoustic energy absorption of this medium (Mulet et al., 2010). Recent advantages in the design and construction of new air borne ultrasonic transducers have opened a broad interest on its use on convective drying. These transducers attain an efficient energy transfer due to a power impedance mismatch with the air, large amplitudes of vibration, high directionality, high power capacities and large radiating areas (Gallego-Juárez, 2010). Previous works with carrot and lemon peel (García-Pérez et al., 2009) have related the efficiency of the ultrasonic application with the properties of the raw material to be dried. In this sense, the study of the ultrasound application on a product with a highly unconsolidated porous structure like eggplant would be interesting for analyze and quantify the ultrasound effects on drying process. Hence, in order to properly evaluate and design a specific ultrasonic application for a product it results convenient to address thoroughly the influence of ultrasound on the drying kinetics (García-Pérez et al., 2009).

Modeling constitutes an approach for analyzing drying processes; both the water equilibrium and the kinetics should be addressed. Water sorption isotherm shows the relationship between the water activity and the equilibrium moisture content. A proper mathematical description of the isotherms is needed in order to thoroughly address the drying kinetic modeling, being the GAB model the most common equation to be used (García-Pérez et al., 2008). There are empirical models, such as the Weibull (Cunha et al., 1998) model, these models do not provide a physical description of the process but rather give an outline of what happen and allow the identification of the most relevant variables. (Mulet, 1994). In this sense, the Weibull model has been used for modeling drying kinetics of different kind of foods (Azzouz et al., 2002, Simal et al., 2005). Other models look for a better description like the diffusion models, based on the Fick's law (Crank, 1975), are built according to some assumptions which establish the degree of complexity for the resolution. The most common assumptions to consider are related to the effective moisture diffusivity (Maroulis et al., 2001), the external resistance to mass transfer (Simal et al. 2003) and the food shrinkage (Mayor and Sereno, 2004). The analysis of the influence on model behavior of assumption related to effective diffusivity or external resistance are often addressed although shrinkage is seldom considered. The importance of including the food shrinkage as a significant phenomenon in modeling has been widely discussed in literature (Queiroz and Nebra, 2001; Hassini et al., 2007). Shrinkage, which is linearly related to water content at the early stages of drying, is extremely important in diffusion mechanisms during drying because it leads to a variation in the distance required for the mobility of water molecules (Hernández et al., 2000). This phenomenon should be included in the development of a model in order to improve the physical representation of the process and to increase the validity of the effective diffusion coefficient (Queiroz and Nebra, 2001). Therefore, in this work, shrinkage is an important variable during drying modeling due to the shrinkage of eggplant is very remarkable and the reduction in sample volume is larger than the volume of removed water due to its high porosity (Souma et al., 2004).

The main aim of this work was to model the ultrasonic assisted drying kinetics of eggplant under different experimental conditions considering different models based on theoretical (diffusion) or empirical approaches. Drying modeling will allow gaining insight into the effects of power ultrasound on drying process, as well as, quantifying those effects.

MATERIALS AND METHODS

Ultrasonic assisted drying kinetics

Drying experiments were carried out using eggplants (*Solanum melongena* var Black Enorma) purchased in a local market. For testing, cylinders (height 20 mm and diameter 24 mm) were taken from flesh of the eggplant using a houseware tool. The experiments were conducted at 40 ºC and 1 m/s applying seven ultrasonic power levels (UP): 0, 6, 12, 19, 25, 31, 37 kW/m^3 until sample weight loss reached 75 %. Ultrasonic power was defined as the electric power supplied to the ultrasonic transducer divided by the drying chamber volume. For each condition tested, drying experiments were carried out at least in triplicate. Drying kinetics were determined from the sample weight loss during drying and the initial moisture content (AOAC, 1997).

For this purpose, a convective drier assisted by power ultrasound already described in previous works (García-Pérez et al., 2006) was used. The drying chamber consist of an aluminum vibrating cylinder (internal diameter 100 mm, height 310 mm and thickness 10 mm) driven by a piezoelectric composite transducer (21.8 kHz). The ultrasonically activated drying chamber is able to generate a high-intensity ultrasonic field in its inside reaching an average sound pressure of 154.3 dB (measured applying an electrical power to the transducer of 75 W at air stagnant conditions). The equipment uses a pneumatic device for weighting the samples at preset times and an impedance matching unit that permits to fit the impedance output of the generator to the transducer providing a better electric yield on the system.

Sorption isotherm

Fresh eggplant samples were dried for different times (from 4 to 48 h) in order to obtain samples with different moisture content at 40 ºC using an air forced tray oven. Dry samples were milled and put in a hermetic glass container for 24 hours to facilitate that the samples reached homogeneous moisture content. Thereafter, the water activity was measured at 40 ºC using an electric hygrometer (Model AW SPRINT TH500, NOVASINA, Air Systems for Air Treatment, Pfäffikon, Switzerland), which was previously calibrated using the followings salts: LiCl, $MgCl_2$, $Mg(NO_3)_2$, NaCl, $BaCl_2$ and $K_2Cr_2O_7$, according to the manufacturer guidelines. Finally, moisture content was measured in each sample by using the AOAC method already mentioned. Thus, around 40 water activity-moisture content experimental points were obtained.

Sorption isotherm of eggplant were modeled using the GAB (Guggenheim-Anderson-De Boer) model (Eq. 1), describing the moisture content as a function of water activity.

$$W = W_m \frac{CKa_w}{(1-Ka_w)(1+(C-1)(Ka_w)} \quad (1)$$

The identification of GAB model parameters (W_m, C and K) were carried out using an optimization procedure that minimized the sum of the squared difference between experimental and calculated average moisture content of samples. For that purpose, the non linear optimization algorithm of the generalized reduced gradient (GRG), available in Microsoft Excel^{TM} spreadsheet from MS Office 2007 was used.

Shrinkage measurement

Cubic-shaped eggplant samples (side 18 mm) were used to determinate the change of sample volume during drying. Cubes were dried at 40 ºC and 1 m/s for different times: 0.5, 1, 2, 4 and 6 hours. Moisture content (AOAC method Nº 934.06), and volume was measured for estimating shrinkage. The volume measurement was performed simultaneously by two different methodologies: image analysis and liquid displacement. For image analysis, digital images were taken (DSC-P100, Sony Corp. Japan) for each face of fresh and dehydrated samples. The area of these surfaces was estimated using the software Sigma Scan Pro 5 (SPSS Inc., USA). The measurement was carried out in pixels and afterwards converted in length. From this measurement, the volume was calculated assuming samples did not lose the cubic shape during drying. The volume measurement by liquid displacement was carried out with toluene (density 0.867 g/mL at 20 ºC) a volumetric standard picnometer (48.89 ml), and an analytical balance (PB 303-S, Mettler Toledo). The shrinkage measurement was carried out in triplicate, at least, in 5 samples for the different drying times.

Modeling drying kinetics

For analyzing the influence of power ultrasound on drying kinetics of eggplant cylinders, three diffusion models based on the 2^{nd} Fick's law with different degree of complexity and one empirical model (Weibull) were used.

Diffusion models

The differential equation for diffusion is obtained combining Fick's law and the microscopic mass balance. For isotropic solids and finite cylinder geometry, the diffusion equation for expressed as follows considering a constant effective moisture diffusivity (Eq. 2):

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

In Eq. 2, the solid symmetry, and a uniform initial moisture content and temperature were considered as boundary and initial conditions, other boundary conditions are given in Table 1. For solving the diffusion equation different models were tested according to the 2nd boundary condition (Table 1) used to describe the properties of the gas-solid interface (x=L or r=R) and also considering the change of sample volume during drying. This strategy allowed testing the ability and reliability of describing the drying kinetics using different assumptions.

Negligible external resistance model (NER)

The simplest diffusion model neglected the external resistance to mass transfer, thus, the water transfer is entirely controlled by water diffusion (Eq. 6 and Eq. 7, Table 1). The analytical solution (Crank, 1975) of the governing equation (Eq. 2) for NER model is showed in Eq. 11 in terms of the average moisture content.

$$\psi(t) = \frac{W(t)-W_e}{W_0-W_e} = \left[\sum_{n=0}^{\infty}\frac{8}{(2n+1)^2\pi^2}e^{\left(-\frac{D_e(2n+1)^2\pi^2 t}{4L^2}\right)}\right]\cdot\left[\sum_{n=1}^{\infty}\frac{8}{\alpha_n^2}e^{\left(-\frac{D_e\alpha_n^2 t}{R^2}\right)}\right] \quad (11)$$

Model considering external resistance (ER)

This model considers significant both internal and external resistance to moisture transport (Hernández et al., 2000). This fact was considered in the model through the boundary conditions stated in Eq. 8 and Eq. 9 (Table 1). A finite difference method was used to solve the ER model. For that purpose, the original volume of cylindrical samples was divided into a constant number of elements (20x20) that constituted the subvolumes network. According to this method, the local moisture content for a subvolume is obtained as a function of the moisture content of the surrounding subvolumes and of the same subvolume at a given time (Eq. 12). From Eq. 12, the particular equation for each specific subvolume must be obtained by combining the particular boundary conditions.

$$W_p\left(r,x,t-1\right)=\frac{D_e\Delta t}{\Delta x^2+\Delta r^2}\times$$
$$\times\left[\begin{array}{l} W_p(r,x,t)\left(\left(\dfrac{\Delta x^2+\Delta r^2}{D_e\Delta t}\right)+2\left(\Delta x^2+\Delta r^2\right)\right)- \\ -\left(\begin{array}{l} W_p\left(r,x+\Delta x,t\right)\Delta r^2+W_p\left(r,x-\Delta x,t\right)\Delta r^2+ \\ +W_p\left(r+\Delta r,x,t\right)\Delta x^2\left(1+\dfrac{\Delta r}{2r}\right)+ \\ +W_p\left(r-\Delta r,x,t\right)\Delta x^2\left(1-\dfrac{\Delta r}{2r}\right) \end{array}\right) \end{array}\right] \quad (12)$$

The position of the subvolume in the radial direction is characterized by the r parameter, the characteristic dimensions of the subvolume was determinate by Δr= r/(n-1) and Δx = L/(n-1), the number of nodes in r or x direction by n (20) and, finally, the time interval considered by Δt (Cárcel et al., 2007). For solving the set of implicit equation of the network a program using Matlab® 7.1 SP3 (The MathWorks, Inc., Natick, MA, USA) was developed. This program calculated the moisture distribution inside a finite length cylindrical body and the average moisture content of the solid as a function of the drying time, the effective moisture diffusivity and the mass transfer coefficient.

Model considering external resistance and shrinkage (ERS)

The most complex diffusion model tested considered not only the external resistance to mass transfer but also the sample shrinkage as a significant phenomenon effecting both axial and radial directions during drying (Mayor and Sereno, 2004). In this case, mass transport was addressed as a moving boundary problem (Table 1).

Like in the ER model, the diffusion model was solved applying an implicit finite difference method using MATLAB. In this case, the subvolumes size is reduced due to the sample's shrinkage adjusting its dimension on the moving boundary, remaining the dry matter at a constant value during the process.

Empirical model

The empirical model of Weibull (Cunha et al., 1998) was used to compare its results with the theoretical models (Eq. 13).

$$W = W_e + (W_c - W_e)\cdot \exp\left(-\left(\frac{t}{\beta}\right)\right)^{\alpha} \qquad (13)$$

Where α and β are the shape and kinetic parameters of the model, respectively. The β parameter is inversely linked to drying rate. This parameter includes all the effects of the process variables (temperature, air velocity and particle size) on the drying kinetics (Blasco et al., 2006), thus, it is expected on influence of power ultrasound on this parameter.

Parameter estimation

The identification of Weibull parameters (α and β) and NER model (D_e) were carried out using an optimization procedure that minimized the sum of the squared difference between experimental and calculated average moisture content of samples. For that purpose, the non linear optimization algorithm of the generalized reduced gradient (GRG), available in Microsoft Excel™ spreadsheet from MS Office 2007 was used.

In the case of ER and ERS models, the effective moisture (D_e) and the mass transfer coefficient (k) were simultaneously identified using the SIMPLEX method available in MATLAB (*fminsearch* function). The objective function minimized the sum of the squared differences between the experimental and calculated average moisture content.

Model fitting evaluation and statistical analysis

The percentage of explained variance (% var) and the mean relative error (% MRE) (Lypson & Sheth 1973) were computed for evaluating the fit of the models to the experimental data (Eq. (14) and Eq. (15)).

$$\%VAR = \left[1 - \frac{S_{xy}^2}{S_y^2}\right] \cdot 100 \tag{14}$$

$$\%MRE = \frac{100}{N}\left[\sum_{i=1}^{N} \frac{|W_{ei} - W_{ci}|}{W_{ei}}\right] \tag{15}$$

In order to evaluate the significance of the differences between the identified parameters, the analysis of variance (ANOVA) was carried out and the LSD (least significant difference) intervals were identified. The statistical analysis was carried out using the Statgraphics Plus 5.1 software package (Statical Graphics Corp., Herdorn, Virginia USA).

RESULTS AND DISCUSSION

Sorption isotherm

Experimental sorption isotherm and estimated curve with GAB model determined at 40ºC are shown in Fig. 1. The experimental data ranged between 2.679 and 0.044 (kg water/kg dry solid) for average moisture content and between 0.993 and 0.174 for water activity. The sorption isotherm of eggplant showed the typical sigmoid curve, according to BET classification (García-Pérez et al., 2008), look like a type III pattern. The parameters obtained by fitting water activity data to the GAB model (Eq. 1) were W_m= 0.093 kg w/kg dry solid, K= 0.99 and C= 3.01. These values were used in drying kinetics modeling for calculating the equilibrium moisture content values (W_e) (NER model) and the local water activity in the sample surface (φ_e) (ER and ERS model).

Eggplant shrinkage

As can be observed in Fig. 2, eggplant sample volume was significantly reduced during drying process, thus, the lower the moisture content, the lower the volume. This fact has been also found in many vegetables, such as carrot, apple and potato (Mayor and Sereno, 2004; Hassini et al., 2007).

Image analysis and liquid displacement provided a similar pattern in shrinkage data, nevertheless, significant differences between both methods were observed at low moisture contents. Sample volume measured at low moisture contents using image analysis was significantly higher than the measured by liquid displacement. A significant ($p<0.05$) linear relationship was established between the dimensionless volume and the moisture content for both shrinkage measurement methods.

$$\frac{V}{V_0} = 0.929\frac{W}{W_0} + 0.112; \quad R^2 = 0.99 \tag{16}$$

$$\frac{V}{V_0} = 0.621\frac{W}{W_0} + 0.309; \quad R^2 = 0.95 \tag{17}$$

A better correlation was found for liquid displacement (Eq. 16, r^2=0.992) than for image analysis data (Eq. 17, R^2=0.953). For that reason, shrinkage data obtained from liquid displacement analysis was chosen to be included in the ERS model. Using the liquid displacement methodology for evaluating the drying shrinkage, Souma et al. (2004), reported for eggplant cylinders slightly different linear equation coefficients, probably due to the different eggplant cultivar. Moreover, Wu et al. (2007) calculating an approximate volume and surface are of vacuum dried eggplant slab samples, found also linear equation coefficient values in the range of the obtained values in this work. These results points to a rather similar behavior independently of size, shape and cultivar.

Experimental drying kinetics

Experimental drying kinetics of eggplant cylinders at the different ultrasonic powers are shown in Fig.3. The constant rate drying period was not observed in the drying kinetics, thus, the average initial moisture content of eggplant (14.70±0.17 kg water/kg dry solid) was considered as the critical moisture content.

Experimental data showed a very intense effect of power ultrasound (Fig. 3). The ultrasonic application sped up the drying kinetics. Thus, for reaching an average moisture content of 2.9 kg water/kg dry solid, the application of the maximum ultrasonic power tested (37 kW/m^3) reduced the drying time by approximately 72 % in comparison to the experiments carried out without ultrasonic application (0 kW/m^3). The drying time reduction induced by the ultrasonic application for eggplant was larger than for other products. García-Pérez et al. (2009) using the same ultrasonic set-up and similar experimental conditions found drying time reductions of 32 and 53 % in the drying of carrot cubes and lemon peel slabs (40 ºC and 1 m/s), respectively. The intense effect of power ultrasound on drying rate for eggplant may be linked to the material structure, being the porosity one of the most important variables in determining the effectiveness of the ultrasonic power on foodstuffs (García-Pérez et al., 2009). Hence, eggplant, which has a tissue with a highly unconsolidated porous structure (Wu et al., 2007), may be considered a more prone material to be affected by the ultrasonic energy than carrot and lemon peel.

Drying modeling

For quantifying the influence of power ultrasound application on the mass transfer process during the convective drying of eggplant cylinders, it is convenient to consider modeling. In addition, modeling should be useful in order to establish the influence of power ultrasound on external and internal mass transport. As already stated, theoretical and empirical approaches for modeling the drying kinetics of eggplant will be evaluated.

Non external resistance model (NER)

The NER diffusion model described by Eq. 11 was used as a first approach for modeling experimental drying kinetics of eggplant cylinders. The average effective moisture diffusivity (D_e) identified from experimental results, the percentage of explained variance (% VAR) and mean relative error (% MRE) obtained are shown in Table 2.

The identified effective moisture diffusivity ($3.31\pm0.37\text{x}10^{-10}$ m^2/s) in the experiments without ultrasound application (0 kW/m^3) is similar to those estimated by different authors for convective drying of eggplant and other foodstuffs at similar temperatures and low drying air velocities. Chaves et al. (2003), reported a similar value ($2.93\text{x}10^{-10}$ m^2/s) for eggplant slices dried at 50 ºC. Queiroz and Nebra (2001), dried bananas (29.9-68.4 ºC) and found values of $1.25\text{x}10^{-10}$ to $7.64\text{x}10^{-10}$ m^2/s. Sabarez and Price (1999), showed effective diffusivity values around to $4.32\text{-}7.64\text{x}10^{-10}$ m^2/s for prunes dried at 70-85 ºC. In these works a NER diffusion model was also used.

As observed in Table 2, the applied ultrasonic power during drying showed a significant ($p<0.05$) influence on the identified effective moisture diffusivity. Thus, the maximum applied ultrasonic power level (37 kW/m^3) increased the effective moisture diffusion coefficient by 237 % in comparison to the identified value in the experiments without power ultrasound application (0 kW/m^3). The ultrasonic effects were dependent on the power applied, the higher the applied ultrasonic power, the higher the identified effective diffusivity values. In the range of the ultrasonic power level (UP) used in this work (0-37 kW/m^3), a significant ($p<0.05$) linear relationship between the ultrasonic power level and the effective moisture diffusivity was found (Fig. 4).

The improvement of the D_e values is associated with the mechanical effects brought about by the ultrasonic application in the material being dried. The alternating expansions and contractions cycles (“sponge effect”) may contribute to easy water leaving the solid matrix thus reducing the internal resistance to mass transfer. García-Pérez et al. (2009) reported an increasing of 40 % and 131 % in the identified effective diffusivity (using a NER model) of carrot and lemon peel, respectively, when the same applied ultrasonic power (37 kW/m^3) was tested. Previous results indicate that high porosity products are more prone to the "sponge effect" showing a low internal resistance to the mechanical stress; therefore, the effects of ultrasound should be more intense in this type of products (García-Pérez et al., 2009).

The NER model provided low percentages of explained variance (ranged between 84-87 %) and high percentages of the mean relative error (ranged between 16.5-18.5 %). The poor fit of NER model may be linked to the boundary conditions proposed (Eq. 6 and Eq. 7, Table 1). Thus, the D_e values are simple fitting parameter, including not only the diffusion mechanisms but also other mechanisms and phenomena not considered in the modeling. In this sense, Akpinar and Bicer (2005) reported that at air velocities of 2.5 m/s or lower, the external mass transport resistance is significant and needs to be considered in the analysis of the eggplant drying data. Therefore, the use of a diffusion model considering external resistance (ER model) would be necessary. In addition, as already mentioned, the ER model will permit to separate external and internal resistance to mass transfer.

Model considering external resistance (ER)

The ER model improved the description of the drying kinetics achieving percentages of explained variance above 99 % and mean relative errors under 1.5 % in all the cases (Table 3). Thus, considering the external resistance seems to be adequate in order to describe the behavior of experimental eggplant drying.

The power ultrasound application affected the external resistance to water transport. The mass transfer coefficient (k) was improved by 229 % when the maximum ultrasonic power (37 kW/m^3) was applied. A similar effect was found for the effective diffusivity. A significant ($p<0.05$) linear relationship between the applied ultrasonic power level (UP) and the effective diffusivity as wee as the mass transfer coefficient (D_e and k) (Figs. 4 and 5) was also found in the range of the ultrasonic power level used in this work (0-37 kW/m^3).

Cárcel et al. (2007), in ultrasonic assisted drying of persimmon, reported an improvement on the mass transfer coefficient of 34.5 % at 1 m/s and 31 kW/m^3 in comparison to the experiments carried out without power ultrasound application. These authors analyzed the influence of drying air velocity on the external mass transport resistance during the ultrasonic drying and concluded that at low drying air velocities (< 4 m/s), the external resistance is significant and should be included in the modeling. The increase of the mass transfer coefficient is linked to the reduction of the boundary layer thickness due to different effects of ultrasound like pressure variations, oscillating velocities and micro-streaming on the solid-gas interfaces. Therefore, these effects should be the responsible of the reduction of the boundary layer of diffusion and as a consequence, the improvement of the water transfer rate from the solid surface to the air medium (Gallego-Juárez et al., 1999).

Although the ER model provides a good description of drying curves, it can be also improved considering the shrinkage of the product as a phenomenon which would explain better the dehydration process and also increasing the confidence on the identified diffusion coefficient.

Model considering external resistance and shrinkage (ERS)

The most complex model showed high percentages of explained variance, in all the cases higher than 99.9 %, and low percentages of mean relative error, less than 1.2 % (Table 4). Both statistical parameters indicate a close fit between calculated and experimental data, even better than the obtained in the ER model. The close fit confirms that the assumption of significant external resistance and shrinkage considered in the modeling seems to be adequate for eggplant drying process. Significant ($p<0.05$) linear relationships were found between mass transfer coefficient and effective moisture diffusivity and the applied ultrasonic power (UP) (Figs.4 and 5).

As can be observed in Fig.4, when shrinkage is not included in modeling (ER model), the values of D_e are overestimated in the range of 81.8-88.7 %. According to this assumption, Rahman and Kumar (2007) analyzed the influence of shrinkage on effective moisture diffusivity during drying of potato cylinders (length 50 mm and thickness of 5,8,10 and 16 mm) and slices (thickness 10 mm) and found overestimated D_e values in the range of 75.9-128.1 % when shrinkage is not taken into account in the analysis. For drying (29.9-68.4 ºC) of banana, Queiroz and Nebra (2001), found overestimated D_e values in the range of 20-50 %. Similar conclusions were also reported by Hernández et al. (2000), during drying (50, 60 and 70 ºC and 3 m/s) of mango (thickness 5, 10 and 15 mm) and cassava (thickness 10, 20 and 30 mm) slices. The overestimated values of effective moisture diffusivity may be attributed to that the fact that shrinkage reduces the distance for the diffusion of water molecules.

The mass transfer coefficients identified in the ERS model were slightly lower than in the ER model but the differences were not significant (Fig. 5). The sample shape may affect the water convective transport, but in this work, the inclusion of the shrinkage did not provide differences in the mass transfer coefficient.

Weibull model

The Weibull model described adequately the drying kinetics at the different experimental condition tested in this work. The percentages of explained variance (VAR) were, in all cases, higher than 99.9 %, while the percentages of mean relative error (MRE) were lower 1.1 % (Table 5). The value of the statistical parameters were similar to the obtained using the ERS model. For real time applications the use of Weibull model maybe advantageous due to its computational simplicity.

On the one hand, the shape parameter, α, was not dependent of the applied ultrasonic power level. On the other hand, the kinetic parameter β decreased as the applied ultrasonic power increased. As the β parameter is inversely proportional to drying rate, a reduction of this value indicates an increase of the drying rate. A significant ($p<0.05$) linear relationship between the ultrasonic power level and 1/β was found in the range of the ultrasonic power level used in this work (0-37 kW/m^3) (Fig. 6). García-Pérez et al. (2006) found a similar correlation in carrot cubes (18 mm) dried at 40 ºC and 0.6 m/s.

Weibull model provides similar information than the diffusion models about the influences of the ultrasonic power on the kinetic parameters. However, Weibull model has two main limitations: its results cannot be extrapolated to other working conditions or product geometries and does not provide information about mass transport mechanisms. Notwithstanding, this empirical model may be used as a first approach to more complex models, and also its use on further industrial applications may be considered relevant due to its simplicity.

CONCLUSIONS

A diffusion model, considering external resistance to mass transfer and shrinkage to be significant phenomena, provided a good description of eggplant drying kinetics. In addition, it allows quantifying the ultrasonic effects on mass transport rate. The Weibull empirical model also provides good results and could be useful for control purposes. From the results obtained in this work, it is considered that power ultrasound has a high potential application in drying processes due to the improvement on both internal and external mass transport. Further research efforts are required in order to apply this technology at industrial scale.

ACKNOWLEDGMENTS

PROMETEO Y MINISTERIO

NOMENCLATURE

a_w	Water activity
C	GAB model parameter, dimensionless (Eq. 1)
D_e	Effective diffusivity, m^2/s
K	GAB model parameter, dimensionless (Eq. 1)
k	Mass transfer coefficient, kg water/m^2/s
L	Half height, m
R	Radius, m
r	Radial co-ordinate, m
S_y	Standard deviation of the sample
S_{yx}	Standard deviation of the estimation
T	Temperature, K
t	Time, s
W	Average equilibrium moisture content, kg water/kg dry solid
W_c	Critical moisture content, kg water/kg dry solid
W_{ci}	Calculated moisture content, kg water/kg dry solid
W_e	Equilibrium moisture content, kg water/kg dry solid.
W_{ei}	Experimental moisture content, kg water/kg dry solid

W_m	Monolayer average equilibrium moisture content, kg water/kg dry solid
W_p	Local moisture content, kg water/kg dry solid
x	Axial co-ordinate, m
α	Weibull model parameter, dimensionless
α_n	Eigenvalues
β	Weibull model parameter, s
ρ_{ss}	Dry solid density, kg/m^3
φ_{air}	Relative humidity drying air
φ_e	Water activity
ψ	Dimensionless moisture

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1. TABLES

TABLE 1. Initial and boundary conditions for diffusion models considered for modeling drying kinetics of eggplant cylinders.

Models		Initial condition		Equation	External resistance	Sample volume
Common	$t=0$	$0\leq x\leq L;\ 0\leq r\leq R$	$W_p(r,x,0)=W_0$	(3)		
		Boundary conditions				
Common	$t>0$	$r=0; 0\leq x\leq L$	$\frac{\partial W_p(0,x,t)}{\partial r}=0$	(4)		
	$t>0$	$x=0\ ;\ 0\leq r\leq R$	$\frac{\partial W_p(r,0,t)}{\partial x}=0$	(5)		
Negligible External Resistance **(NER)**	$t>0$	$r=R\ ;0\leq x\leq L$	$W_p(R,x,t)=W_e$	(6)	Negligible	Constant
	$t>0$	$x=L\ ;0\leq r\leq R$	$W_p(r,L,t)=W_e$	(7)		
External Resistance **(ER)**	$t>0$	$r=R\ ;0\leq x\leq L$	$-D_e\rho_{ds}\frac{\partial W_p(R,x,t)}{\partial r}=k\left(\varphi_e\left(R,x,t\right)-\varphi_{air}\right)$	(8)	Significant	Constant
	$t>0$	$x=L\ ;0\leq r\leq R$	$-D_e\rho_{ds}\frac{\partial W_p(r,L,t)}{\partial x}=k\left(\varphi_e\left(r,L,t\right)-\varphi_{air}\right)$	(9)		
External Resistance and Shrinkage **(ERS)**	$t>0$	$r=R\ ;0\leq x\leq L$	$-D_e\rho_{ds}\frac{\partial W_p(R,x,t)}{\partial r}=k\left(\varphi_e\left(R,x,t\right)-\varphi_{air}\right)$	(10)	Significant	Variable $L=f(W)$

TABLE 2. NER model. Effective diffusivity (D_e). Percentage of explained variance (% VAR) and mean relative error (% MRE) identified from modeling. Subscrips (a,b,c,d) show homogeneous group established from LSD intervals ($p<0.05$).

UP (kW/m^3)	D_e (10^{-10} m^2/s)	VAR (%)	MRE (%)
0	$3.31±0.3_a$	85.9	16.5
6	$4.26±0.8_a$	85.2	18.1
12	$6.19±0.5_b$	85.8	18.1
19	$6.31±0.2_b$	84.9	18.5
25	$8.84±0.2_c$	86.7	17.3
31	$9.14±1.0_c$	85.9	18.0
37	$11.16±1.0_d$	86.8	16.8

TABLE 3. ER model. Effective diffusivity (D_e) and mass transfer coefficient (k). Percentage of explained variance (% VAR) and mean relative error (% MRE) identified from modeling. Subscrips (a,b,c,d,e,f) and (w,x,y,x) show homogeneous group established from LSD intervals ($p<0.05$).

UP (kW/m^3)	D_e (10^{-10} m^2/s)	k (10^{-3} kg $W/m^2/s$)	VAR (%)	MRE (%)
0	$8.9\pm1.0_a$	$1.87\pm0.2_w$	99.9	0.9
6	$11.8\pm2.7_{ab}$	$2.32\pm0.4_w$	99.9	0.9
12	$16.3\pm1.2_{bc}$	$3.35\pm0.3_x$	99.9	0.7
19	$17.8\pm4.1_{cd}$	$3.43\pm0.3_x$	99.8	1.3
25	$22.7\pm3.0_{de}$	$4.86\pm0.2_y$	99.9	0.9
31	$23.5\pm3.1_{ef}$	$4.79\pm0.7_y$	99.9	1.0
37	$27.9\pm3.6_f$	$6.16\pm0.9_z$	99.8	1.4

TABLE 4. ERS model. Effective diffusivity, average of percentage explained and mean relative error. Subscrips (a,b,c,d) and (w,x,y,z) show homogeneous group established from LSD intervals ($p<0.05$).

UP (kW/m^3)	D_e (10^{-10} m^2/s)	k (10^{-3} kg w/m^2/s)	VAR (%)	MRE (%)
0	$4.9±0.1_a$	$1.79±0.1_w$	99.9	0.4
6	$6.3±1.4_a$	$2.22±0.4_w$	99.9	0.5
12	$8.9±1.8_b$	$3.20±0.2_x$	99.9	0.6
19	$9.4±1.7_b$	$3.29±0.1_x$	99.9	1.0
25	$12.3±1.4_c$	$4.65±0.1_y$	99.9	0.9
31	$12.7±1.7_c$	$4.58±0.7_y$	99.9	0.5
37	$15.2±1.8_d$	$5.89±0.8_z$	99.9	1.1

Table 5. Weibull model. Parameters, *α* and *β*, percentage of explained variance and mean relative error. Subscrips (a,b,c,d,e) show homogeneous group established from LSD intervals ($p<0.05$).

UP (kW/m^3)	β (10^3 s)	α	VAR (%)	MRE (%)
0	$15.30\pm0.8_{a}$	1.08±0.01	99.9	0.6
6	$12.46\pm2.8_{a}$	1.11±0.02	99.9	0.6
12	$8.51\pm0.7_{ab}$	1.09±0.02	99.9	0.5
19	$8.21\pm0.6_{bc}$	1.11±0.10	99.9	0.7
25	$5.96\pm0.3_{c}$	1.07±0.06	99.9	0.4
31	$6.00\pm0.8_{d}$	1.10±0.03	99.9	0.6
37	$4.80\pm0.6_{e}$	1.07±0.04	99.9	1.0

1. FIGURE CAPTIONS

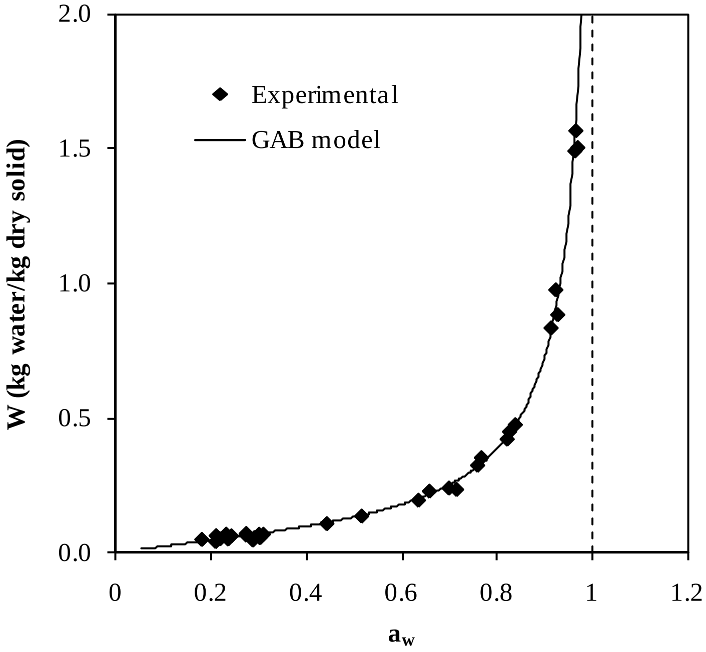

FIG.1. Experimental sorption isotherm and estimated curve with GAB model at 40 ºC.

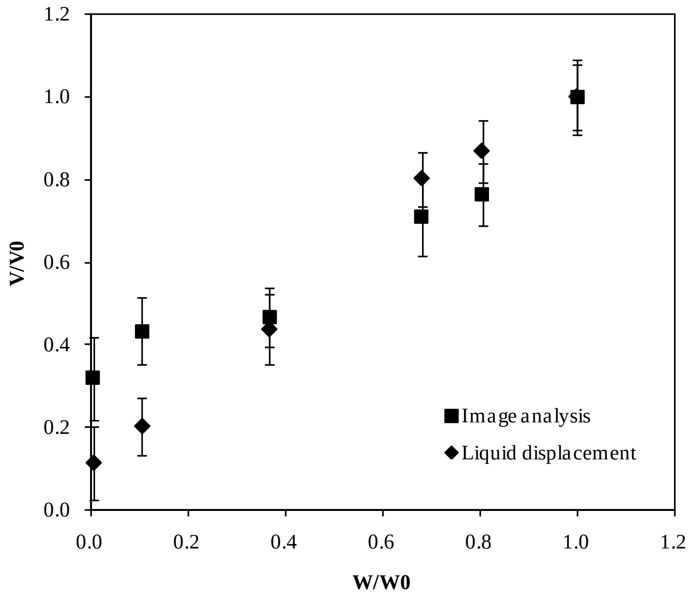

FIG. 2. Experimental shrinkage data for eggplant drying. V: Volume (m^3), W: Average moisture content (kg water/kg dry solid), subscript 0: Initial. Standard deviation values.

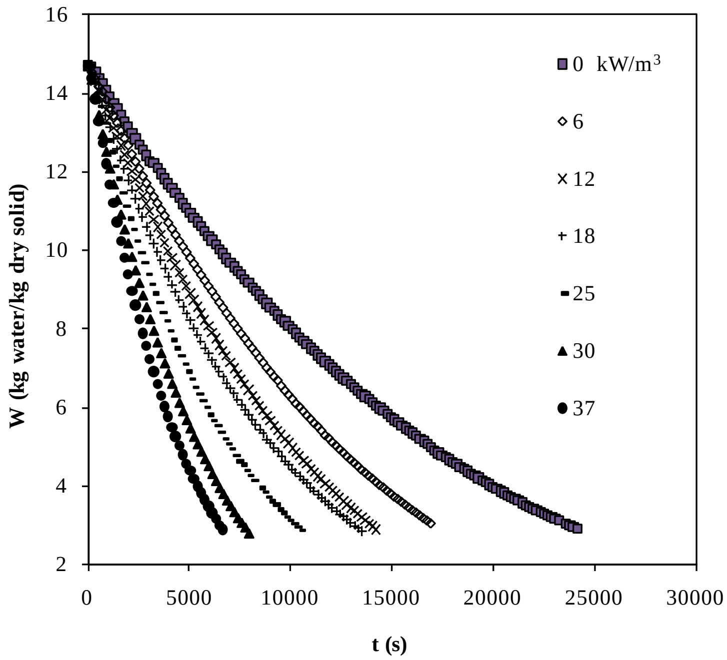

FIG 3. Drying kinetics of eggplant cylinders at 40ºC and 1 m/s applying different ultrasonic power levels (kW/m^3).

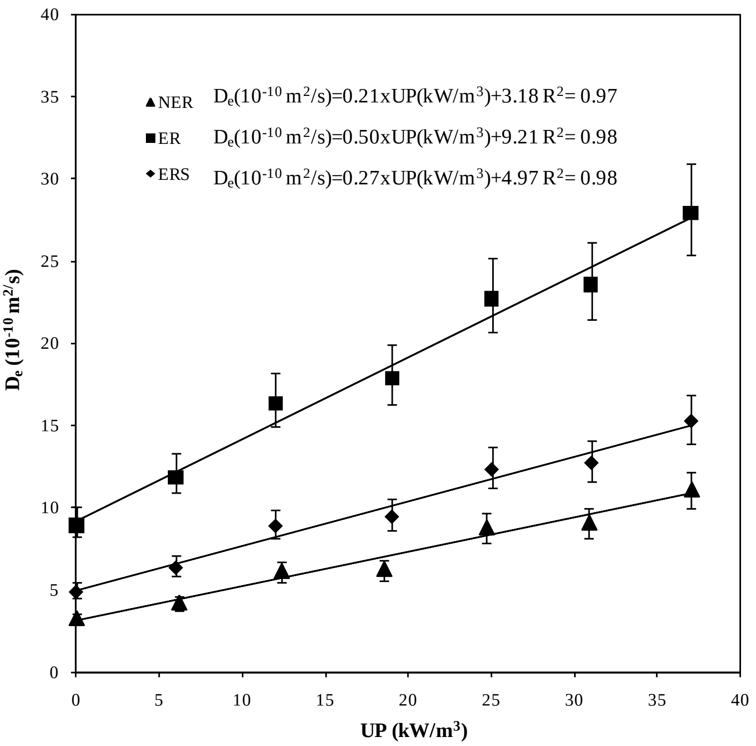

FIG 4. Influence of the ultrasonic power density (UP) on the mass transfer coefficient. Average values ± LSD intervals ($p<0.05$).

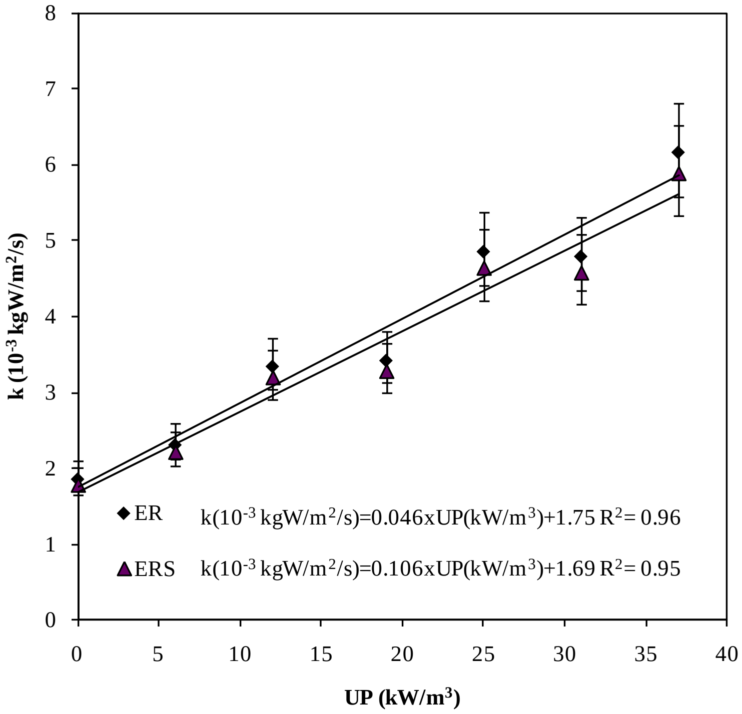

FIG 5. Influence of the ultrasonic power density (UP) on the mass transfer coefficient. Average values ± LSD intervals ($p<0.05$).

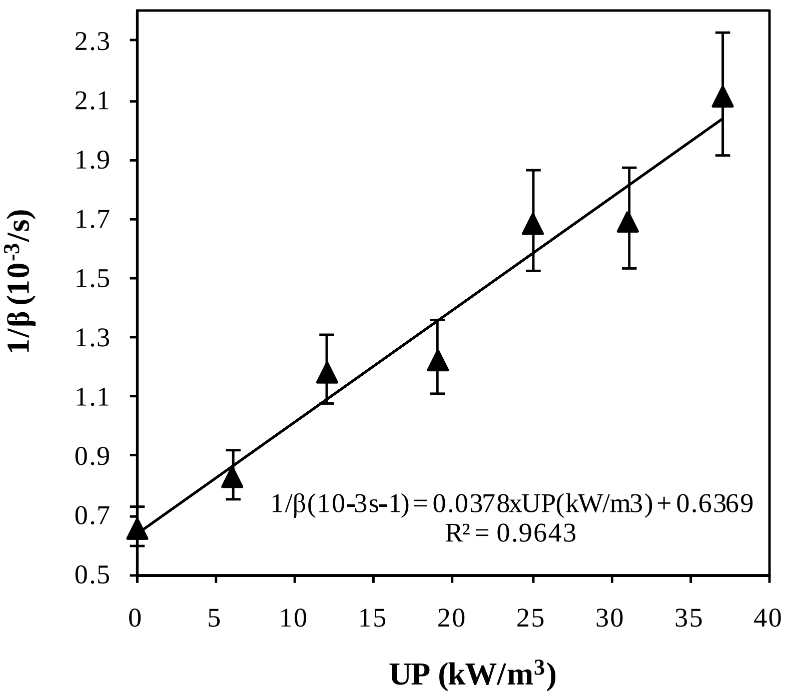

FIG. 6. Influence of ultrasonic power density on kinetic parameter 1/β of eggplant cylinders at 1 m/s. Average values ± LSD intervals ($p<0.05$).