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INFLUENCE OF PROCESS VARIABLES ON HOT AIR DRYING ASSISTED BY POWER ULTRASOUND

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ABSTRACT

Power ultrasound application on convective drying of foodstuffs may be considered an emergent technology. Acoustic energy may improve drying rate without significantly heating the material due to phenomena affecting mass transfer resistances. As a consequence, ultrasound application on the drying of heat sensitive materials or in process carried out at low temperatures is quite interesting.

The aim of this work was to address the influence of the main processing variables on the convective drying assisted by power ultrasound (21.7 kHz) of different foodstuffs. The influence of air velocity and temperature, raw material characteristics, mass load density and ultrasonic power applied was addressed.

From the experimental results, a significant influence of the application of power ultrasound on both external and internal resistance to mass transfer has been found. Nevertheless, the ultrasonic effects depended strongly on the experimental conditions used. In the case of carrot drying at different temperatures, the application of power ultrasound increased the effective moisture diffusivity by 55 % at experiments carried out at 30 ºC, however the improvement was non significant at experiments conducted at 70 ºC.

INTRODUCTION

Convective drying constitutes a traditional dehydration method. Although it has been widely studied, it still present some limitations which difficult its application in some specific fields [1]. Among other things, the drying rate is low mainly during the falling rate period or in processes carried out at low temperatures. Drying process may be improved by application of complementary energy sources to hot air. In comparison to other technologies, like microwave or infrared radiation, power ultrasound does not significantly heat the product, thus avoiding quality loss during drying [2]. As a consequence, ultrasound present a high potential use to dry heat sensitive materials or to be applied in drying process carried out at low temperatures, like atmospheric freeze drying.

A series of effects associated to acoustic energy are responsible for increasing drying rate [2]. Power ultrasound introduces pressure variations at interfaces gas/solid and causes oscillating velocities and microstreaming which may affect the diffusion boundary layer characteristics. Furthermore, ultrasonic waves also produce rapid series of alternative contractions and expansions (sponge effect) of the material in which they are travelling; which may make the moisture removal easier.

Ultrasonic applications on gas-solid systems, like convective drying, are quite difficult [3] due to the high impedance mismatch between ultrasound generating systems and air and also the high energy absorption of this medium. In literature, ultrasonic systems with direct contact between the vibrating element and the material being dried have been shown [2]. Despite their high efficiency, the adaptability to traditional convective driers is quite difficult. The development of a new and efficient ultrasonic technology has already been the matter of previous research [4].

The aim of this work was to show the influence of the main variables involved on convective drying assisted by power ultrasound. The variables considered were air velocity and temperature, raw material characteristics, mass load density and ultrasonic power applied. Modelling was considered as a useful tool to quantify the influence of power ultrasound [5-6].

MATERIALS AND METHODS

Convective drier assisted by power ultrasound

The ultrasound assisted drier has already been described in a previous work [4], a scheme of the ultrasonic system is shown in Figure 1. The system was assembled from a conventional hot air drier. The main modification of the system fell on the drying chamber (Figure 1). The new drying chamber not only acts as the container for placing the samples, furthermore constitutes the vibrating element transferring the acoustic energy to air. For that purpose, an aluminium vibrating cylinder (internal diameter 100 mm, height 310 mm and thickness 10 mm) driven by a piezoelectric transducer (21.7 kHz) constitutes the drying chamber. The ultrasonic driving transducer consists of an extensional piezoelectric sandwich element together with a mechanical amplifier.

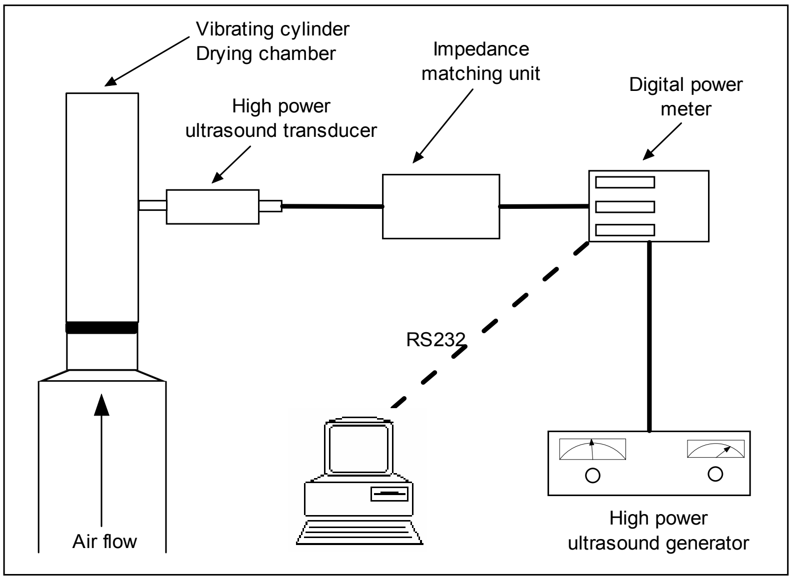

Figure 1.- Scheme of the ultrasonic drying system.

An impedance matching unit permits to optimize the electric energy transfer from the power ultrasonic generator to transducer. The main parameters of the signal at working conditions were measured using a digital power meter (WT210, Yokogawa, Japan), when applying an electric power of about 90 W to the transducer, the values displayed were frequency 21.7 kHz, voltage 60 V, phase 4° and intensity 1.55 A. In order to detect an erratic behaviour of the ultrasonic system, an application was developed using LabVIEW^{TM} (National Instruments) to record with a PC the parameters measured by the digital power meter during the experiments.

The acoustic field inside the drying chamber was measured using a microphone (1/8”, sensibility 1.06 mV/Pa, GRAS, Denmark). An average sound pressure level around 154.3 dB was measured in the cylinder for an electrical power applied to the transducer of 75 W and without air flow.

Sample weight was logged at preset times using a balance. Two independent pneumatic systems controlled by a PLC (CQM41, OMRON, Japan) allowed to carry out the measurement automatically. The air temperature and velocity were controlled using a PID algorithm; the PC also supervised the whole process. Air room conditions, relative humidity (%) and temperature (ºC), were also logged.

Drying experiments

Drying experiments with (US, 21.7 kHz, 75 W) and without (AIR) ultrasound application were carried out at several conditions to address the influence of the different variables involved.

1. Drying experiments at air velocities between 0.5 and 12 m/s, constant temperature and mass load density, using carrot (cubes, side 8.5 mm), lemon peel (slabs, thickness 10 mm) and persimmon (cylinders, radius 6.5 mm and height 30 mm).
2. Drying experiments at air temperatures between 30-70 ºC, constant air velocity and mass load density, using carrots (cubes, side 8.5 mm).
3. Drying experiments at mass load densities between 12-120 kg/m^3, constant air temperature and velocity, using carrot (cubes, side 8.5 mm)
4. US (21.7 kHz) experiments applying different electric powers to the transducer between 0-90 W, constant air temperature, velocity and mass load density, using lemon peel (slabs, thickness 7 mm).

Drying kinetics modelling

Different diffusion models were used, according to the geometry involved, to describe the drying kinetics at different experimental conditions. Models considering external resistance to mass transfer (ER models) on boundary condition, or not considering it (NER models) were developed [7]. ER models were solved using the implicit finite difference method from an application programmed in Matlab.

The parameters of the models were identified from optimization procedures, GRG for NER models and Simplex for ER models. The objective function chosen in both cases was the squared difference between experimental and calculated average moisture contents. The analysis of parameters identified, effective moisture diffusivity (D_e, m^2/s) for NER models and D_e and mass transfer coefficient (k, kg water/m^2/s) for ER models, contributes to assess the influence of power ultrasound on external and internal resistance to mass transfer.

RESULTS AND DISCUSSION

Influence of air velocity and material structure

The air velocity has been found as one of the most important variables involved on drying assisted by power ultrasound [8, 9]. Figure 2 shows D_e figures identified for AIR and US experiments carried out with carrot cubes. The values identified on US experiments were only higher than those found on AIR experiments at low air velocities. For air velocities higher than 4 m/s, a significant influence of ultrasound application was not observed. This behaviour may be explained by the disruption of acoustic field at high air velocities. From experimental results, a reduction of sound pressure level in the drying chamber was found by increasing air velocity [4, 8]. As a consequence, the energy available for the samples at high air velocities was not enough to affect the mass transfer process in carrot drying.

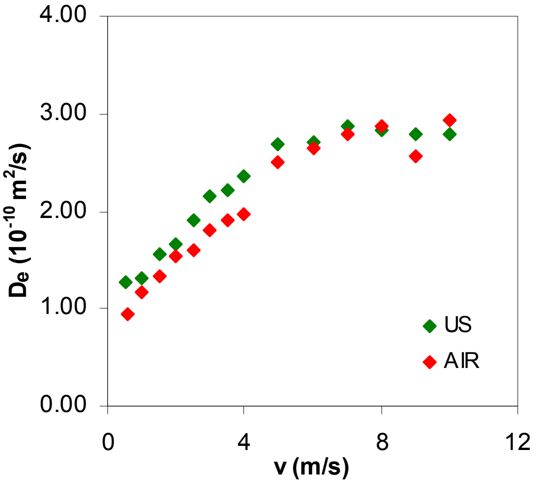

Figure 2.- Effective moisture diffusivities, NER model, on US (75 W, 21.7 kHz) and AIR drying of carrot cubes at 40 ºC and different air velocities (v, m/s).

The influence of power ultrasound on lemon peel drying was quite different to those found on carrot. Despite the acoustic energy reduction by air flow, the drying rate was also increased by ultrasound application at high air velocities. The improvement on effective moisture diffusivity was also more important for lemon peel, the application of power ultrasound increased by 63 % the D_e value found at AIR experiments carried out at 1 m/s. The different behaviour observed between carrot and lemon peel may be explained from the structure of these products [9], being lemon peel a higher porosity product than carrot. Expansions and contractions (sponge effect) produced by ultrasound may be more intense on high porosity products due to its low mechanical resistance; also the effects on interfaces would be more intense by the large porous volume. Furthermore, a larger absorption of acoustic energy would be expected on high porosity products, thus increasing the energy available in the particle to affect mass transfer processes.

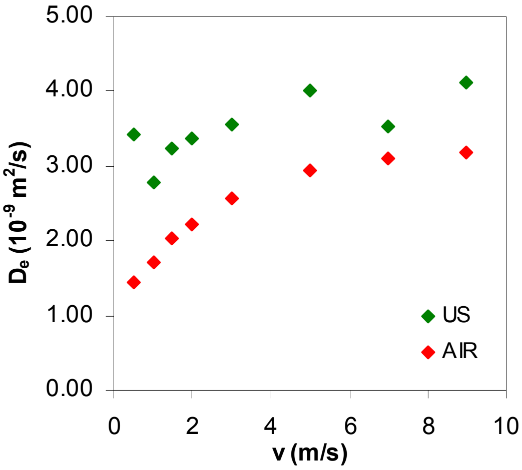

Figure 3. Effective moisture diffusivities, NER model, on US (75 W, 21.7 kHz) and AIR drying of lemon peel slabs at 40 ºC and different air velocities (v, m/s).

At low air velocities, the NER diffusion models did not fit adequately the drying kinetics since at these experimental conditions external resistance was not negligible. As a consequence, the ER models were used to describe the drying kinetics at low air velocities. Table I shows the effective moisture diffusivity and mass transfer coefficient identified on drying experiments of persimmon at low air velocities. The ER model provided percentages of explained variance (VAR) and mean relative error (EMR) higher than 99 % and lower than 10 %, respectively. Both statistical parameters indicated that drying kinetics were well fitted. The application of power ultrasound increased significantly ($p<0.05$) the effective moisture diffusivity (D_e) and the mass transfer coefficient (k), which means that power ultrasound contributes to reduce external and internal resistance to mass transfer.

Table I.- Drying modelling of US (75 W, 21.7 kHz) and AIR experiments, ER model, of persimmon cylinders carried out at different air velocities (v) and 50 ºC.

v (m/s)	AIR				US			
	D_e (10^{-10} m^2/s)	k (10^{-3} kg water/m^2/s)	VAR (%)	MRE (%)	D_e (10^{-10} m^2/s)	k (10^{-3} kg water/m^2/s)	VAR (%)	MRE (%)
0.5	5.25	0.54	99.6	7.5	6.75	0.61	99.8	2.9
1	5.70	0.58	99.5	5.0	6.93	0.78	99.9	1.3
2	5.49	0.96	99.9	1.5	6.67	1.09	99.9	1.7
4	6.02	1.45	99.9	1.2	6.09	1.59	99.8	4.2

Influence of air temperature

A different influence of ultrasound on carrot drying was observed depending on the temperature used in experiments carried out at 1 m/s [10]. Table II shows the effective moisture diffusivity and mass transfer coefficient figures identified with the ER model. The application of power ultrasound increased significantly ($p<0.05$) the effective moisture diffusivity at temperatures lower than 60 ºC. Thus, D_e values identified at 30 ºC in AIR experiments were increased by 55 % due to ultrasound application (US experiments). The influence of power ultrasound on D_e decreased at 60 ºC and it was almost negligible at 70 ºC. These experiments also showed the influence of power ultrasound on external resistance to mass transfer when low air velocities were used, mass transfer coefficient values were significantly ($p<0.05$) higher in US than AIR experiments in the range tested.

Table II.- Drying modelling of US (75 W, 21.7 kHz) and AIR experiments, ER model, of carrot cubes carried out at different air temperatures (ºC) and 1 m/s.

T	**AIR**				**US**			
(ºC)	**D_e** (10^{-10} m^2/s)	**k** (10^{-4} kg water/m^2/s)	**VAR** (%)	**MRE** (%)	**D_e** (10^{-10} m^2/s)	**k** (10^{-4} kg water/m^2/s)	**VAR** (%)	**MRE** (%)
30	1.38	2.87	99.9	1.1	2.14	3.06	99.9	1.8
40	1.93	4.13	99.9	0.9	2.71	5.86	99.9	1.4
50	2.87	6.17	99.9	1.4	3.91	8.80	99.9	1.3
60	3.83	6.77	99.9	1.5	4.69	9.07	99.9	2.5
70	4.57	8.83	99.9	2.1	4.88	9.40	99.9	1.6

Influence of mass load density

The experiments carried out varying the mass load introduced in the drying chamber provided interesting results about the influence of power ultrasound [11]. The application of power ultrasound increased the mass transfer coefficient (Figure 4) in the experimental range tested (12-120 kg/m^3), although the differences were not significant for mass load densities higher than 90 kg/m^3. This may be explained by the reduction of the amount of energy available per mass unit at high mass load densities. No influence of mass load density was found on effective moisture diffusivity. Nevertheless, the average of this parameter was higher for US experiments (2.88×10^{-10} m^2/s) than for AIR experiments (2.06×10^{-10} m^2/s) (Figure 4).

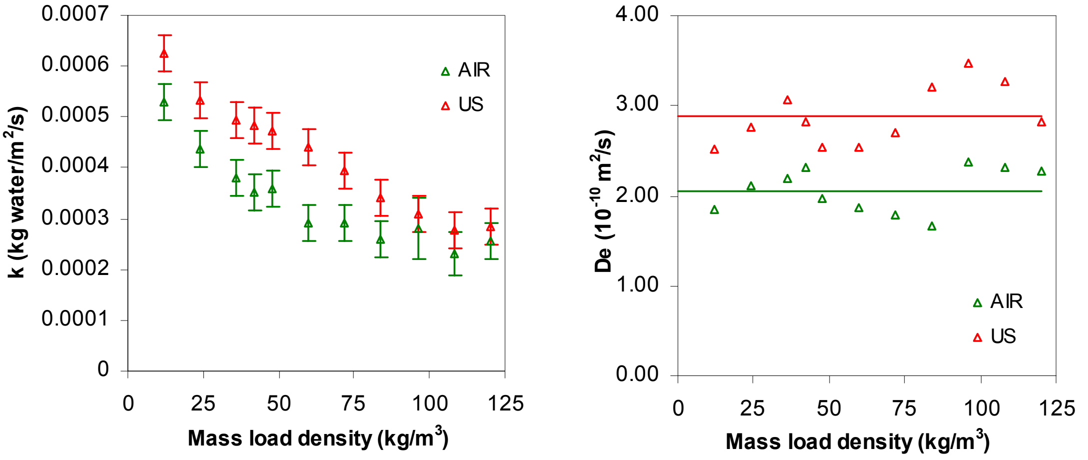

Figure 4.- Mass transfer coefficient (k) and effective moisture diffusivity (D_e), ER model, on US (75 W, 21.7 kHz) and AIR drying of carrot cubes at 40 ºC and 1 m/s.

Influence of ultrasonic power applied

A significant influence of the ultrasonic power level applied was found on drying experiments of lemon peel slabs (Figure 5) [12]. The increase of drying rate was proportional to the ultrasonic power applied, as a consequence the drying time needed to reach a moisture content of about 1.5 (kg water/kg dry matter) was reduced by 53 % when the ultrasonic power applied increased from 10 to 90 W. Two linear correlations were identified to describe the relationship between the effective moisture diffusivity or the mass transfer coefficient and the ultrasonic power applied, which were valid for all the range tested.

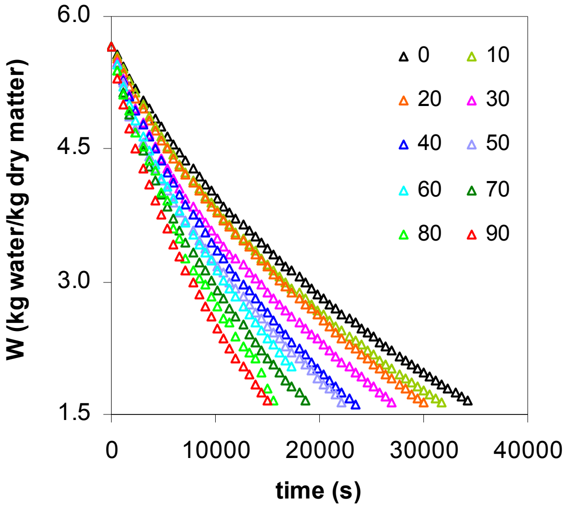

Figure 5.- AIR and US (75 W, 21.7 kHz) drying kinetics of lemon peel at different ultrasonic power applied (W) and 40 and 1 m/s.

CONCLUSIONS

A significant influence of power ultrasound on food drying rate has been found in this work, although, it depended on the magnitude of some variables. Ultrasonic energy available in the medium decreased as air velocity got higher, ultrasonic effects were only found for low porosity products at low air velocities. An influence of ultrasounds was found even at high velocities for high porosity products. A significant influence of power ultrasound on external and internal resistance to mass transfer was observed for air temperatures lower than 60 ºC, being the effect non significant at high temperatures (60-70 ºC). Drying rate increased by ultrasound application in a wide mass load density range (12-120 kg/m^3). The effects of power ultrasound on drying rate were proportional to the power ultrasound applied.

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