IMPROVEMENT OF WATER TRANSPORT MECHANISMS DURING POTATO DRYING BY ULTRASONIC APPLICATION

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ABSTRACT

Drying rate of vegetables is limited by the internal moisture diffusion and convective transport mechanisms. The increase of drying air temperature leads to faster water mobility; however it provokes quality loss in the product and presents a higher energy demand. Therefore, the search of new strategies to improve water mobility during convective drying constitutes a topic of relevant research. The aim of this work was to evaluate the use of power ultrasound to improve convective drying of potato and quantify the influence of the applied power.

Drying kinetics (40 ºC and 1 m s^{-1}) of potato cubes (side 8.7 mm) were carried out applying different ultrasonic power levels: 0, 6, 12, 18, 25, 30 y 37 kW m^{-3}. A diffusion model considering internal and external resistance to mass transfer was used to quantify the effects.

Drying kinetics of potato cubes were sped up by the ultrasonic application. The influence of power ultrasound was dependent on the ultrasonic power, the higher the applied power, the faster the drying kinetic. The proposed diffusion model allowed a good fit of drying kinetics. From modeling, it was observed a proportional and significant ($p<0.05$) influence the applied ultrasonic on the identified kinetic parameters, effective diffusivity and mass transfer coefficient.

Key-words: dehydration, energy efficiency, modeling, diffusion

INTRODUCTION

Nowadays, global consumption is shifting from fresh to value-added processed products. [1] In this context, the dehydration process constitutes an alternative for producing novelty products of high quality at a competitive cost; furthermore, it provides longer shelf-life, lighter weight for transportation and smaller space for storage. [2] However, drying process can affect sensory and nutritional attributes due to textural and biochemical changes that occur mainly by the high temperatures applied in the process [3] and the long drying times.

Drying is a complex process, involving simultaneously coupled heat and mass transfer phenomena [4] with on external and internal transport. [5] Actually during drying of vegetables, drying rate may be affected by both diffusion and convective water transports. [6] Drying rate could be sped up by adequately combining other energy sources, such as, microwave, infrared radiation, radio frequency and power ultrasound. [7] In comparison to those technologies, ultrasound assisted convective drying represents an interesting way to improve dehydration rate due to a low heating effect, which limits the quality loss in the product. [8, 9]

Literature reports that the application of efficient ultrasonic energy involves the improvement of drying rate [9, 10, 11, 12] due to the mechanical effects associated to the ultrasonic wave. Ultrasound brings about the reduction of boundary layer thickness by pressure variations, oscillating velocities and microstreaming that affects the solid-gas interfaces. In addition, ultrasound may also affect internal water transfer by alternating expansions and compressions waves produced in the material ("sponge effect"). [13] This alternating stress creates microscopic channels that involves an easier moisture removal. In addition, high-intensity acoustic waves could produce cavitation in the moisture phase inside the solid matrix, which may be beneficial for the removal of the strongly attached water molecules. [14] Therefore, the ultrasonic effects could contribute to reduce the external and internal resistance to mass transfer during drying.

The application of power ultrasound in gas systems may be more difficult than in liquid medium due to both, the high impedance mismatch between the application systems and air, and the high acoustic energy absorption of this medium. [15] Ultrasound-assisted drying has been mainly addressed by using two different strategies: air-borne and direct contact applications. [13] The direct contact between samples and the vibrating element facilitates the acoustic energy transfer, resulting in a high efficiency of the ultrasound application. [9] In the last years, advances in the design and development of efficient air-borne ultrasonic transducers have allowed a better energy transfer achieving a low impedance mismatch with the air, large amplitudes of vibration, high directionality, high power capacities and large radiating areas. [10, 15, 16]

Ultrasound assisted convective drying techniques have been applied to accelerate the drying of several products including, carrot, [8,12] onion, [17] wheat and corn, [18] rice, [19] persimmon, [11] eggplant, [20] olive leaves, [21] lemon peel [12] and surimi. [22] Despite all these works showed a significant ultrasonic effect on the water transport during drying, it should be remarked that the ultrasonic application becomes more o less efficient depending on the process variables, such as, air velocity, [11, 23] temperature [24] or, applied ultrasonic power. [12] In addition, product characteristics also affect to the ultrasonic influence in drying processes. [11] Thus, high porosity products are more prone to the mechanical stress (sponge effect) produced by the ultrasonic wave due to their low mechanical resistance [12] which increases the ultrasonic effects on drying rate.

Therefore, it results very difficult to predict the efficiency of the ultrasonic application on a target product due to the effect of both the process and the product variables. The study of the ultrasonic effect on the mass transport process should be carried out when an ultrasonic application is designed for a specific product not previously addressed. For this purpose, modeling is a useful tool not only to quantify the influence of ultrasound on the drying kinetics but also to gain insight into the effect of power ultrasound into the mass transfer process and separate on external and internal mechanisms. [5, 11] Thereby, the aim of this work was to evaluate the use of air-borne power ultrasound on convective drying of potato establishing the ultrasonic influence on water transport mechanisms.

MATERIALS AND METHODS

Raw material

Drying experiments were conducted with cubic samples (side 8.7 mm) of potato (*Solanum tuberosum* var. Monalisa) purchased in a local market. Samples were obtained using a household tool, sealed in plastic films to avoid moisture loss, and stored at 4±1 ºC until processing. Initial moisture content was determined by keeping the samples at 70 ºC and 200 mmHg until constant weight according to the AOAC method Nº 934.06. [25]

Drier assisted by power ultrasound

The convective drier assisted by power ultrasound has already been described in previous works (Fig. 1). [11, 12, 20, 24] The equipment consists of a pilot scale convective drier with an aluminium cylindrical vibrating element (internal diameter 100 mm, height 310 mm and thickness 10 mm) working as an ultrasonically activated drying chamber. The cylinder is driven by a piezoelectric composite transducer (21.8 kHz), thus, the ultrasonic system is able to generate a high-intensity ultrasonic field with an average sound pressure of 154.3 dB (measured using an ultrasonic power of 31 kW m^{-3} and air stagnant conditions). In order to supervise and monitor the behavior of the ultrasonic device, some electric parameters of the electrical signal (voltage, intensity, frequency, power, and phase) were measured using a digital power meter (WT210, Yokogawa, Japan) and logged using an application developed in LabVIEW™ (National Instruments, Austin, Texas, USA). The drier operates automatically and a PC supervises the whole process; the air velocity and temperature were controlled using a PID algorithm. A balance allowed the samples to be weighed at preset times by using two pneumatic moving arms.

Drying kinetics

Drying experiments were carried out at 40 ºC and 1 m s^{-1} using an initial mass load density of 12 kg m^{-3}, these values were chosen according to previous results. [10, 11] Experiments were conducted applying seven different ultrasonic power levels (**UP**): 0, 6, 12, 19, 25, 31, 37 kW m^{-3}. For each one of the different ultrasonic powers tested, experiments were conducted at least in triplicate.

Before starting the experiments, the sealed samples were warmed for 15 min at the drying temperature. Then, the samples were unwrapped and placed on the trays of the drying chamber. Samples weight was measured every 5 minutes until 70 % loss of the initial weight.

Modeling

Drying kinetics of potato cubes were modeled according to the diffusion theory. The governing equation of the mass transfer process for a cubic geometry, considering the material as isotropic and homogeneous and constant the average effective moisture diffusivity (D_e), is shown in Eq. 1.

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

where W_p is the local moisture content (dry basis, kg W kg dry matter^{-1}), D_e is the average effective moisture diffusivity (m^2 s^{-1}), t time (s) and x, y, z represent characteristic coordinates of cubic geometry.

For modeling, it was considered as uniform the initial moisture content (Eq. 2), negligible the shrinkage during drying and the solid symmetry (Eq. 3). The external resistance to mass transfer was also considered (Eq. 4 to 6) due to previous works have pointed out a significant effect of the flow characteristics when a low figure of the air velocity is used (1 m s^{-1}). [11]

$$W_p(x,y,z,0) = 0 \qquad \text{(Eq. 2)}$$

$$\frac{\partial W_p(0,y,z,t)}{\partial x} = 0 \,; \quad \frac{\partial W_p(x,0,z,t)}{\partial y} = 0 \,; \quad \frac{\partial W_p(x,y,0,t)}{\partial z} = 0 \qquad \text{(Eq. 3)}$$

$$t > 0 \qquad x = L \qquad -D_e \rho_{ds} \frac{\partial W_p(L,y,z,t)}{\partial x} = k\left(\varphi_e(L,y,z,t) - \varphi_{air}\right) \qquad \text{(Eq. 4)}$$

$$t > 0 \qquad y = L \qquad -D_e \rho_{ds} \frac{\partial W_p(x,L,z,t)}{\partial y} = k\left(\varphi_e(x,L,z,t) - \varphi_{air}\right) \qquad \text{(Eq. 5)}$$

$$t > 0 \qquad z = L \qquad -D_e \rho_{ds} \frac{\partial W_p(x,y,L,t)}{\partial z} = k\left(\varphi_e(x,y,L,t) - \varphi_{air}\right) \qquad \text{(Eq. 6)}$$

where L represents the half length of the cubic side (m), ρ_{ds} is the dry solid density (kg dry matter m^{-3}), k the mass transfer coefficient (kg W m^{-2} s^{-1}) and φ_{air} the relative humidity of drying air.

These boundary conditions makes difficult to find an analytical solution of the model. For that reason, an implicit finite difference numerical method was used for solving the model considered. The set of implicit equations for the whole sub volume net was solved by programming a series of functions in Matlab® 7.1 SP3 (The MathWorks, Inc., Natick, MA, USA). The program provided the local moisture distribution inside the solid and the average moisture content (W) of the solid, both as functions of the drying time, the characteristic dimension (L), the effective moisture diffusivity and the mass transfer coefficient. The effective moisture diffusivity (D_e) and the mass transfer coefficient (k) were simultaneously identified by fitting the model to the experimental data using the SIMPLEX method (*fminsearch function*). The objective function (OF) to be minimized was the sum of the squared differences between the experimental and the calculated average moisture content (Eq. 7).

$$OF = \sum_{i=1}^{N} \left(W_{ei} - W_{ci} \right)^2 \qquad \text{(Eq. 7)}$$

Where W_{ei} and W_{ci} are the experimental and calculated average moisture content.

The explained variance (Eq. 8) and the mean relative error (Eq. 9) were computed to determine the fitting ability of the model to the experimental data.

$$VAR = \left[1 - \frac{S_{tW}^2}{S_W^2} \right] \cdot 100 \qquad \text{(Eq. 8)}$$

$$MRE = \frac{100}{N} \left[\sum_{i=1}^{N} \frac{\left| W_{ei} - W_{ci} \right|}{W_{ei}} \right] \qquad \text{(Eq. 6)} \qquad \text{(Eq. 9)}$$

Where S^2_w and S^2_{tw} are the variance of the sample and the estimation respectively and N the number of experimental data.

The analysis of variance (ANOVA) and the Least Significant Difference intervals (LSD) were calculated to evaluate the significance ($p<0.05$) of the differences between the identified kinetic parameters. The statistical analysis was carried using Statgraphics Plus 5.1 software package (Statistical Graphics Corp., Herdorn, Virginia, USA).

RESULTS AND DISCUSSION

Experimental drying data

Experimental drying kinetics of potato cubes are plotted in Fig. 2. The average initial moisture content of potato was 4.59±0.14 (dry basis); this value was considered as the critical moisture content due to only the falling rate period was found at these experimental conditions, which is the usual behavior for agro-food products. [27]

The effect of power ultrasound on experimental drying kinetics can be observed in Fig. 2. The drying kinetics were sped up by the ultrasonic application, increasing the ultrasonic effects with the applied ultrasonic power. Thus, the experiments carried out at the highest ultrasonic power tested (37 kW m^{-3}) reduced the drying time by approximately 40 % in comparison to experiments without ultrasound application (0 kW m^{-3}).

Because the efficiency of the ultrasonic application is very dependent on the characteristics of the vibrating element which transfers the acoustic waves to the air medium, it results complicated to compare the effects brought about by different ultrasonic devices. Thus, Gallego-Juárez et al. [15] using a **direct contact** technique with stepped plate transducers (21 kHz, 100 W and 55 ºC) found an approximated time reduction of 58.3 % for carrot, 300 % for apple and 62.5 % for mushroom slices. Nakagawa et al. [22] working on surimi slabs drying observed an increase of drying rate from 600 % (155.5 dB, 19.5 kHz, 30 ºC) to 250 % (155 dB, 19.5 kHz, 50 ºC). These authors used vibrating plates activated by an exponential horn. In the case of **air-borne applications**, García-Pérez et al., [12] found drying time reductions of 32 % in carrot cubes and 53 % in lemon peel slabs, Cárcel et al., [11] 40 % in persimmon cylinders, and Ortuño et al., [20, 26] 72 % in eggplant cylinders and 49 % in orange peel slabs. It is observed that the effects of the ultrasonic application are dependent on the material being dried. In this sense, potato and carrot may be considered a less sensitive material to be affected by the ultrasonic application than eggplant. [12]

Regarding the use of other additional energy sources to accelerate drying rate, Chua and Chou [28] found a time saving of 42 % for potato and 31 % for carrot slabs (thick, 4 mm x long, 20 mm x wide, 20 mm) by combining hot air (40 ºC) and microwave power (100 W). It should be remarked that the microwave power (100 W) was chosen to minimize the temperature increase avoiding the burning of the samples, being the high heating effect of microwave a key issue for drying of heat sensitive materials. The heating effect is also the main factor on the application of infrared ration. Hebbar et al. [29] found drying times reduction by nearly 48 % in carrot slices (25 mm diameter x 5 mm) and potato cubes (17 mm x 17 mm x 5 mm) using a combination of infrared radiation (17 kW) and hot air (80 ºC and 1 m s^{-1}). As can be observed the application of power ultrasound involved similar saving times than microwave and infrared radiation but presents the advantage of producing low heating of samples that could provide products with better quality water mobility is increased using pressure waves and not thermically.

For quantifying the influence of power ultrasound application on the drying rate of potato cubes it is convenient to consider to modeling.

Drying kinetic modeling

Modeling is a useful tool to predict the behaviour of the drying process under different experimental conditions, and also it can be used to evaluate the application of ultrasound. [30] In this work, the diffusion model considered was adequate for describing the drying kinetics of potato cubes at the different experimental condition tested, achieving percentages of explained variance over 98 % and mean relative errors under 6 % in all cases (Table 1). Figure 3 shows the high agreement between experimental and calculated data, a similar tendency was found. Therefore, the assumptions considered in the model such as considering significant the external resistance seem to be adequate to describe the behavior of experimental potato drying.

The effective moisture diffusivity identified ($4.58\pm0.03 \times 10^{-10}$ m^2 s^{-1}) in the experiments without power ultrasound application (0 kW m^{-3}) is in the same order that others reported in the literature for convective drying of potato at similar temperatures (40-50 ºC). Thus, Hassini et al. [31] found values in the range of 4.30×10^{-10} – 3.60×10^{-10} m^2 s^{-1}, Zogzas & Maroulins [32] reported a range from 5.3 $\times 10^{-9}$ to 2.8 $\times 10^{-10}$ m^2 s^{-1}, Pavón-Melendez et al. [33] showed values between 2.2 $\times 10^{-10}$ to 9.4 $\times 10^{-10}$ m^2 s^{-1} and Ronald et al., [34] values between 8.8×10^{-10}-1.2×10^{-9} m^2 s^{-1}. The application of power ultrasound during drying produced the increase of the identified effective diffusivity. Thus, for the maximum ultrasonic power level tested (37 kW m^{-3}), the increase of the effective moisture diffusion coefficient was 64 % higher than the value identified in the experiments without power ultrasound application (0 kW m^{-3}). The ultrasonic effects were dependent on the applied power, the higher the ultrasonic power the higher the effective diffusivity values identified. In the range of the ultrasonic power level (UP) used in this work (0-37 kW m^{-3}), a significant linear relationship ($p<0.05$) between the UP and the effective moisture diffusivity (D_e) was found (Fig. 4).

The activation energy founded by Bon et al. [35] was used to compare the effects of ultrasound with the effect of air drying temperature on internal resistance to mass transfer. Thus the D_e achieved applying ultrasound (37 kW m^{-3}) at 40 ºC was similar than the D_e calculated if the air temperature will increase 25 ºC. The increase of the D_e produced by ultrasound could be mainly related to the "sponge effect". The samples were subbmitted to alternating expansions and contractions, which accelerate the water reaching the solid surface thus reducing the internal resistance to mass transfer. High porosity products present a low internal resistance due to large intercellular spaces; as a consequence, the mechanical effects associated to the acoustic energy are more intense that in low porosity products. [12, 23] Thereby, Ortuño et al., [20] found an increase of 211 % in D_e of ultrasonic assisted drying (37 kW m^{-3}) of eggplant compared to a conventional air drying process and García-Pérez et al., [12] reported an increase of 40 % for carrot drying. In this sense, the influence of ultrasound on potato drying rate was interesting due to it could be considered as a low porosity product.

Comparing the effects of combining energy sources to increase drying rate, Tang and Cenkowski, [36] using superheated steam and hot air (125 ºC) on drying of cylindrical potato samples (5 mm diameter and 30 mm length) reported similar diffusivity values (7×10^{-10} – 9×10^{-10} m^2 s^{-1}) than the identified at the maximum ultrasonic power tested in this work (37 kW m^{-3}). Afzal and Abe [37] found effective moisture diffusivity values for far infrared radiation drying (0.125 W cm^{-2} - 0.500 W cm^{-2} and 30 ºC) of slab potatoes (40 x 40 mm and different thickness levels) ranged between 5.93×10^{-11} and 1.73×10^{-9} m^2 s^{-1}. McMinn et al. [38] combining microwave (250 W) and convective drying (1.5 m s^{-1} and 30 ºC) of slab (13.5 mm radius, thickness 3.5 mm) and cylinder (radius 13.5 mm, length-to-radial ratio 4:1) potato samples showed D_e values from 0.13×10^{-8} to 3.73×10^{-8} m^2 s^{-1}, and from 2.90×10^{-8} to 24.22×10^{-8} m^2 s^{-1} respectively. In the case of microwave, it should be remarked that at high power levels the biomaterial dry so fast that the steam or other vapours could not escape quickly enough, leading to internal pressure build up, which could rupture the material. [39] As already mentioned, infrared radiation and microwave involve a high heating effect in comparison to the acoustic energy, which mainly involves mechanical effects. [13]

The external resistance to water transport was also affected by power ultrasound application during drying. The mass transfer coefficient (k) was increased by 58 % by the application of power ultrasound (37 kW m^{-3}) in comparison with the conventional drying experiments (0 kW m^{-3}) (Table 1). As in the case of D_e, the ultrasonic effect on k was dependent on the applied power, the higher the ultrasonic power, the higher the mass transfer coefficient. A significant ($p<0.05$) linear relationship between the applied ultrasonic power level (UP) and the mass transfer coefficient (k) was also found (Fig. 5). Then, in the range of ultrasonic power tested, the ultrasonic effects were proportional to the energy supplied to the medium. This fact suggest a high interest in designing and developing more efficient ultrasonic devices of high power in order to deeply affect the mass transfer processes during drying.

A similar behaviour about the influence of ultrasound in mass transfer coefficient was observed [11]. In the case of persimmon drying, Cárcel et al. [11] analyzed the influence of air drying velocity on the ultrasonic application. These authors found an improvement on mass transfer coefficient of 34.48 % at 1 m s^{-1} and 31 kW m^{-3} and concluded that high-intensity ultrasound increased the drying rat at the lowest air velocities tested, affecting both external and internal resistance. The increase of the mass transfer coefficient can be linked to the reduction of the boundary layer thickness produced by pressure variations, oscillating velocities and microstreaming generated by ultrasound on the solid-gas interfaces. The aforementioned effects could reduce the boundary layer of diffusion and improve the water transfer rate from the solid surface to the air medium. [40]

Then, from the results obtained can be observed that the ultrasonic application during drying represents an interesting alternative to traditional drying, accelerating drying kinetics that could represent. That could represent an important energy saving. In addition the low heating effect of ultrasound will permit to achieve products with a better quality.

CONCLUSIONS

Power ultrasound application represents a real alternative for improving water transport in convective drying process in order to reduce drying time. Drying kinetics of potato cubes were significantly ($p<0.05$) sped-up by the application of power ultrasound shortening the drying time. Experimental drying kinetics were well described by a diffusion model considering external resistance to mass transfer. Both kinetic parameters, the effective moisture diffusivity and the mass transfer coefficient, were significantly ($p<0.05$) increased by the application of power ultrasound. Therefore the ultrasound application involved the reduction involved the reduction of both internal and external resistance to mass transfer.

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TABLE

Table 1. Identified effective diffusivity (D_e) and mass transfer coefficient (k), and calculated percentage of explained variance (% VAR) and mean relative error (% MRE). Subscrips (a,b,c,d,e) and (x,y,z) shows homogeneous group established from LSD intervals ($p<0.05$).

UP ($kW\ m^{-3}$)	D_e ($10^{-10}\ m^2\ s^{-1}$)	k ($10^{-4}\ kg\ W\ m^{-2}\ s^{-1}$)	VAR (%)	MRE (%)
0	$4.58\pm0.03_{a}$	$2.03\pm0.36_{x}$	99.50	4.29
6	$5.23\pm0.18_{ab}$	$2.09\pm0.15_{x}$	99.08	4.47
12	$5.43\pm0.25_{abc}$	$2.32\pm0.12_{xy}$	99.35	3.63
19	$6.09\pm0.37_{bcd}$	$2.52\pm0.16_{xy}$	99.17	5.66
25	$6.46\pm0.86_{cd}$	$2.68\pm0.01_{yz}$	98.69	5.92
31	$6.06\pm0.34_{d}$	$3.19\pm0.42_{z}$	99.25	4.15
37	$7.51\pm0.34_{e}$	$3.21\pm0.35_{z}$	98.84	4.84

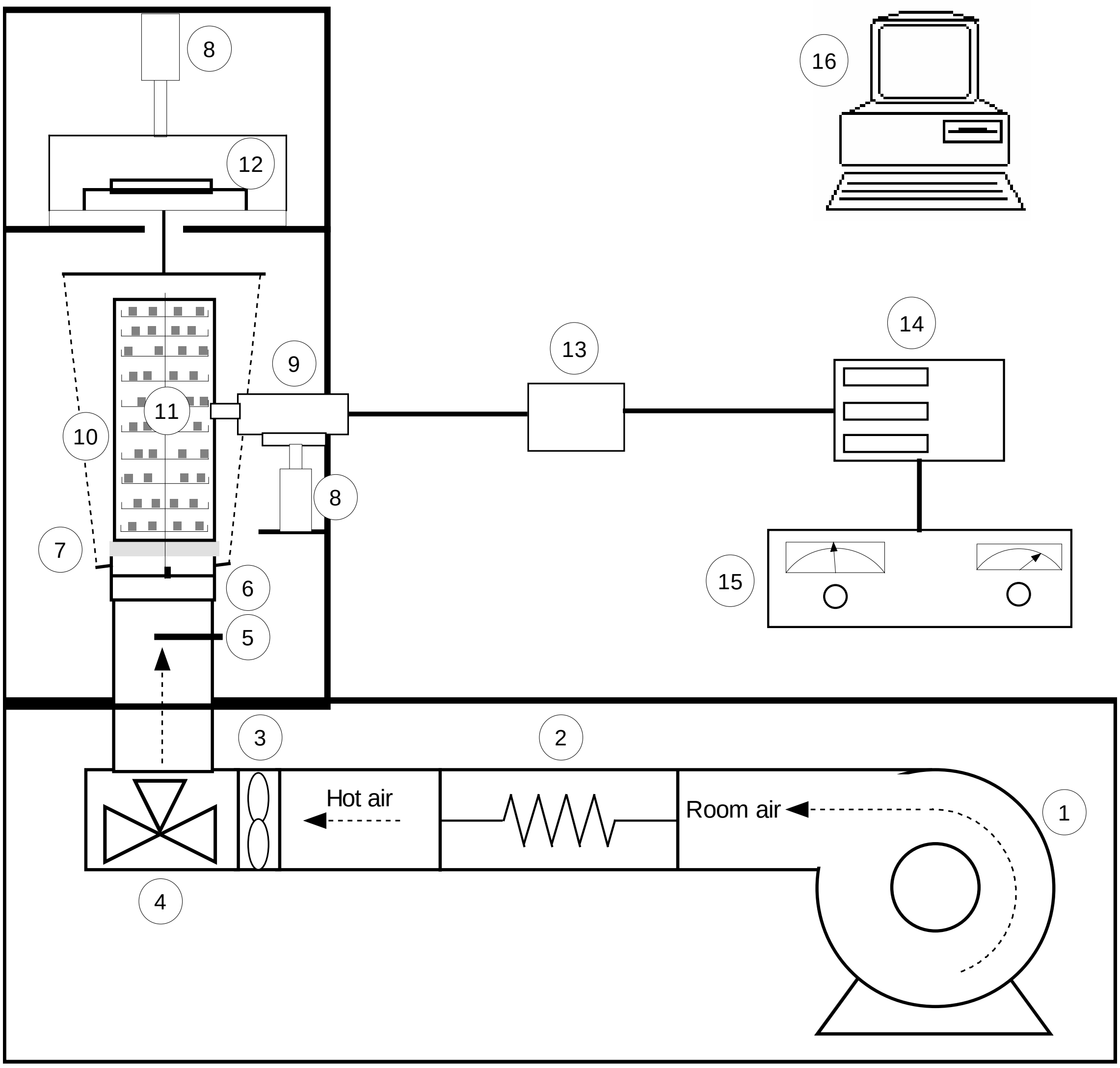

Fig. 1. Diagram of the ultrasonic assisted convective drier. [26] 1. Fan, 2. Heating unit, 3. Anemometer, 4. 3-way valve, 5. Thermocouple, 6. Sample loading chamber, 7. Coupling material, 8. Pneumatic moving arms, 9. Ultrasonic transducer, 10. Vibrating cylinder, 11. Trays, 12. Balance, 13. Impedance matching unit, 14. Digital power meter, 15. High power ultrasonic generator, 16. PC.

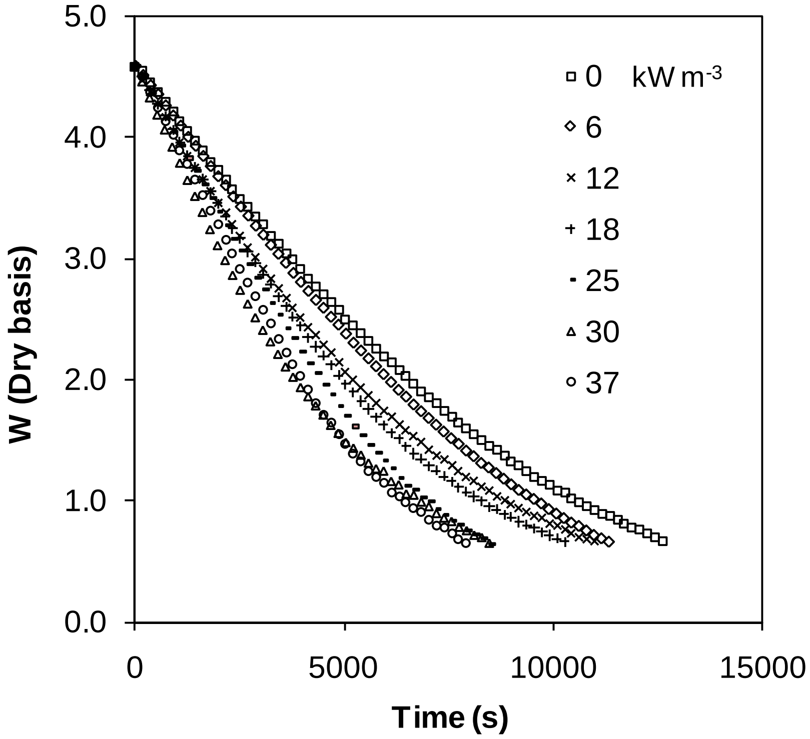

Fig. 2. Evolution of moisture content during drying of potato cubes (1 m s^{-1}, 40 ºC) applying different ultrasonic power levels.

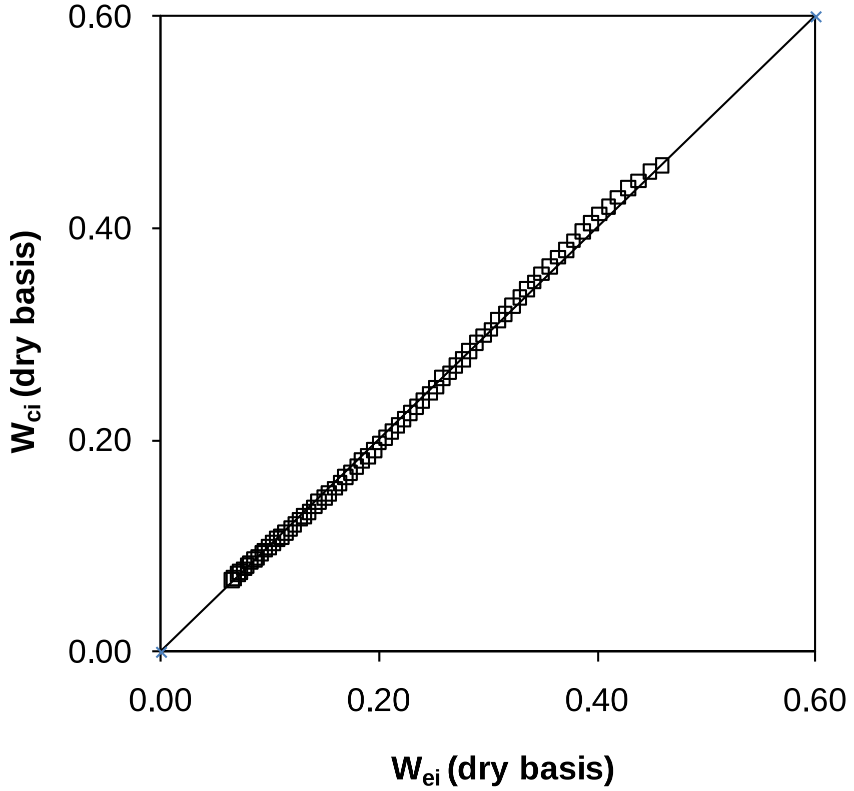

Fig. 3. Experimental vs calculated moisture content of potato cubes dried without applying ultrasound (0 kW m^{-3})

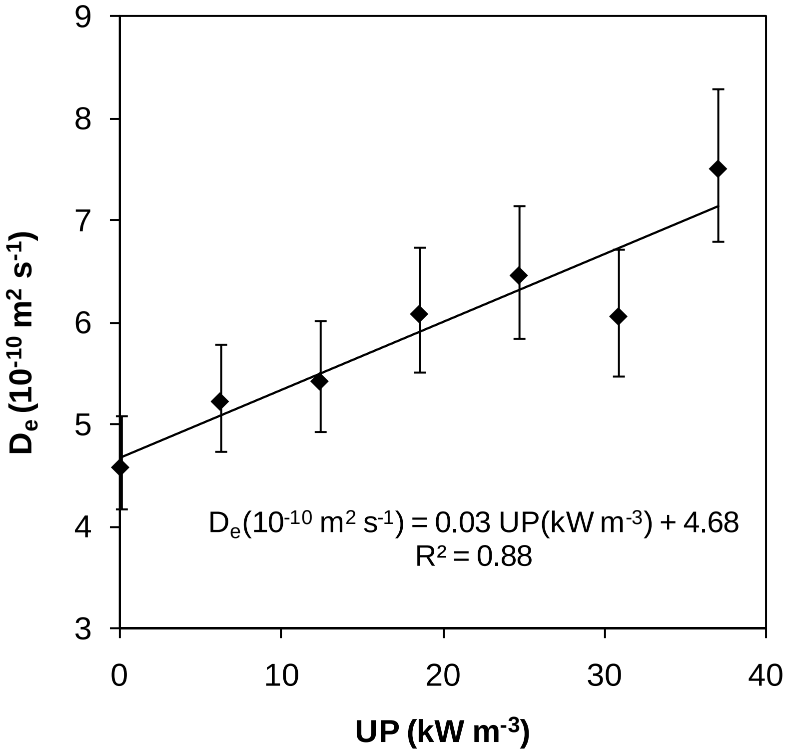

Fig. 4. Influence of the applied ultrasonic power level applied on the identified effective moisture diffusivity. Average values ± LSD intervals ($p<0.05$).

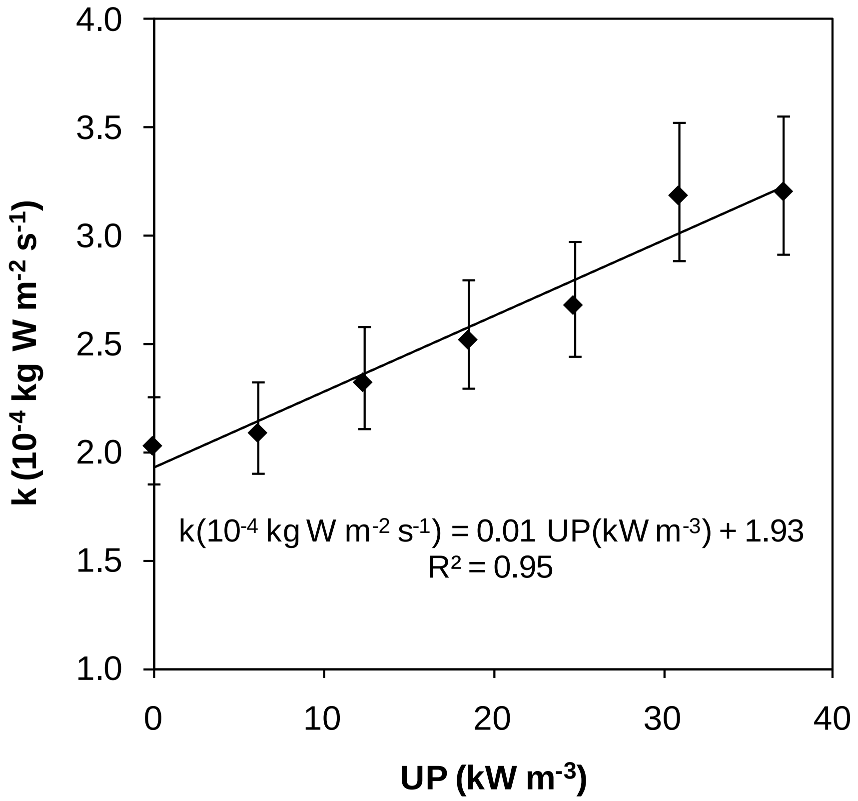

Fig. 5. Influence of the applied ultrasonic power level on the identified mass transfer coefficient. Average values ± LSD intervals.