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Convective drying of lemon peel assisted by power ultrasound: influence of ultrasonic power applied

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Abstract: The effects associated to the introduction of acoustic energy into a medium may influence food drying processes due to the reduction of mass transfer resistance. In particular, power ultrasound may be useful for drying heat sensitive materials since it permits drying to be increased without significantly heating the material. The main aim of this work was to determine the influence of power ultrasound on lemon peel drying, by evaluating the effect of the ultrasonic power applied. Lemon peel, a by-product of lemon processing, is a source of valuable heat sensitive products.

An aluminium vibrating cylinder, which is able to create a high intensity ultrasonic field in the gas medium, was used as drying chamber. The cylinder is driven at its centre by a power ultrasonic vibrator at 21.7 kHz. Convective drying kinetics of lemon peel slabs (thickness 7± 1 mm) were carried out at 40 ºC and 1 m/s. Experiments were performed without ultrasound application (AIR) and also by applying different ultrasonic power levels: 10, 20, 30, 40, 50, 60, 70, 80 and 90 W. A diffusion model considering external resistance to mass transfer was used to model drying kinetics.

Results showed that drying kinetics of lemon peel were affected by the application of power ultrasound. Drying rate increased as the ultrasonic power applied got higher. From the modelling, a linear relationship was found between effective diffusivity (D_e, m^2/s) or mass transfer coefficient (k, kg $w/m^2/s$) and the ultrasonic power applied (W). Therefore, power ultrasound increased both external and internal resistance to mass transfer, the improvement being proportional to the ultrasonic power applied.

Key words: Drying, lemon peel, modelling, power ultrasound

A. Introduction

Convective drying constitutes a traditional preserving method for foodstuffs. Despite the fact that it is a process which has been thoroughly addressed, it still presents some limitations, which may be considered as challenges to any improvement of the process. Among other things, the low process rate, especially during the falling rate period, and the quality loss of the product may be considered as particular problems [1].

Using additional energy sources during drying constitutes an adequate way to overcome those limitations [2]. As regards other technologies, such as microwave, infrared radiation and radio frequency, power ultrasounds are considered a sound alternative since they may affect drying rate without significantly heating the material. This fact may contribute to their application in the drying of heat sensitive materials [3] or in drying processes carried out at low temperatures.

A series of effects associated to power ultrasound application may improve the mass transfer rate that takes place during convective drying [3]. On one hand, the external resistance to mass transfer may be affected by pressure variations, oscillating velocities and microstreaming at the solid-gas interfaces thus reducing the boundary layer thickness and therefore improving water transfer from solid surface to air medium. On the other hand, internal resistance may be reduced by alternating expansion and compression cycles produced by ultrasound in the material (a phenomenon known as the “sponge effect”) and also through some effects on the interfaces of intercellular spaces, or even by cavitation which may contribute to removing the strongest attached moisture from the solid matrix.

Power ultrasounds have been applied to affect mass transfer processes in food treatments in liquid systems, like meat [4] and cheese brining [5], osmotic dehydration of fruits [6] and several extraction processes [7]. Nevertheless, applications in food-air systems, like convective drying, are much less frequent due to some technical difficulties [3], which prevent this technology from being fully developed. Among other things, the high impedance mismatch between the application systems and air, which makes the acoustic wave transmission difficult, and the high acoustic energy absorption of the air, must be considered.

Power ultrasound assisted drying has been reported using direct contact between vibrating elements and food particles [8]. The direct contact system permits the improvement of the acoustic energy transfer from the vibrating element to the food, providing a higher drying rate than samples dried using hot air only. Nevertheless, adapting their to conventional convective driers constitutes the main limitation of these transducers.

The design of an air-borne power ultrasound transducer which would achieve an adequate ultrasonic energy transfer to the material being dried has been the

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subject of previous research [9]. Furthermore, addressing the influence of the main processing variables constitutes a basis of relevant research.

From the literature, the influence of acoustic intensity on mass transfer rate in food-liquid treatments has been shown [4], [6]. However, this topic has been scarcely addressed in literature for acoustic drying processes [9].

The main aim of this work was to address the influence of the ultrasonic power applied on the convective drying kinetics assisted by power ultrasound of lemon peel. To this end, modelling is not only a useful tool to extract information about the mass transfer process, but it may also be useful for drier design [10].

B. Materials and Methods

B.1. Raw material

Fresh lemons (*Citrus limon* v. Fino) were picked in Javea (Alicante, Spain) in an advanced stage of ripeness. The average dimensions of the lemons were: major diameter 74.6±4.4 mm and major length 90.1±6.8 mm, while the average weight was 220.7±22.2 g.

The peel reached 41±1 % of the total weight of the lemon, the albedo being 42.3±3.2 % and the flavedo 57.7±3.2 % of total peel weight. The lemon peel was separated from the pulp by hand. Lemon peel samples were cut into slabs (thickness, L=7±1 mm), sealed and stored at 4 ºC until processing. Moisture content of fresh lemon peel was determined according to AOAC method nº 20.013 [11]. The determination was carried out at 70 ºC and 800 mbar vacuum level until constant weight.

B.2. Drying experiments

The power ultrasound assisted drier used has already been described in a previous work [9]. It involves a pilot scale convective drier modified to apply power ultrasound. The conventional drying chamber was replaced by an aluminum vibrating cylinder (internal diameter 100 mm, height 310 mm and thickness 10 mm) driven by a piezoelectric composite transducer (21.7 kHz) generating a high-intensity ultrasonic field inside the cylinder. A scheme of the ultrasonic system is shown in Fig.1. An impedance matching unit permits the impedance output of the generator to be fitted to the transducer providing a better electric yield of the system. The most important electric parameters of the acoustic signal (voltage, intensity, frequency, power and phase) were measured using a digital power meter (WT210, Yokogawa, Japan) and logged using an application developed on LabVIEW™ (National Instruments).

Drying experiments were carried out at 40 ºC and 1 m/s according to previous results. Both variables were controlled using a PID algorithm from an application programmed on Visual Basic. Drying tests were carried out without ultrasound application (AIR) and also at several acoustic power levels, which were set varying the electric power supplied to the transducer: 10, 20, 30, 40, 50, 60, 70, 80 and 90 W. An initial mass load density of 36 kg/m^3 was used in the experiments. At least three drying experiments were carried out for each one of the different experimental conditions tested.

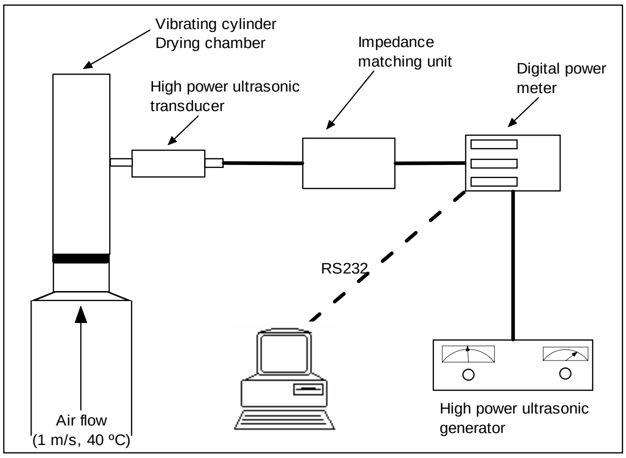

Fig.1. Scheme of the ultrasonic system.

The sealed samples were warmed for 15 min until the drying temperature was reached prior to be unwrapped and placed in the drying chamber. Sample weight was automatically measured and recorded at regular time intervals (10 min).

B.3. Mathematical modelling

The diffusion theory is widely used to model convective drying kinetics [10], [11]. The equation describing the moisture transfer for a slab geometry and considering effective moisture diffusivity (D_e, m^2/s) as constant and material as isotropic and homogeneous is shown in Eq. (1).

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

Where W_p is the local moisture content in dry basis (d.b., kg water/kg dry matter), x is the characteristic transport direction and t is the time (s).

In order to solve Eq. (1) initial (Eq. (2)) and boundary conditions, Eq. (3) and Eq. (4), are needed. According to previous results [10], [11], for the air velocity figure used in these experiments, 1 m/s, external resistance to mass transfer is significant and therefore it must be considered in boundary conditions Eq. (4).

$$W_p(x,0) = W_o \tag{2}$$

$$\frac{\partial W_p(x,t)}{\partial x} = 0 \tag{3}$$

$$-D_e \rho_{ds} \frac{\partial W_p(L,t)}{\partial x} = k\left(\varphi_e(L,t) - \varphi_{air}\right) \tag{4}$$

Where W_o is the initial moisture content (d.b.), ρ_{ds} is the dry solid density (kg/m^3), k is the mass transfer coefficient (kg water/m^2/s) which determines the water transfer from the solid surface to the air medium, φ_e is the air relative humidity of the air at equilibrium with the surface of the material (points characterized by x coordinate equal to L) and φ_{air} is the relative humidity of the hot air.

A numerical solving method (implicit difference method [10]) was used to solve Eq. (1) according to the

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initial and boundary conditions previously stated. Eq (5) shows the general relationship of the local moisture content for a node, $W_p(i,t)$, which is a function of the moisture content at the neighbour nodes, $W_p(i+1,t)$ and $W_p(i-1,t)$, and at the same node at a previous time, $W_p(i,t-\Delta t)$. The particular expression at each kind of node must be obtained by adequately combining the boundary conditions.

$$W_p\left(i,t\text{-}\Delta t\right)=\frac{D_e\Delta t}{\Delta x^2}\left[\begin{array}{l} W_p\left(i,t\right)\left(\left(\dfrac{\Delta x^2}{D_e\Delta t}\right)+2\right)- \\ -W_p\left(i+1,t\right)-W_p\left(i\text{-}1,t\right)\end{array}\right] \quad (5)$$

Where Δx determines the distance between nodes (m) and Δt is the time interval considered (s).

Several functions were programmed on Matlab to solve the set of implicit equations. They provided both the local moisture distribution inside the slab geometry body and the average moisture content of the solid (W, d.b.), as a function of drying time, effective moisture diffusivity and mass transfer coefficient.

The SIMPLEX optimization method available in MATLAB (fminsearch function) was used to identify jointly the effective moisture diffusivity and the mass transfer coefficient from experimental data. The objective function chosen was the squared differences between the experimental and the calculated average moisture content.

In order to evaluate how accurately the model fit the experimental data, the percentages of explained variance (VAR) and mean relative error (MRE) were computed.

C. Results and Discussion

C.1. Experimental resuls

Drying kinetics of lemon peel slabs determined by applying different ultrasonic powers are plotted in Fig. 2. The drying rate in experiments carried out without ultrasound application (AIR) was lower than in sonicated experiments, although the differences depended on the level of ultrasonic power applied (Fig. 2).

The higher ultrasonic power applied, the higher the drying rate. The drying rate needed to reach a moisture content close to 1.5 (d.b.) was reduced by 53 % when the ultrasonic power applied increased from 10 W to 90 W.

Garcia-Pérez et al. [9] carried out similar experiments with carrot using the same experimental set-up. From those results, a minimum power ultrasonic threshold of about 25 W, from which the effects of ultrasounds were observed, was established. However, no ultrasonic power threshold was found in this work, and as a consequence the influence on the drying kinetics was observed even at the lowest level of ultrasonic power tested (10 W).

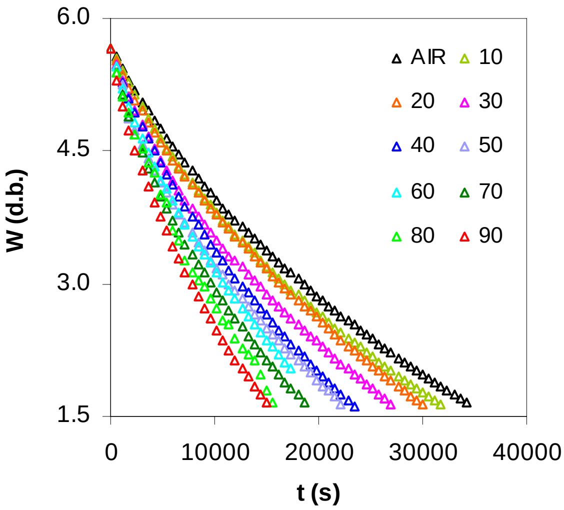

Fig.2. Drying kinetics of lemon peel slabs (L= 7 mm) without ultrasound application (AIR) and applying different ultrasonic powers (W), 40 ºC and 1 m/s.

The different behaviour observed between lemon peel and carrot may be explained by considering the different structure of these products. Lemon peel is considered a more highly porous product than carrot [12] and, as consequence, more acoustic energy may be absorbed by the material which, in turn, leads to more intense effects being found at the same level of applied acoustic intensity. Furthermore, due to fact that the resistance to water movement is considered to be lower in high porosity products, less acoustic energy is needed to affect this process [11]. Nevertheless, a more rigorous experimentation would be necessary to confirm it.

Modelling would be considered a useful tool to quantify the observed influence of the ultrasonic power on the experimental drying kinetics of lemon peel [10].

C.2. Modelling

Drying kinetics of lemon peel were modelled using a diffusion model for a slab geometry (L=7 mm) and considering the external resistance to mass transfer. The effective moisture diffusivity values (Table 1) are close to others found for this product in literature [11], as are the mass transfer coefficient figures (Table 1), which are similar to those reported in convective drying processes controlled by external resistance [10].

Table 1. Modelling of drying kinetics of lemon peel slabs. Subscripts (a,b,c,d,e,f) and (w,x,y,z) show homogeneous groups established from LSD intervals ($p<0.05$).

P (W)	$\mathbf{D_e}$ (10^{-10} m^2/s)	**k** (10^{-4} kg w/m^2/s)	**VAR** (%)	**MRE** (%)
0 (AIR)	$6.39\pm0.23_a$	$18.50\pm1.34_w$	99.8	1.5
10	$7.54\pm0.58_{ab}$	$18.97\pm0.91_w$	99.8	1.6
20	$7.70\pm0.58_{ab}$	$20.43\pm3.25_w$	99.7	1.9
30	$9.14\pm0.45_{bc}$	$24.40\pm7.50_y$	99.5	1.9
40	$10.33\pm0.35_{cd}$	$24.73\pm0.93_{wx}$	99.8	1.7
50	$10.93\pm0.88_{cd}$	$29.93\pm0.42_{xy}$	99.8	1.4
60	$11.89\pm0.92_{de}$	$34.67\pm2.83_{yz}$	99.7	1.7
70	$11.65\pm0.37_{ef}$	$39.13\pm0.78_y$	99.7	1.7
80	$13.05\pm0.67_f$	$37.10\pm1.77_{yz}$	99.8	1.4
90	$14.25\pm0.43_f$	$42.70\pm1.61_z$	99.8	1.5

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The diffusion model considered was very useful to describe the drying kinetics under the different experimental conditions tested. The percentages of explained variance (VAR) reached were, in all cases, higher than 99 %, while the percentages of mean relative error (MRE) were lower than 2 %. Both statistical parameters indicate a close fit with the diffusion model of experimental data [10].

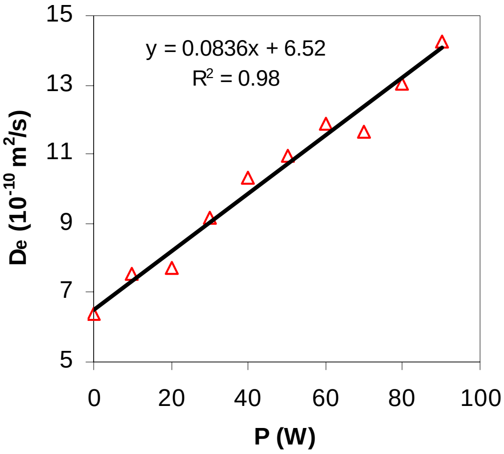

Fig.3. Influence of ultrasonic power on effective moisture diffusivity.

Ultrasonic power showed a significant ($p<0.05$) influence on both effective moisture diffusivity (Fig.3) and mass transfer coefficient (Fig.4). Both parameters increased as the ultrasonic power applied got higher. A linear relationship was established for both parameters (D_e and k) and the ultrasonic power applied (Fig.3 and Fig.4).

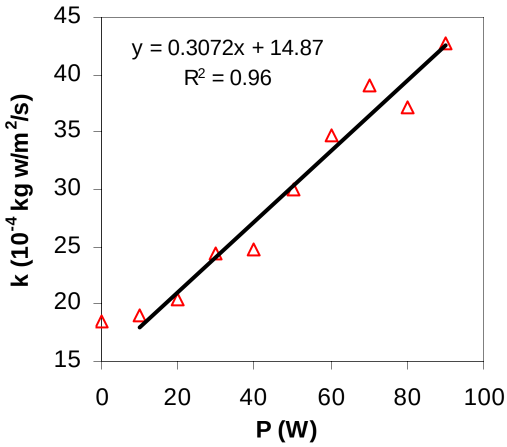

Fig.4. Influence of power ultrasonic on mass transfer coefficient.

As was previously stated, a series of phenomena associated to acoustic energy may be responsible for the influence of power ultrasound application on external and internal resistance to mass transfer [3]. Both effective moisture diffusivity and mass transfer coefficient increased in line with the level of power applied, and this leads to more intense effects of ultrasound on both internal and external resistance to mass transfer.

D. Conclusion

From the experimental results, a significant influence of power ultrasound application was observed on the convective drying of lemon peel. A linear relationship was identified to describe the influence of the ultrasonic power level on effective moisture diffusivity and mass transfer coefficient, and was valid in all the experimental range tested (0-90 W). Therefore, it can be stated that the higher ultrasonic power applied, the higher the influence of power ultrasound on external and internal resistance to mass transfer.

E. Acknowledgements

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