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Influence of the ultrasonic power applied on freeze drying kinetics

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Abstract

The atmospheric freeze drying (AFD) constitutes an interesting alternative to vacuum freeze drying providing products with similar quality at lowest cost. However, the long process time needed represent an important drawback. In this sense, the application of high intensity ultrasound can enhance heat and mass transfer and intensify the operation. In hot air drying operation, the ultrasonic effects are dependent on the process variables such as air velocity, internal sample structure or ultrasonic power applied. However, in AFD processes, the internal structure of material or the air velocity has not significant influence on the magnitude of ultrasonic effects. The aim of this work was to determine the influence on drying kinetics of the ultrasonic power applied during the AFD of apple. For that purpose, AFD experiments (-10ºC, 2 m/s and 15% relative humidity) of apple slabs (cv. Granny Smith, 30 x 30 x 10 mm) were carried out with ultrasound application (21 kHz) at different power levels (0, 10.3, 20.5 and 30.8 kW/m^3). The drying kinetics was obtained from the initial moisture content and the weight evolution of samples during drying. Experimental results showed a significant ($p<0.05$) influence of the ultrasound application on drying. Thus, drying time was shorter as higher the ultrasonic power applied. From modeling, it was observed that the effective diffusion coefficient identified was 4.8 times higher when ultrasound was applied at the lowest power tested (10.3 kW/m^3) that illustrated the high intensification potential of ultrasound application in the AFD.

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Keywords: apple; power; ultrasound; diffusivity

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1. Introduction

Food preservation by drying is one of the oldest operations in food industry, being the convective drying one of the main process used for that. This method is usually carried out at high temperatures to reduce the long processing time required. However, this fact can decrease the final product quality. For that reason were developed others methods such as vacuum freeze-drying. However, the need of vacuum and the batch production converts this process in an expensive technique, only applied for high added value products. A cheapest alternative is the atmospheric freeze drying, that reduce the energy consumption of vacuum freeze drying while maintaining a high product quality (Claussen et al. 2007). Its main advantages are the possibility of continuous production and no vacuum needed. Nevertheless, the low drying velocity made this process prone to be intensified.

In this sense, the application of power ultrasound can improve mass and heat transport enhancing drying process. Thus, ultrasound waves produce the compression-decompression of solid materials and the creation of micro-channels that can make easier the exit of water from the inner part to the solid surface (Cárcel et al. 2012). Moreover, at the solid surface, ultrasound can reduce the boundary layer of diffusion by creating micro-currents. It must be point out that the power ultrasound application does not lead to a significant rise of the product's temperature because the effects are mainly mechanical (García-Pérez et al. 2012) maintaining the added value of the final product (Awad et al. 2012).

In hot air drying application, it has been shown that the effects of ultrasound are dependent of process variables such as air speed, mass load or ultrasonic power applied (Cárcel et al. 2007; 2011; Ozuna et al. 2011). Less research has been done for ultrasonic application at low temperature drying (Santacatalina et al. 2015). The main aim of the present work was to assess the effect of the ultrasonic power applied in the kinetics of the atmospheric freeze drying of apple slabs.

2. Materials and methods

2.1. Sample preparation

Drying experiments were carried out with apple (*Malus domestica* cv. Granny Smith). For that, samples of a 30 x 30 x 10 mm were obtained using a sharp knife. Afterwards, samples were set in a sample holder and frozen at -28ºC during at least one day. The initial moisture of apple was determined by applying the AOAC standard method nº 925.40 (AOAC, 2012). For that, samples were dried at 70ºC and 0.8 atm until constant weight (24 ± 1 h).

2.2. Drying process

An ultrasonically assisted convective dryer (Figure 1) previously described (García-Pérez et al. 2012) was used for the process. The drying chamber (internal diameter 100 mm, height 310 mm, thickness 10mm) constitutes a vibrating element excited by an ultrasonic transducer at a frequency of 21.9 kHz. Drying experiments were carried out at -10ºC, 2 m/s and a maximum relative humidity of 15% using a mass load of 30±1 g. The experiments were conducted without (0 kW/m^3) and with ultrasound application at three different power levels (10.3, 20.5 and 30.8 kW/m^3). At least four replicates were carried out for each condition tested.

2.3. Modeling

The modeling of experimental data was carried out with the aim of quantify the influence of the ultrasonic power applied on drying kinetics. For that purpose a simple diffusion model based in Fick's law was considered. Equation (1) shows the solution of the model assuming uniform temperature, constant effective diffusivity, negligible shrinkage and external resistance to mass transfer negligible compared to the internal one.

$$W(t) = W_e + (W_0 - W_e)\sum_{n=0}^{\infty} \frac{8}{(2n+1)^2 \pi^2} \exp\left(-\frac{D_e (2n+1)^2 \pi^2 t}{4L}\right) \quad (2)$$

Where W is the particle average moisture content (kg water/kg dm), t is the time (s), L is the half-length of the thickness of the slab (m), and subscripts o and e refer to the initial and equilibrium states, respectively. A multifactor analysis of variance (ANOVA) and Least Significant Difference (LSD) intervals were calculated to determine the significance of differences between treatments.

3. Results and discussion

3.1. Experimental drying kinetics

The initial moisture content of apple was 6.2 ± 0.4 kg water / kg d.m. Experimental drying kinetics took place in the falling rate period. The drying process finished when sample moisture was 0.40 ± 0.06 kg water/ kg d.m. that corresponded with an initial weight loss of the 80 %. It can be highlight the slow kinetics of the process. Thus, the drying kinetics of samples dried without ultrasound application needed more than 80 h to be dried. The application of ultrasound significantly ($p<0.05$) accelerated the drying process decreasing the drying time (Figure 2). In this sense, the drying time of experiments carried out with the lowest level of ultrasonic power tested (10.3 kW/m^3) was 15 h (Table 1) that means a reduction of the 80 % compared with conventionally dried samples. Therefore, a relative low ultrasonic power applied is able to produce a high increase of the drying kinetics. This significant reduction of drying time can be translated in an important decrease of energy consumption.

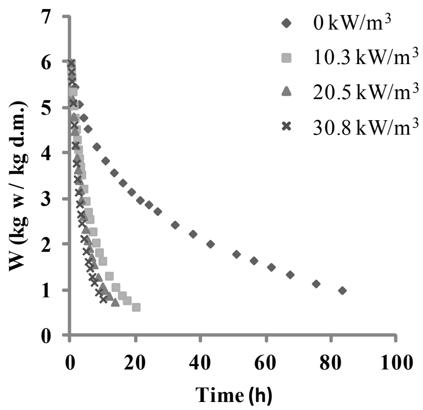

Fig. 2. Experimental drying kinetics (-10 ºC; 2 m/s) of apple slabs without and with ultrasound application (21.9 kHz) at different power levels.

Moreover, the higher the ultrasonic power applied the shorter the drying time (Figure 2, Table 1). Thus, at the highest ultrasonic power tested, the needed drying time was a 10 % of the drying time needed for non ultrasonically assisted dried samples (Table 1).

3.2. Modeling

The considered diffusion model fitted adequately the experimental data as can be observed by the fact that the percentage of explained variance was above 98 % (Table 1). The slightly worst fit of the ultrasonically assisted drying experiments could indicate other drying mechanisms introduced by ultrasonic effects.

Table 1. Effective diffusivity (D_e), explained variance (VAR) and drying time (t) of air freeze drying experiments.

Power US (kW/m^3)	0	10.3	20.5	30.8
De (m^2/s)	$6.98 \cdot 10^{-11}$	$3.39 \cdot 10^{-10}$	$5.24 \cdot 10^{-10}$	$6.87 \cdot 10^{-10}$
VAR (%)	99.86	99.30	98.90	98.85
t (h)	80 ± 1	15.0 ± 0.3	10.0 ± 0.2	7.0 ± 0.1

The identified De was in the same range than other published (García-Pérez et al., 212b). The application of ultrasound significantly ($p<0.05$) increased the De and the calculated LSD intervals showed that these increase was significantly ($p<0.05$) higher as higher was the acoustic power applied (Table 1). Thus, the application of the lower ultrasonic power tested, 10.3 kW/m^3, produced an increase of the identified De of 386 %. In the case of the maximum ultrasonic power tested, the increase of the De was of 884%. This increase can be attributed to the ultrasonic effects as the 'sponge effect' or the creation of micro-channel (Cárcel, et al., 2011; García-Pérez, et al., 2012) that reduce the internal resistance to mass transfer improving moisture mobility within the apple sample.

It must emphasize the high increase of drying kinetics produced by a relative low ultrasonic energy that show the interest of this technique not only in the intensification of the drying process but also the reduction of the energy consumption.

4. Conclusions

The application of high intensity ultrasound during the atmospheric freeze drying process increased significantly the drying kinetics even at low level of ultrasonic power applied. The effects of ultrasound were higher as higher was the power applied. The proposed diffusion model allowed quantifying the ultrasound effects despite it became in an empirical model due to some assumptions that do not correspond with the conditions on atmospheric freeze drying.

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