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2012 IOP Conf. Ser.: Mater. Sci. Eng. 42 012021

(http://iopscience.iop.org/1757-899X/42/1/012021)

Atmospheric freeze drying assisted by power ultrasound

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Abstract. Atmospheric freeze drying (AFD) is considered an alternative to vacuum freeze drying to keep the quality of fresh product. AFD allows continuous drying reducing fix and operating costs, but presents, as main disadvantage, a long drying time required. The application of power ultrasound (US) can accelerate AFD process. The main objective of the present study was to evaluate the application of power ultrasound to improve atmospheric freeze drying of carrot. For that purpose, AFD experiments were carried out with carrot cubes (10 mm side) at constant air velocity (2 ms^{-1}), temperature (-10ºC) and relative humidity (10%) with (20.5 kWm^{-3}, USAFD) and without (AFD) ultrasonic application. A diffusion model was used in order to quantify the influence of US in drying kinetics. To evaluate the quality of dry products, rehydration capacity and textural properties were determined. The US application during AFD of carrot involved the increase of drying rate. The effective moisture diffusivity identified in USAFD was 73% higher than in AFD experiments. On the other hand, the rehydration capacity was higher in USAFD than in AFD and the hardness of dried samples did not show significant ($p<0.05$) differences. Therefore, US application during AFD significantly ($p<0.05$) sped-up the drying process preserving the quality properties of the dry product.

1. Introduction

The increasing need to achieve an equilibrium between high quality of dried products and low-operating cost has induced researchers to investigate the use of new techniques to intensify drying processes. From a quality point of view, freeze drying is considered to be one of the best food drying methods, but it is quite expensive due to freezing and the low pressures applied [1]. Atmospheric freeze drying (AFD) is an alternative consisting in the use of cold gas with low water vapor pressure as drying medium to cause direct moisture sublimation from frozen material at atmospheric pressure [2]. This technique could combine the advantages of both freeze drying (high product quality) and convective drying (low cost and continuous process). However, it presents as main drawback longer drying times than in traditional freeze drying processes.

Power ultrasound (US) has been recently applied in hot air drying of different products reducing both the drying times and energy costs. The potential of power ultrasound to improve mass transfer phenomena during drying of several fruits and vegetables has been showed in previous works [3] [4]. Ultrasonic energy could be applied during AFD to accelerate the drying process due to the mechanical energy introduced in the medium, which could contribute to reduce both the external and the internal mass transfer resistance.

Mathematical modeling constitutes an approach for analyzing drying and drier's operation [5]. Modeling of drying kinetics allows obtaining the effective moisture diffusivity of the product, essential parameter in simulation and optimization of drying process [6].

On the other hand, most of dried products should be rehydrated before consumption. Thus, it is interesting the knowledge of the behavior of the rehydrated product, being softening and loss of texture the main problems. The texture profile analysis is frequently used to evaluate the textural properties of rehydrated products indicating the tissue damage underwent during the operation.

The main aim of this work was to evaluate the application of power ultrasound to improve atmospheric freeze drying of carrot, quantifying its influence on drying kinetics and quality of dried products.

2. Materials and methods

2.1. Drying experiments

Carrot (*Daucus carota* var. Nantesa) cubes (10 mm side) were obtained using a houseware tool. Samples were sealed with film, frozen and stored at -18ºC during 24 hours before drying. Initial moisture content was measured placing samples at 70ºC and 200 mmHg until constant weight according to AOAC standards [7].

Atmospheric freeze drying experiments were conducted in a convective drier with air recirculation, temperature and air velocity control and an ultrasonically activated drying chamber, already described in literature [8]. Kinetics were carried out at constant air velocity (2 ms-1), temperature (-10ºC) and relative humidity of the air (10%) with (20.5 kWm-3, USAFD) and without ultrasonic application (AFD). AFD and USAFD kinetics were carried out, at least, in triplicate and extended until samples lost 82% of the initial weight.

2.2. Rehydration experiments

The dried cubes (AFD and USAFD) were rehydrated until constant weight in distilled water at 25 ºC using a thermostatic bath. Experiments were conducted, at least, in triplicate and samples were weighed at preset times.

2.3. Texture

Textural properties of dried/rehydrated and fresh carrot cubes were measured with a TA-XT2 texturometer (SMS, Godalming, UK) with a load cell of 25 kg. Texture profile analysis (TPA) was carried out by two compression cycles between parallel plates, at 25% strain, using a flat 75 mm diameter aluminium plunger (SMS P/75) and with a 5 s set period of time between cycles. Hardness was calculated from force/deformation profiles. At least, 10 samples were analyzed for each set of samples (AFD and USAFD rehydrated and fresh carrot cubes).

Analysis of variance (ANOVA) ($p<0.05$) was carried out and LSD (Least Significant Difference) intervals were identified using the statistical package Statgraphics Plus 5.1. (Statistical Graphics Corp., Warrenton, USA) in order to estimate significant differences.

2.4. Modeling drying kinetics

A diffusion model based on the Fick's law was used to mathematically describe the drying kinetics (AFD and USAFD) of carrot cubes. The differential equation of diffusion can be obtained combining Fick's law and the microscopic mass balance. For cubic geometry, the diffusion equation was written (1) considering constant effective moisture diffusivity and isotropic solid.

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

where W_p is the local moisture (kg w/kg d.m.), t is the time (s), D_e is the effective moisture diffusivity (m^2s^{-1}) and x, y and z represent the characteristic coordinates in cubic geometry (m).

In order to solve equation (1), some assumptions were considered: solid symmetry, uniform initial moisture content and temperature, constant shape during drying and negligible external resistance to water transfer. Taking into account these assumptions, the analytical solution of the diffusion equation is expressed in terms of the average moisture content in equation (2) [9].

$$W(t) = W_e + (W_e - W_0)\cdot\left[\sum_{n=0}^{\infty} \frac{8}{(2n+1)^2 \pi^2} e^{\left(-\frac{D_e (2n+1)^2 \pi^2 t}{4L^2}\right)}\right]^3 \tag{2}$$

where W is the average moisture content (kg w/kg d.m.), L the half-length of the cube side (m) and subscripts 0 and e represent the initial and equilibrium state, respectively.

2.5. *Model fitting*

For drying kinetics, the effective moisture diffusivity was identified by minimizing the sum of the squared difference between experimental and calculated average moisture content of samples. Identification was carried out by using the Generalized Reduced Gradient (GRG) method, available in Microsoft Excel TM spreadsheet (Microsoft Corporation, Seattle, WA, USA). The goodness of the fit was determined by the percentage of explained variance (%VAR, (3)) [10].

$$\%VAR = \left[1 - \frac{S_{xy}^2}{S_y^2}\right]\cdot 100 \tag{3}$$

where S_{xy} and S_y are the standard deviation of the estimation and the sample, respectively.

3. Results and discussion

3.1. *Drying kinetics*

AFD and USAFD kinetics of carrot cubes carried out at -10ºC and 2 ms^{-1} are shown in figure 1. It can be observed that the application of US accelerated the AFD of carrot obtaining a reduction of drying time by 60% to achieve a weight loss of 82%. The kinetic improvement by US application was also observed in the values of the effective moisture diffusivity identified, which was 73% higher in USAFD ($7.98\cdot10^{-11}$ m^2s^{-1}) than in AFD ($4.62\cdot10^{-11}$ m^2s^{-1}) experiments. The percentage of explained variance obtained was 92.45 and 97.64% for USAFD and AFD, respectively, showing the better fit of the model to the AFD experimental data (figure 1). This fact could be explained considering that in the AFD experiments the internal resistance to mass transfer was much higher than the external one, which was nearly negligible. In the case of USAFD experiments, US diminished the internal resistance to mass transfer, which leads to a more significant external resistance [8]. This fact explains also the low %VAR provided by the diffusion model in the USAFD experiments.

3.2. *Rehydration kinetics*

The USAFD samples rehydrated faster than AFD ones (figure 2). The equilibrium moisture (W_{eq}) reached by the USAFD and the AFD samples was 5.05±0.06 and 4.06±0.21 kg w/kg d.m., respectively. The long drying times in AFD could involve a high degradation of carrot structure, which could explain the lower value of W_{eq} obtained in AFD than in USAFD experiments.

3.3. *Texture*

The hardness, determined from force/deformation profiles obtained by texture profile analysis of the rehydrated samples, was 3.34±0.63 N and 3.76±0.43 N for AFD and USAFD, respectively. Therefore, the hardness of the AFD and USAFD dried samples did not show significant ($p<0.05$) differences. The value for the fresh cubes (100.12±5.91 N) was much higher than for dried samples because dehydration involved a high degradation of carrot structure. Thereby, rehydrated samples do not recover the initial texture and dried/rehydrated samples were much softer than fresh ones.

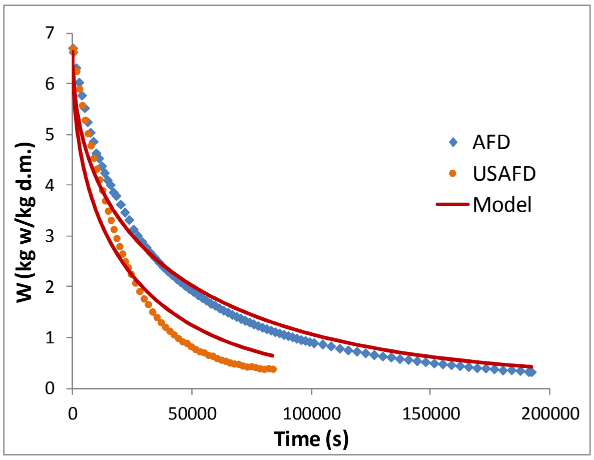

Figure 1. Atmospheric freeze drying kinetics of carrot cubes with (USAFD, -10ºC, 2 ms^{-1} and 20.5 kWm^{-3}) and without (AFD, -10ºC and 2 ms^{-1}) power ultrasound application.

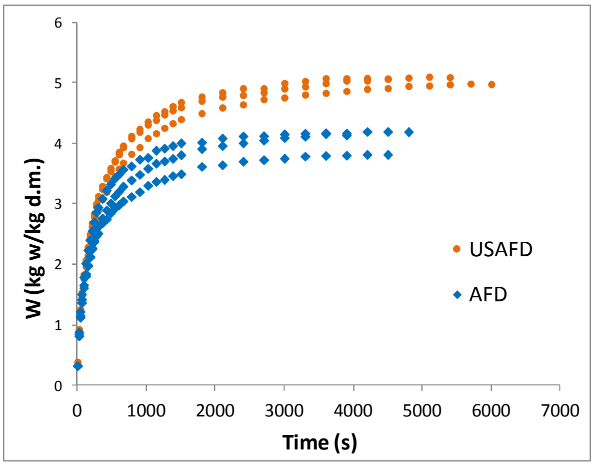

Figure 2. Rehydration kinetics (25ºC) of AFD and USAFD dried carrot cubes.

4. Conclusion

The ultrasonic application during AFD kinetics of carrot involved the increase of drying rate achieving a reduction of drying time by 60%. The diffusion model proposed was adequate for describing the AFD kinetics but not fitted well to the USAFD experimental data. The effective moisture diffusivity identified in USAFD was 73% higher than in AFD experiments. On the other hand, the rehydration capacity was higher in USAFD than in AFD and the hardness of dried samples did not show significant ($p<0.05$) differences. Therefore, USAFD could represent an interesting alternative to vacuum freeze drying to achieve high quality dried products with lower cost.

Acknowledgments

The authors acknowledge the financial support of the Ministerio de Economía y Competitividad (MINECO) of Spain from the project DPI2009-14549-C04-04.

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