PARAMETRIC STUDY OF ULTRASONIC DEHYDRATION PROCESSES

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Abstract

Power ultrasound in food industry processing represents a novel tool, which is becoming increasingly appreciated. The use of ultrasonic energy is very promising because it can act without affecting the main characteristics and quality of the products.

This work investigates the kinetics of ultrasonic dehydration processes of vegetables by direct contact vibrator-product. To that purpose, a parametric study of the relative influence of the main physical parameters involved in the process has been carried out. A specific experimental set-up has been designed, developed and tested. Trials were carried out with potatoes and apples. A 20kHz resonant transducer was designed with the aim to obtain high-amplitude displacements. Assessment of the properties of the samples (residuary moisture content and viscoelastic constants) is obtained from the analysis of high frequency (0.5-1MHz) wideband ultrasonic signals transmitted through the samples by using air-coupled transducers.

The dehydration results show a notable influence of ultrasonic vibration on the kinetics of the process.

Introduction

Dehydration is a method to preserve food. Nowadays, some dehydrated products like fruits and vegetables have suffered a notable increase on their demand in the market. Therefore new drying technologies are under development with the aim to obtain good quality product at moderate cost.

Ultrasonic energy has been used in drying processes because high-amplitude vibrations are capable of increasing heat and mass transfer processes in materials. In this way is possible to remove moisture without significantly heating the product. This is one of the main reasons to use ultrasonic energy in many applications in food technology [1,2,3,4,5,6,7,8].

The aim of this work is to investigate the kinetics of the ultrasonic dehydration process of fruits and vegetables, in which the ultrasonic vibrations are applied in direct contact with the product under certain static pressure. Dehydration curves were determined by a parametric study of the main physical parameters involved in the process. Drying kinetics was modeled by the diffusion equation (Fick's second law) [9], for which a very good agreement with the experimental data was obtained. The effective diffusivity (D_e) was determined by a correlation based on the air velocity, the temperature and the nondimensional moisture content of the samples. In parallel, an ultrasonic characterization technique of moisture content in food materials was developed. It is based on the analysis of high frequency (0.5-1MHz) wideband signals transmitted through the samples by using air-coupled transducers.

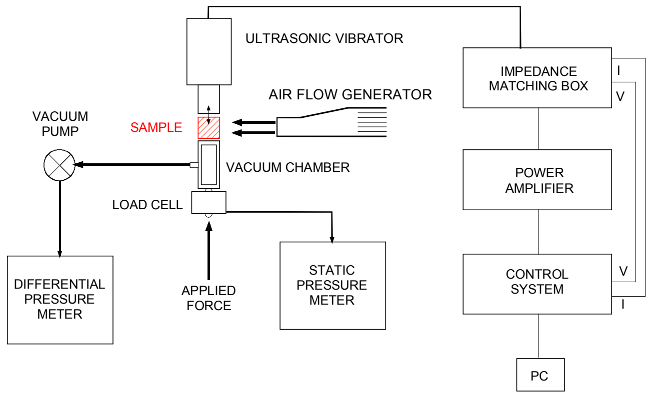

Figure 1. Scheme of the ultrasonic dehydration unit of materials

Experimental procedure for ultrasonic dehydration processes

The experimental set-up developed and tested for the dehydration of materials by direct contact ultrasonic vibration is shown schematically in Figure 1. It consists in a piezoelectric transducer working at 20 kHz with a power capacity of 100W driven by a power generator system. The generator is composed of an impedance matching unit, a power amplifier and a resonant control system. This system was specifically developed to keep constant the power applied at the resonance frequency of the transducer during the process.

The sample to be treated is placed between the tip of the transducer and a porous layer. The layer has 3.2mm in thickness and 25cm in diameter. It is made of high-density polyethilene and has a porous size distribution from 15 to 25 microns. This layer closes the top of a cylindrical vacuum chamber where a suction pump is applied to remove the moisture extracted from the lower face of the sample. A differential pressure meter allows to measure the vacuum (or suction) value during the trials. A static pressure was applied to get a good and homogeneous mechanical coupling between the sample, the vibrating tip of the transducer and the porous layer. The magnitude of the static pressure is controlled by means of a static pressure meter.

The experimental procedure in all trials basically consisted of measuring the moisture content of food samples after different times of application of high-amplitude ultrasonic vibrations in combination with forced-air (flow velocity = 1m/s at 31ºC). To examine the effect of the ultrasonic energy all experiments were carried out with (+US) and without (-US) ultrasound and replicated three times. In all the trials, the frequency was kept constant at about 20 kHz, while different vibration amplitudes (0, 30 and 42 microns) (see Figure 2), static forces (70 and 220 g) and suctions (10 and 20 mbar) were applied. In addition, the environmental conditions of the laboratory were monitored. The moisture content of the samples was measured by weighting them. The weight of dried samples was measured after drying 24h at 70ºC in an oven.

Figure 2 shows the vibration amplitude-power curve of the tip of the transducer under the operational conditions. This measurement was carried out with a Laser Vibrometer in order to quantify the magnitude of the displacement directly in contact with the upper surface of the samples.

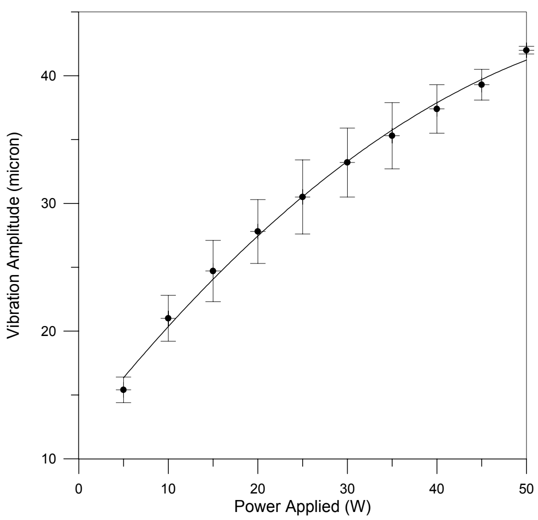

Figure 2 Vibrating amplitudes of the tip of the transducer versus power applied

Acoustic characterization technique of moisture content in fruits and vegetables

Final product quality assessment is accomplished by detailed analysis of the internal changes brought about in the sample by the dehydration process: chemical transformations, texture changes, cell's wall disruption, etc. Techniques used for this purpose are light microscopy, FTIR spectroscopy, etc. [10,11]

In this section the possibility to use a technique based on the study of the propagation of high frequency ultrasonic pulses through the samples to determine water content is investigated. Main advantages of this technique are that it is nondestructive, non-invasive, and very fast. In addition, it is also shown that different dehydration routes give rise to a different evolution of the acoustic properties of the sample; it is then suggested that this technique can be also used to study the internal changes that take place in the sample during the dehydration process.

Because of sample's properties a non-contact ultrasonic technique has to be used. In this case, two pairs of air-coupled piezoelectric transducers having center frequency at 0.5 MHz and 1 MHz respectively were used; working frequency range is 0.3-1.2 MHz. Through transmission technique is employed to determine both velocity and attenuation of ultrasonic waves in the samples. Cross- correlation of time domain signals and phase and magnitude analysis of the FFT was used. Further details about the technique and about the experimental set-up can be found in [12,13].

The parameter time-shift is defined as:

$$time - shift(\%) = \frac{\Delta t}{\Delta t_0} \times 100$$

where Δt_0 is a reference time and is the time-of flight of the ultrasonic pulse from transmitter to receiver when sample has a 100% moisture content (initial stage), Δt is the time-of flight measured at any other moisture content. This parameter provides information about velocity of sound in the sample and the thickness of the sample. The former is related to sample density and elasticity while the later is related to sample shrinkage.

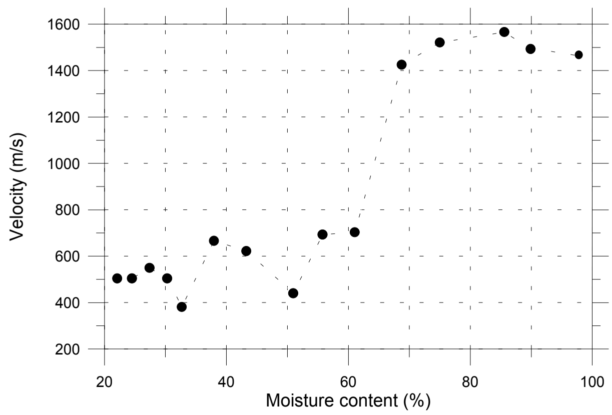

Figure 3. Velocity of ultrasonic waves (at 1 MHz) versus moisture content in a potato slice dehydrated using force-air.

Potato slices about 1 mm thick were used for this study. Two dehydration processes where used; samples were either let to dry at ambient conditions or subjected to forced-air. At intervals, samples were weight, thickness measured, and measured with the air-coupled through transmission device here proposed.

Velocity of ultrasound versus moisture content for a sample dehydrated under forced-air is shown in Figure 3. For high moisture content (70-100%), there is almost no variation in the velocity, it is close to velocity in water. As moisture content decreases, there is a sharp decrease of the velocity; this can be considered as the transition from wet to dry state; eventually, at very low moisture content value (30%) velocity approaches a lower bound about 400 m/s. Figure 4, shows the time-shift versus moisture content obtained for samples subjected to different processes: ambient conditions and forced-air. The differences in the time-shift for the same moisture content observed in the figure can be explained if it is considered that ultrasonic measurements are affected by changes in other internal parameters of the sample apart from moisture content.

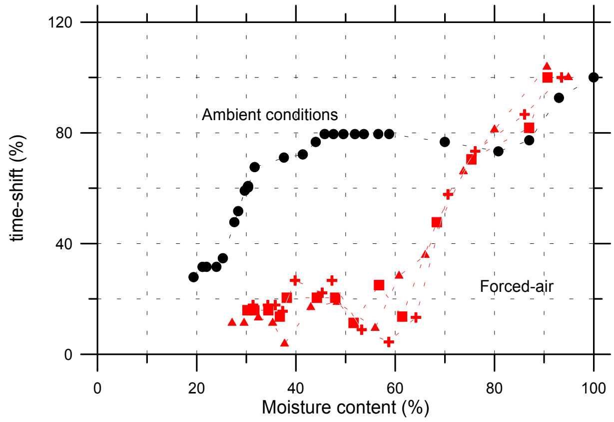

Figure 4. Time-shift (%) at 1 MHz versus moisture content for different dehydration conditions. Ambient: ●; Forced-air: ■, ▪, π.

Materials and Modeling

Two different kinds of samples were used for experiments: apples of the Granny Smith variety and potatoes. Prior to the dehydration process, apples and potatoes were washed, peeled, cored, cut into disks (4mm in thickness and 24mm in diameter). In addition, the samples were blanched in boiling water during a certain time, then put it fresh water to decrease their temperature, and finally drained. Pretreatment reduces vitamin and flavor loss, browning, and deterioration during storage.

In case of foods, the approach to modeling mass transfer is to use the concept of effective diffusivity (D_e) which allows to describe diffusion of moisture by the Fick's second law [9]

$$\frac{\partial W}{\partial t} = D_e \nabla^2 (W) \qquad (1)$$

where W is the moisture content in dry basis, (kg water /kg dry solid), D_e the effective diffusivity (m^2/s), and t the time.

Equation (1) can be integrated for different geometries and boundary /initial conditions. The solution of Eq. (1) for a plane sheet of thickness $2l$ is given by [14]:

$$W(t) = W_e + (W_o - W_e) \cdot \sum_{n=0}^{\infty} \frac{8}{(2n+1)^2 \cdot \pi^2} \cdot \exp\left(\frac{-D_e \cdot (2n+1)^2 \pi^2 t}{4l^2} \right) \qquad (2)$$

where the subscripts indicate equilibrium (e) and initial conditions (o).

Drying kinetics were modeled by using Eq. (2), the parameter D_e was calculated by using a nonlinear regression method.

Dehydration curves and effective water diffusivity in apples and potatoes were calculated from Eq. (2).

Results and Discussion

Apple and potato samples were daily prepared depending on the number of trials to be done in order to minimize the dispersion of initial values. To that purpose maximum dispersion in samples of about 2g was ±0.025g.

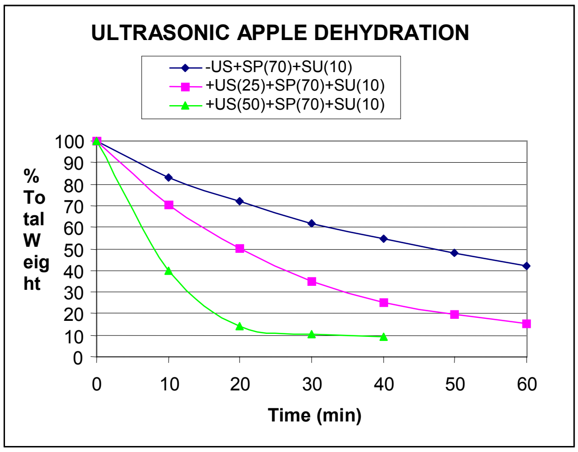

Figure 5. Apple forced-air dehydration curves with (+US) and without (-US) ultrasound.

Moisture was measured by weight in disk samples at different times (0,10,20,30,40,50 and 60min) in experiments with (+US) and without (-US) ultrasound. Figure 5 shows the results obtained with ultrasound in combination with forced-air (flow velocity = 1m/s at 31ºC). The effect of increasing ultrasonic energy is clearly appreciated and it is more significant when the moisture is lost rapidly (i.e.. the first 10-20min), and diminishes as the drying curves start to power off.

By means of the proposed diffusional model, the effective water diffusivity coefficient was identified for the experiments carried out at the operational conditions. Identified D_e in these experiments ranged in apples from $2{,}93 \times 10^{-08} m^2/s$ (-US+70g+10mbar) to $8{,}84 \times 10^{-07} m^2/s$ (+US(50W)+220g+20mbar); and in potatoes up to $1{,}37 \times 10^{-07} m^2/s$ (+US(50W)+220g+20mbar). Taking into account the diameter of the transducer one applied force of 70-220g produces a static pressure on the sample of 0.0155-0.050kg/cm^2.

In Figure 6 a good agreement between experimental and calculated values by using Eq. (2) can be observed. Therefore the experimental results are well predicted by the diffusional model.

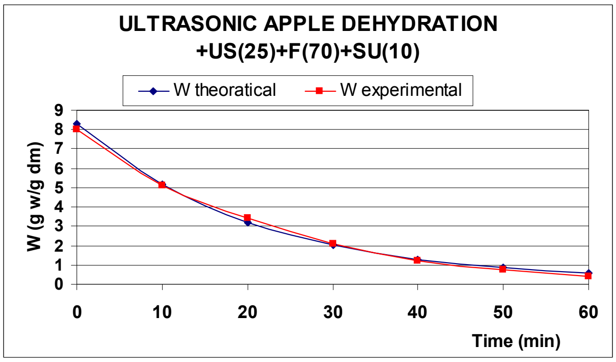

Figure 6. Estimated and experimental moisture vs process time

Conclusions

From this investigation it can be concluded that high-intensity ultrasonic vibrations affect mass transport during dehydration increasing the water losses. Ultrasonic dehydration uses lower temperatures than conventional forced-air drying methods to obtain higher water loss while preserving color, texture and structure.

Mass transfer in apple and potato samples was modeled by the diffusion equation (Fick's second law), for which a good agreement with the experimental data was obtained.

The transition from wet to dry state was detected in potato samples by using a non-contact ultrasonic technique. It seems to correspond with the presence of a sharp decrease in the velocity value of the ultrasonic waves. Such promising result supports the need to further experimental research.

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