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Kinetic and microstructural changes induced by power ultrasound application on convective drying of eggplant

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ABSTRACT

Power ultrasound is a novel technology to be applied in drying processing taking energy saving aims into consideration. The main goal of this work was to address from a kinetic and microstructural point of view the influence of power ultrasound application on convective drying of a high porosity product like eggplant.

Convective drying kinetics of eggplant cylinders (height 20 mm and diameter 20.4 mm) were carried out at 40 °C and 1 m/s. Trials were also conducted at the same experimental conditions applying acoustic powers from 15 to 90W. A diffusion model was used to quantify the kinetic effects on mass transfer process induced by ultrasound. All these samples were analysed by Cryo Scanning Electron Microscopy (Cryo-SEM).

Experimental results showed the reduction of drying time with the ultrasonic power, the higher the power applied, the faster the drying kinetic. Thus, a maximum drying time reduction (70 %) was reached when the maximum acoustic power tested of 90W was applied. The ultrasonic effect was quantified by the effective moisture diffusivity, which showed a significant ($p<0.05$) linear relationship with the acoustic power.

The main cellular tissue in eggplant is endocarp. This tissue is formed by cells interconnected each other with large intercellular spaces occupied by air, similar to a highly porous sponge. In hot air dried samples, endocarp cells appeared highly degraded and a compacted tissue may be observed without practically intercellular spaces. However, the combined treatments with ultrasound were less drastic in degradation terms than those only with air, this fact was more evident when ultrasound was applied at moderate powers (45W). In these samples, the microstructure of the tissue appeared less modified, endocarp cells still maintained the individuality and even, intact cell walls were found. Therefore, 45W may be considered an optimal power for the application of ultrasound on eggplant drying concerning not only kinetic aspects but also quality issues.

INTRODUCTION

Convective drying is a traditional method to preserve foods, extending shelf life and reducing transport and storage cost. However, chemical, physical, structural and nutritional changes are induced during dehydration affecting the product's quality. Those changes are mainly provoked by the water loss and the high temperatures involved (Chaves et al, 2004). Structural changes are more intense in high porosity products, such as eggplant. Convective drying of eggplant has already been reported in literature (Chaves et al 2003, 2004; Ertekin and Yaldiz, 2004; Akpinar and Bicer, 2005; Wu et al, 2007), but few works have addressed the effect of drying on product's structure. Chaves et al. (2004) studied the shrinkage during hot air drying of eggplant slabs. Otero et al. (1998) tested the effects of high-pressure-assisted freezing and conventional air-freezing in the microstructure of eggplant tissue. Other authors have tested the addition of enzymes and calcium to eggplant tissue to protect the microstructure during drying (Banjongsinsiri et al, 2004).

Power ultrasound is a promising technology to be applied in hot air drying reducing both energy costs and drying time. Previous works have showed the potential of power ultrasound to improve mass transfer phenomena during drying of several fruits and vegetables (Gallego-Juarez et al., 1999; Garcia-Perez et al., 2006, 2007 and 2009; Cárcel et al., 2007). In order to fully develop the ultrasonic assisted drying, it results also convenient to determine the effect of this technology on the product's microstructure. The reduction of drying time by the application of power ultrasound may induce a lower structural damage due to a shorter exposure time to hot air drying than when ultrasound are not applied. Thereby, the main goal of this work was to determine the kinetic and microstructural changes induced by power ultrasound application on convective drying of a high porosity product like eggplant.

MATERIALS AND METHODS

Drying experiments

Cylindrical samples (height 2 cm and diameter 2.4 cm) were obtained from the flesh of Spanish origin eggplants (*Solanum melongena* var. Black Enorma) using a houseware tool. Samples were sealed and stored at 4 ºC until processing (maximum storage time of 2 hours). Initial moisture content of sample was measured at 70ºC and 200 mmHg until constant weight following the AOAC procedures (AOAC, 1997).

Drying kinetics were carried out in a power ultrasound assisted convective drier already described in the literature (Garcia-Perez et al., 2006, 2009). It mainly consists of an air borne ultrasonic device constituting the drying chamber. The ultrasonic device includes an aluminium vibrating cylinder (internal diameter 100 mm, height 310 mm and thickness 10 mm) driven by a piezoelectric composite transducer (21.7 kHz). This system is able to generate a high-intensity ultrasonic field in the medium (154.3 dB). Air temperature and velocity are controlled using a PID algorithm and sample weight is automatically logged at preset times.

Hot air drying experiments (AIR) of eggplant cylinders were carried out at constant air velocity (1 m/s) and temperature (40 ºC). Experiments assisted by power ultrasound (US) were carried out at the same experimental conditions applying acoustic powers from 15 to 90 W to the ultrasonic device. In all the cases, AIR and US experiments were carried out, at least, in triplicate. Experiments were extended until a sample weight loss of 70 % was reached.

Drying modelling

A diffusion model based on the 2nd Fick's law was used to describe the drying kinetics of eggplant cylinders. The differential equation of diffusion can be obtained combining Fick's law and the microscopic mass balance. For isotropic solids and finite length cylindrical geometry the resulting equation is as follows (Simal et al., 1998):

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

Where τ is the local moisture (kg w/kg d.m.), t is the time (s), D_e is the effective moisture diffusivity (m^2/s) and x and r represent the axial and radial directions, respectively.

In order to solve Eq. 1, initial and boundary conditions are needed. Some of the assumptions considered in this work are depicted as follow:

(i) The initial moisture content and temperature are uniform inside the sample due to the previous tempering of the sealed samples.

(ii) The shape of the solid remains constant during the drying period.

(iii) The solid symmetry is considered.

(iv) The external resistance to water transfer is assumed to be negligible, thereby; the solid surface is at equilibrium with the air during drying time.

If the aforementioned assumptions are taken into consideration, the Eq. 1 may be analytically solved. Eq. 2 shows, in terms of the average moisture content, the analytical solution of Eq. 1:

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

Where D_e is the average moisture content (kg w/kg d.m.), α_n the eigenvalues and L the half-length (m) and R the radius (m) of the cylinders, respectively.

The influence of the power ultrasound application on drying kinetic was quantified by identifying the effective moisture diffusivity (D_e) from experimental data. Thus, the optimal D_e figure was identified by minimizing the squared differences between experimental and calculated average moisture content for the different experimental conditions tested. Optimization was carried out by using the GRG method available in the Solver tool of the Excel^{TM} spreadsheet (Microsoft Corporation, Seattle, WA, USA). The goodness of the fit was determined by calculating the percentage of explained variance (%*VAR*) (Eq. 3).

$$\%VAR = \left(1 - \frac{S_{tw}^2}{S_w^2}\right) \cdot 100 \quad (3)$$

Where S_w^2 and S_{tw}^2 are the variance of the sample and the estimation, respectively.

Analysis of variance (ANOVA) was carried out by using Statgraphics® Plus 5.1 (StatPoint, Inc., Warrenton, VI, USA) to evaluate the effect of power ultrasound on effective moisture diffusivity.

Cryo-Scanning Electron Microscopy (Cryo SEM)

The microstructure of fresh, AIR and US (45 and 90W) dried samples was studied using Cryo-SEM techniques. For the microstructural analysis, samples containing flesh and also skin were obtained in order to study the effect of the different drying conditions in all the parts of the eggplant.

The experimental set-up involves a Cryostage CT-1500C (Oxford Instruments, Witney, UK) coupled to a Jeol JSM-5410 scanning electron microscope (Jeol, Tokyo, Japan). Samples were immersed in slush N2 (at -210 ºC) and then quickly transferred to the Cryostage at 1 kPa, where sample fracture took place. The sublimation was carried out at -95 ºC and the final point was determined by direct observation in the microscope (5 kV). Once again in the Cryostage unit, the sample was coated with gold using an ionization current of 2 mA and applying vacuum (0.2 kPa) for 3 min. The observation in the scanning electron microscope was carried out at 15 kV, using a working distance of 15 mm and at -130 ºC.

RESULTS AND DISCUSSION

Effect of power ultrasound on drying process

Drying kinetics of eggplant cylinders carried out applying different acoustic powers are plotted in Figure 2, drying kinetic was slower in AIR than in US experiments. Thereby, the drying time needed to reach an average moisture content of 3 kg w/kg d.m. was reduced by approximately 70% applying 90W compared to the time needed in AIR experiments. The ultrasonic effect was dependent on the power applied, thus, when the power applied was 45W, the drying time reduction achieved 45% regarding US experiments. The improvement of drying rate by power ultrasound application in eggplant was very intense if compared to the effect reported for other products (Gallego-Juarez et al., 1999; Garcia-Perez et al., 2006, 2007 and 2009; Cárcel et al., 2007). According to previous literature (Garcia-Perez et al., 2007), the porous products are more prone to be influenced by ultrasonic waves than the low porosity products The results of this work agree with this statement since eggplant is considered a high porous material.

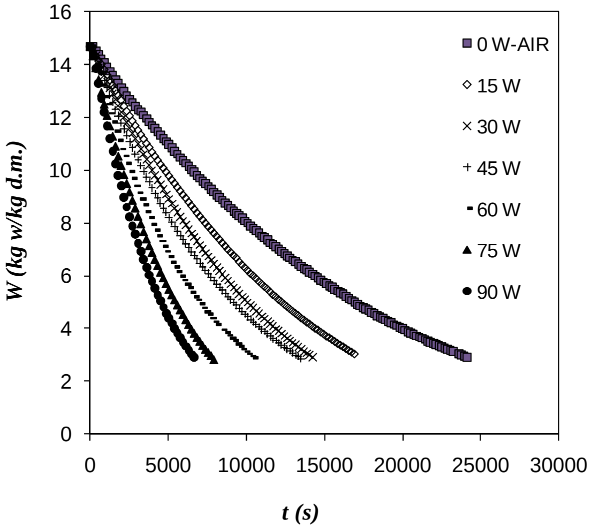

Figure 1. Drying kinetics of eggplant cylinders at different acoustic powers, 40ºC and 1 m/s.

The results of drying kinetics modelling are shown in Table 1. The value of effective moisture diffusivity for AIR experiments was similar to those reported for this product in literature (Akpinar and Dincer, 2005). The application of power ultrasound significantly ($p<0.05$) increased the D_e, thus, the figure for experiments carried out applying 90W was almost one order of magnitude higher than that for AIR experiments. As may be observed in Figure 2, the effect of power ultrasound was proportional to the power applied, thus, a significant ($p<0.05$) linear relationship was established between D_e and the power applied. According to the literature, the improvement of D_e by ultrasonic application is related to the mechanical effects provoked in the material (Garcia-Perez et al., 2009). Power ultrasound generates alternating expansions and contractions when traveling in a medium (Gallego-Juarez et al., 1999), this mechanical stress contributes to the water leaving to the product surface. Due to the weak structure of high porosity products, it should be expected a more intense effect of ultrasound than in low porosity products (Garcia-Perez et al., 2009).

Table 1. Results of drying kinetics modeling.

Power (W)	*D_e (10^{-10} m^2/s)*	*VAR (%)*
0	3.31_a	85.9
15	4.26_a	85.2
30	6.19_b	85.8
45	6.31_b	84.9
60	8.84_c	86.7
75	9.14_{cd}	85.9
90	11.16_d	86.8

Note: Subscripts (a,b,c,d) show homogenous groups established from LSD intervals ($p<0.05$).

The diffusion model proposed provided a low value of the explained variance (Table 1), which means that assumptions considered in the model formulation were not adequate. Two significant effects (external resistance to mass transfer and shrinkage) should be considered in the model according to literature in order to obtain a better fit of experimental data (Chaves and Avanza, 2004; Cárcel et al., 2007; García-Pérez et al., 2007). Thus, the D_e reported in Table 1 would include not only the effect of diffusion mechanism but also other phenomena not considered in the modeling. Therefore, the improvement of the D_e values by the ultrasonic application should be also due to effect of ultrasound on external resistance to mass transfer. The application of power ultrasound in solid/gas systems produces a mechanical stirring of the gas medium due to oscillating velocities, micro-streaming and pressure variation on the interfaces, which reduce boundary layer and, as a consequence improve water movement from the solid surface to air. Further research should be addressed to obtain a better mathematical description of drying kinetics, in order to split the influence of power ultrasound in both internal and external resistance to mass transfer, as well as to consider the shrinkage phenomenon.

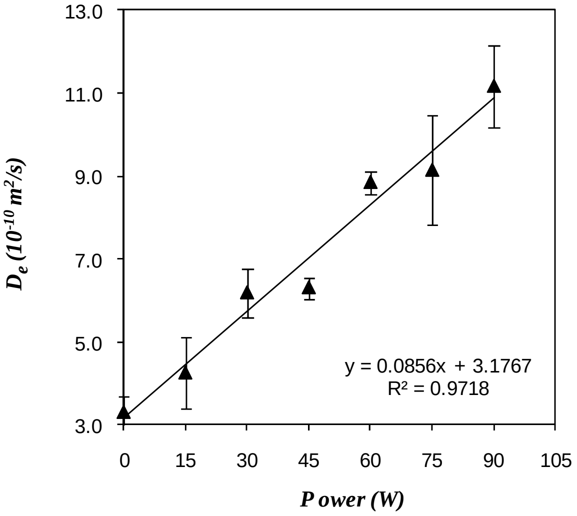

Figure 2. Influence of acoustic power on the average effective moisture diffusivity. Error bars show the standard deviation.

Effect of power ultrasound on microstructure

Two main tissues may be observed at macroscopic level in a section of eggplant. An external layer, named epicarp, appears containing the anthocyanins pigments, which provide the typical purple color of the eggplant. Under the epicarp and occupying almost the rest of the flesh fruit, a spongy and white tissue is placed, which is usually called endocarp. Both tissues were characterized in this work at microscopic level by Cryo-SEM (Figure 3A). The epidermis is characterized by a continuous layer of rounded cells getting really close, almost without intercellular spaces and covered by a uniform and non-porous waxy layer. Under the epidermis, the typical tissue of the epicarp is found, it is mainly compound by 4-5 layers of rounded cells (10-25 μm). Epicarp is considered a compact tissue almost without intercellular spaces. As the microstructural observation progress to the inner part (following the radial direction) of the fruit, the cells are progressively getting larger and also large intercellular spaces may be observed. This area corresponds to the endocarp, which is characterized by tubular and interconnected cells (Figure 3A).

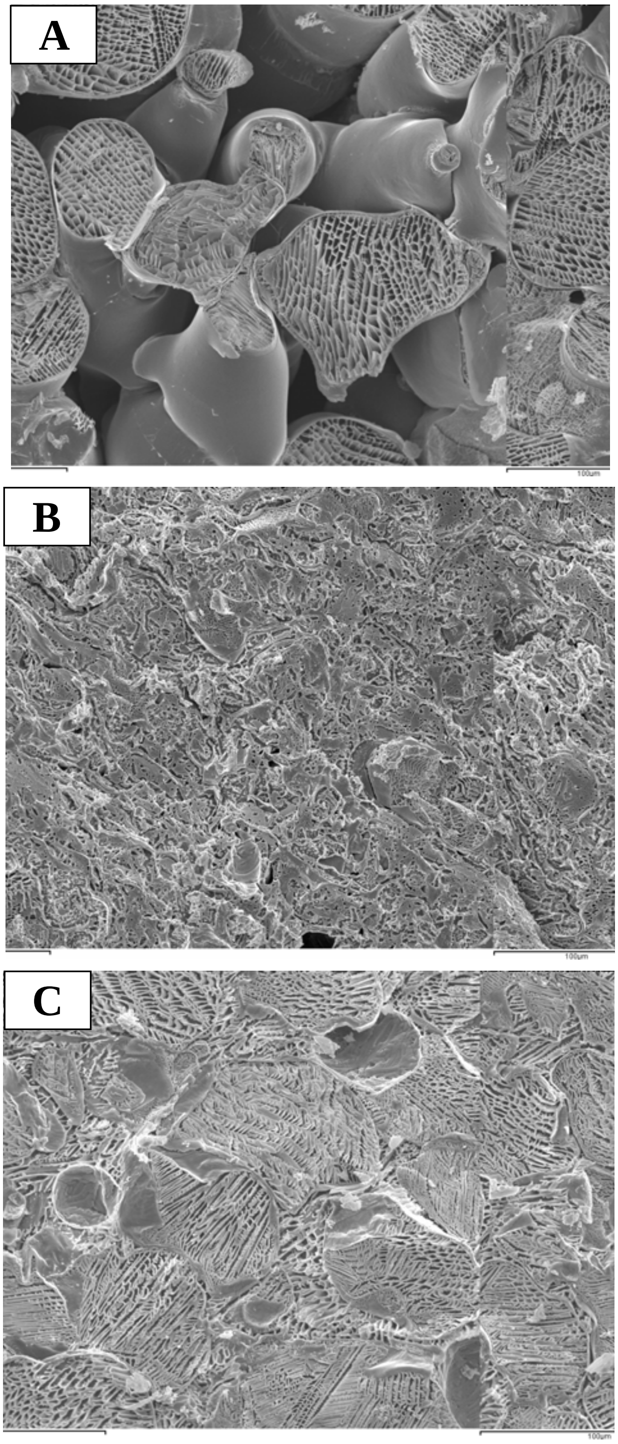

Figure 3. Microstructural observations of eggplant endocarp. A: fresh eggplant, B: hot air dried, C: dried applying an acoustic power of 45W.

The microstructure of the eggplant was affected in both AIR and US experiments. The drying without power ultrasound application (AIR experiments) involved the separation between the epicarp and the epidermis, although the waxy compounds were not affected. In addition, the endocarp tissue was dramatically degraded (Figure 3B), thereby, the intercellular spaces disappeared being lost the spongy structure. The high degradation of eggplant structure may be linked to the long time of exposure to hot air in AIR experiments (Figure 1). The ultrasonically assisted drying experiments (US) led to the scattering of waxy compound on the epidermis, being lost the characteristic uniformity of this layer. Ortuño et al. (2010) already observed the effect of power ultrasound during drying on the waxy compounds of the orange peel epidermis. Epidermis is considered an interface solid/air, as consequence, the observed effects are linked to the aforementioned stirring mechanisms associated to ultrasound application. The oscillating velocities, micro-streaming and pressure variation on the interfaces should not only reduce the boundary layer thickness improving mass transfer phenomena, but also induce the degradation of interface structure. In this work, both effects have been observed.

A high effect of power ultrasound was also observed in the endocarp (internal tissue), being more intense the effects as higher the ultrasonic power applied. Thus, the encocarp of dried samples at 45W (Figure 3C) was less degraded if compared to AIR dried samples (Figure 3B). In dried samples at 45W (Figure 3C), endocarp cells still maintains the individuality and even, intact cell walls were found. Nevertheless, the internal microstructure of samples dried at 90W is highly degraded, being more similar to AIR dried samples than to those dried applying 45W. This fact may be explained considering both the effect of ultrasound in internal structure and the power applied. The alternating expansions and contractions brought about by ultrasonic wave when is traveling in a medium should promote not only the water leaving but also the degradation of endocarp cells. Obviously, the effect on the internal structure should be dependent on the power applied, as already showed for kinetic parameters (Figure 2). When a power of 45W is applied, the effect of ultrasound may be considered moderate and highly efficient since a reduction of drying time of around 45%, compared to AIR experiments (Figure 1), is reached applying only 45W (50% of the maximum acoustic power). In these conditions, the exposure time to hot air drying is shortened with a moderate compression and expansion of endocarp cells by ultrasonic waves, which may explain the better preservation of microstructure. However, when 90W are applied, the compression and expansion of endocarp tissue is very intense, this induces a high degradation of the internal tissue, even for a short exposure time (Figure 1). Therefore, 45W may be considered an optimal power for the application of ultrasound on eggplant drying concerning not only kinetic aspects but also quality issues.

CONCLUSIONS

Ultrasonic application during convective drying of eggplant leads to a significant reduction of drying time. The ultrasonic effect was dependent on the power applied, thus, the higher the power applied, the faster the drying kinetic. The microstructure of eggplant endocarp was highly affected during drying using only hot air due to the long exposure times. The application of a moderate ultrasonic power (45W) involves a better preservation of microstructure due to the shortening of drying time and the weak mechanical effects of ultrasound in the endocarp cells. Therefore, ultrasonic assisted drying of eggplant may be considered an efficient alternative to conventional hot air drying in terms of energy (reduction of drying time) and quality (internal product structure).

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