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Intensification of drying processes due to ultrasound enhancement

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The aim of this article is to present a modern method of convective drying intensification caused by the external action of ultrasound. The purpose of this study is to discover the mechanism of ultrasonic interaction between the solid skeleton and the moisture in pores. This knowledge may help to explain the enhancement of drying mechanism affected by ultrasound, particularly with respect to biological products like fruits and vegetables. The experimental kinetics tests were conducted in a hybrid dryer equipped with a new ultrasonic generator. The drying kinetics curves determined on the basis of drying model developed by the author were validated with those by the ones obtained from experimental tests. The intensification of heat and mass transfer processes due to ultrasound induced *heating effect* and *vibration effect* are analysed. The obtained results allow to state that ultrasound makes drying processes more effective and enhance the drying efficiency of biological products without significant elevation of their temperature.

Keywords: hybrid drying, ultrasound, kinetics, drying efficiency, synergistic effect

1. INTRODUCTION

An increasing amount of literature has reported very positive influence of higher-power ultrasound at frequencies 20 kHz to 100 kHz on the drying efficiency of biological materials such as fruits and vegetables (Carcel et al., 2011; Cheng et al., 2015; De la Fluente-Blanco et al., 2006; Fan et al., 2017; Galego-Juarezet et al., 2007; Garcia Perez et al., 2013; Kentish and Ashokkumar, 2011; Kumar et al., 2014; Legay et al., 2011; Szadzińska et al., 2016). Some reviews concerning ultrasound-assisted drying technique can be found in Carcel et al. (2014); Musielak et al (2016) and Siucińska and Konopacka (2014). These reports show the ability of ultrasound to enhance drying rate and improve quality of food products.

Apart from using ultrasound to enhance drying of biological materials it is worth mentioning its other applications, e.g. in adsorbent regeneration or food drying/dehydration (Yao et al., 2014; 2015; 2016).

Judging from the published literature (Galego-Juarez et al., 2007; Gamboa-Santos et al., 2014; Garcia-Perez et al., 2013; Mulet et al., 2003; Mulet et al., 2011; Ortuno et al. 2010) high-power ultrasound is capable of improving heat- and mass-transfer processes in drying materials, in particular, in the drying of heat-sensitive biological materials such as fruits and vegetables. The limited applicability of ultrasound to drying methods is primarily due to ultrasound high-power demand (Kudra and Mujumdar, 2002; Patist and Darren, 2008; Sinha, 2006; Śliwiński, 2001; Sobarez et al., 2012). The currently used ultrasound radiators operating in gas media (e.g. siren) mostly do not fulfil this requirement. An original construction

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of a laboratory hybrid dryer based on an ultrasound airborne transducer was constructed in the author's drying laboratory (Fig. 1). This dryer enables hybrid drying in combinations of convective, microwave and ultrasound techniques.

The main aim of this article is, first of all, to recognise the interaction mechanism of ultrasound transferred to biological material, which could entail the reason for the intensification of moisture removal from such products by drying. The research hypothesis is a supposition that the periodical waves which are characteristic for ultrasound cause periodical changes of porosity and pore pressure. In this way they may evoke the moisture streaming from the material inside towards the surface where it evaporates.

Biological materials such as fruits and vegetables need very sublimed drying methods as they are very sensitive to temperatures higher than 60–70 °C and also to long drying time. The common drying methods (e.g. hot convective air drying), may cause degradation of their valuable features (colour, vitamin, minerals). For this reason the author of this paper has developed hybrid methods as a combination of convective, microwave and infrared drying (Kowalski et al., 2010a; Kowalski et al., 2013; Kowalski and Pawłowski, 2015). However, this work proposes an extension of the mentioned hybrid drying additionally with ultrasound assistance. This needs first a more detailed analysis of ultrasound wave distribution in wet materials subjected to drying (Kowalski, 2015; Kowalski and Mierzwa, 2015). The positive outcome of these studies may contribute to essential improvement of drying processes important in the drying technology of biological materials. Modified drying technology carried out in dryers supported with ultrasound equipment could find application in the industry, increase competitiveness by increasing productivity and decrease energy consumption, contributing to balanced research and development (R&D).

The present work extends the analysis of ultrasound influence on drying effects that was presented in the above-mentioned articles through a detailed description of the so-called *vibration effect* and *heating effect*, and pointing to the possible existence of a *synergistic effect*. The experimental tests presented in this work were carried out on new hybrid dryer equipment with a convective, microwave, and ultrasonic set-up, newly gained in the authors' laboratory. It was proved that convective drying assisted with ultrasound significantly improves the efficiency of heat and mass transfer in strawberries, which were used as the testing material. The model of drying kinetics that was developed earlier by the author is used to compare the theoretical drying kinetics with the experimental one, and thus to create basis for evaluation of the above-mentioned *vibration effect* and *heating effect* as provoked by ultrasounds.

2. EXPERIMENTAL

2.1. Material

Strawberries (*Fragaria ananassa*) var. Elsanta used for drying experiments were purchased on the local market. Elsanta is a very popular dessert variety. The fruits are large and conical, and their flesh is juicy with a raspberry aftertaste. Prior to each drying experiment, four fresh fruits of about 80 g with an initial water content of 8.96 ± 0.15 kg/kg db, were deprived of stalks, washed in tap water, drained with blotting Paper and cut into 8 halves along the longitudinal axis. The samples were placed on a reticular pan in the form of a ring with skin-side down, and then were dried to the final moisture content of 0.01 ± 0.001 kg/kg db, on average.

2.2. Drying tests

Figure 1 presents a scheme of a laboratory hybrid dryer constructed by PROMIS-TECH – Wrocław (Poland), equipped with the ultrasonic air-born systems provided by PUSONICS – Madrid (Spain), which is the set-up located in the Department of Process Engineering at Poznań University of Technology (Poland).

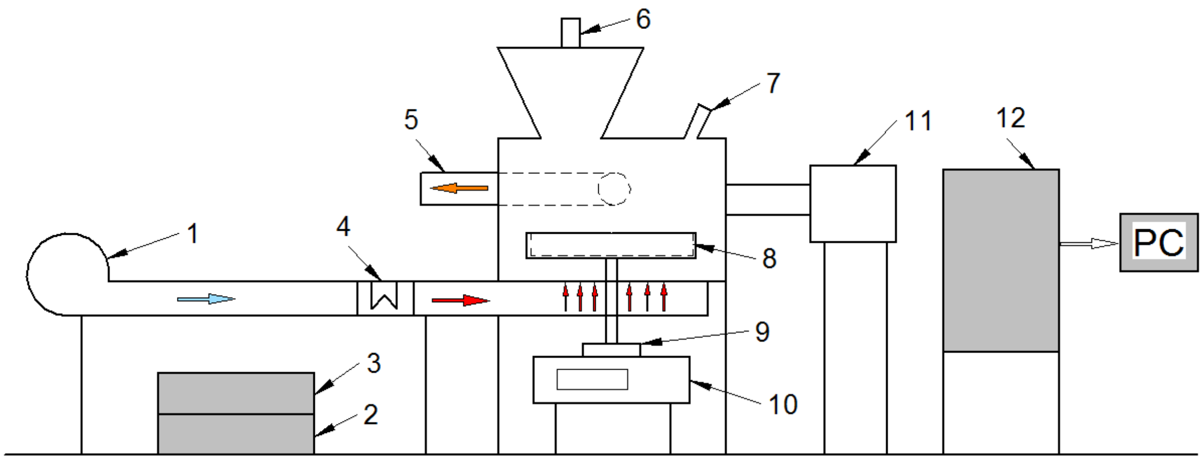

Fig. 1. Scheme of ultrasound assisted hybrid dryer: 1. Fan, 2. Ultrasound generator AUS, 3. Ultrasound feeder, 4. Electric heater, 5. Air outlet, 6. Ultrasound transducer AUS, 7. Pyrometer, 8. Rotating sample Pan, 9. Drive sample Pan, 10. Balance, 11. Microwave generator, 12. Control cupboard

The drier is equipped with three sources of energy: air heater, microwave magnetron, and ultrasound generator, which can work simultaneously or separately. The drier can work with air temperature up to 90 °C, the microwave power up to 500 W and ultrasound power up to 200 W with frequency of 26 kHz. It is also possible to set the wanted air flow through the scale pan with velocity up to 1 m/s. The air temperature and humidity at the inlet and outlet of the hybrid dryer are measured by temperature-humidity sensors (HD29371TC1.5 and HD4817ETC1.5, Delta OHM, Italy). The temperature of sample's surface during drying is measured by an infrared thermometer (pyrometer) (CT LT15, Optris, Germany), with a precision of 0.1 °C.

A great advantage of the experimental set-up is the possibility to measure all process Parameters online, that is: drying time, material temperature, inlet air temperature, outlet air temperature, inlet air humidity, outlet air humidity, air flow, microwave power, ultrasound power, and the energy use. The dryer enables convective drying with different temperatures and velocities of the air flow, possible to set in advance with the programmer (12), and convective drying enhanced with ultrasound and/or microwaves. The ultrasonic transducer (6) generates an ultrasound wave propagating through the air towards the drying sample, being a saturated porous medium placed on the rotating Pan (8).

2.3. Drying curves

The drying effectiveness of hybrid drying processes of strawberries was evaluated on the basis of the drying kinetics curves and the material temperature changes during drying. At first, the CV drying tests as a reference were carried out (Fig. 2).

As it follows from the drying curve in Fig. 2, convective drying is a very long-lasting process, as it takes about 21 hours, i.e. 1258 ± 11 min, on average. During CV drying, the material temperature (T_m) was maintained below the air temperature (T_a) for a long time, and only after about 800 min it reached 50 °C. Even with a rather low air temperature, the dried strawberries were characterized by a strongly shrunken surface, and their colour darkened. Then, four different hybrid drying tests with convection as a heat energy source were carried out.

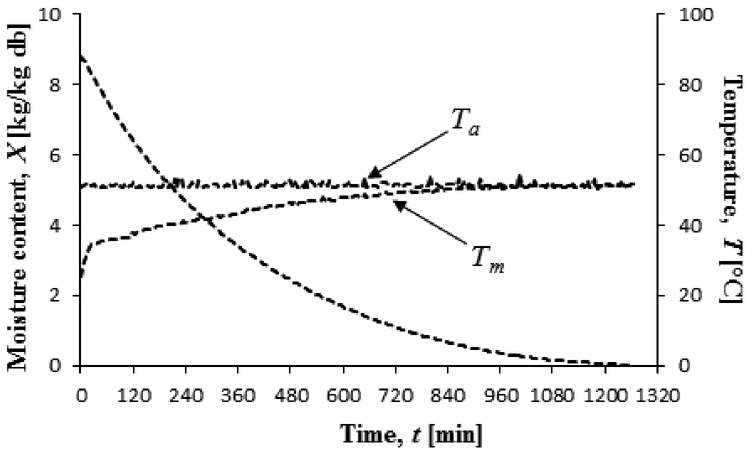

Fig. 2. Convective drying of strawberries

Subsequent series of experiments involved convective drying assisted with ultrasound (CV-US). Application of the high power ultrasound affected the moisture removal in strawberries and reduced the total drying time (Fig. 3). In CV-US drying the overall drying time was 600 ± 7 min, on average, so it was shorter by about 52%, as compared to CV drying test. The ultrasound application enhances heat and mass transfer both by diffusion inside the material and by convection close to the material surface. A number of different mechanisms that could result in ultrasonic acceleration of the drying process were proposed (Kudra and Mujumdar, 2002; Musielak et al., 2016). In the investigated case of drying, the crucial thing is the improvement of heat and mass exchange by the boundary layer. Various mechanisms may cause such an effect: e.g. cavitation inside liquid layer, pressure fluctuations, microstreaming.

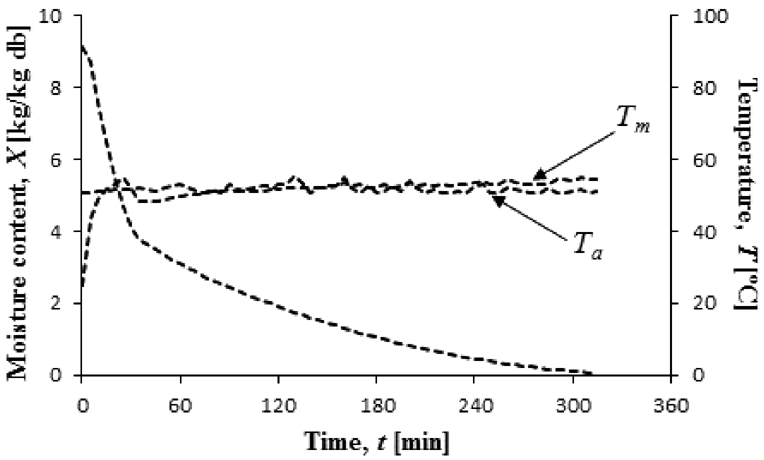

Fig. 3. Convective drying of strawberries assisted with ultrasound

High power ultrasound is an additional heat energy source. As the seen in Fig. 3, within first two hours the value of material temperature was lower than air temperature, but after this period (i.e. 130 min) the temperature of strawberry surface began to rise above the drying medium temperature. It is the so-called *heating effect* due to ultrasound absorption. Because the increase in material temperature is marginal (up to 55 °C), its effect on drying rate can be regarded as negligible.

The main reason of drying time reduction is rather *vibration effect*, which arises due to vibration of air molecules with high frequency generated by the ultrasonic transducer near the dried body. Both effects resulting from the application of ultrasonic waves have definitely more powerful action (are compensated) in heat and mass transfer, i.e. *synergistic effect*.

3. EQUATIONS OF DRYING KINETICS

In order to assess numerically the "heating effect" and the "vibration effect" the equations of drying kinetics are needed. Such equations were developed by Kowalski and Pawłowski, (2010b). Drying kinetics exposes changes of moisture content and temperature of the drying body as function of time. The proposed mathematical model enables numerical computation of these quantities. The numerically determined material temperature and drying curves should reveal a satisfactory adherence to those determined experimentally. The mass and energy balances and the principles of irreversible thermodynamics (Berry et al., 2000; Gumiński, 1962; Szarawara, 1985) constituted the basis for construction of the respective equations of drying kinetics. The final form of the governing equations describing the kinetics of drying, with neglected small coupling Soret and Dufour effects, reads (Kowalski and Pawłowski, 2010b; Kowalski et al., 2010a):

$$m_s \frac{dX}{dt} = -A_m h_m \ln \frac{\varphi|_{\partial B} p_{vs}(T)}{\varphi_a p_{vs}(T_a)} \tag{1}$$

$$m_s \frac{d}{dt}\left[(c_s + c_l X)T\right] = A_t h_t (T_a - T) - A_m l h_m \ln \frac{\varphi|_{\partial B} p_{vs}(T)}{\varphi_a p_{vs}(T_a)} + a_U \chi_U P_U \tag{2}$$

The pressure of saturated vapour p_{vs} is related to the temperature of phase transition T_{ph} through *the equation of evaporation* (Elwell and Pointon, 1976):

$$p_{vs} = p_{vs0} \exp\left[\frac{1}{R}\left(\frac{1}{T_{ph0}} - \frac{1}{T_{ph}}\right)\right] \tag{3}$$

Equation (3) shows that $p_{vs} > p_{vs0}$ when $T_{ph} > T_{ph0}$, where p_{vs0} and T_{ph0} are the initial (reference) drying conditions. Relation (3) will be used further for estimation of the effectiveness of drying assisted with ultrasounds.

In the above formulas φ_a and T_a denote the air relative humidity and temperature, termed further the parameters of drying. Function $p_{vs}(T)$ is given in the literature in the form of tables (Strumiłło, 1983; Wiśniewski and Wiśniewski, 1997). The air relative humidity close to the surface of dried sample $\varphi|_{\partial B}$ depends on the sample moisture content. A similar form of the air relative humidity at the sample surface was proposed in Kowalski et al. (2010a).

This model is meant to describe drying kinetics of biological materials like fruits and vegetables, which are strongly deformable ones. Therefore, it is necessary to take into account the material behaviour undergoing large shrinkage during drying, and this model enables also such description. It is assumed that the heat and mass exchange occurs on the whole material surface, and also that dried material undergoes linear volumetric shrinkage. Hence, the change of surface dimension $A_m = A_T = A(X)$ is a function of moisture content described by the following equation

$$A_m = A_T = A(X) = \left[1 - \alpha_v (X_0 - X)\right]^{2/3} A_0 \tag{4}$$

where denotes the volumetric shrinkage coefficient and X_0 the initial moisture content.

The proposed model enables description of both the constant (CDRP) and the falling (FDRP) drying rate periods. The CDRP is characterized by constant densities of mass and heat fluxes. In the case of non-shrinking materials, the drying rate is constant during CDRP. In the case of highly shrinking materials (like strawberries) the drying rate during CDRP decreases because of surface decrease. To describe these two periods it should be assumed that the air relative humidity close to the material surface $\varphi|_{\partial B}$ is a function of the moisture content X (Musielak and Banaszak, 2007):

$$\varphi|_{\partial B} = \begin{cases} (1 - \varphi_{cr}) \dfrac{X - X_{cr}}{X_0 - X_{cr}} & \text{for } \mathrm{X_0 \le X \le X_{cr}} \\ (\varphi_{cr} - \varphi_a) \dfrac{X - X_{eq}}{X_{cr} - X_{eq}} & \text{for } \mathrm{X_{cr} \le X \le X_{eq}} \end{cases} \tag{5}$$

Based on data given in the textbooks (Strumiłło, 1983; Wiśniewski and Wiśniewski, 1997), one can state that the saturated vapour pressure p_{vs} is temperature dependent, and can be approximated using the following function (6):

$$pvs(T) = 9.61966 \cdot 10^{-4} T^4 - 1.084405264 T^3 + 4.61325529 \cdot 10^{-2} T^2 + \\ - 2.77803513 \cdot 10^4 T + 6.29588464 \cdot 10^6 \tag{6}$$

The absorption coefficient of ultrasonic waves a_U should be estimated experimentally from measurement of the material temperature increase. A part of ultrasound energy during wave incidence is absorbed by drying material and converted into heat. Thus, the absorption coefficient of ultrasonic waves can be calculated from Equation (2) for the adiabatic process, that is, under the assumption that the convective heat and mass transfer are excluded:

$$m_s \frac{d}{dt}[(c_s + c_s X)T] = a_U \chi_U P_U \tag{7}$$

In the presented experimental tests the amount of acoustic energy absorbed by drying material is estimated on the basis of drying kinetics, strictly, on the basis of material temperature curves obtained by drying with and without ultrasonic assistance. The difference between these two curves follows just from the absorption of the ultrasound energy. As seen from the temperature curves in Fig. 3, the temperatures of drying samples with and without ultrasonic assistance differ insignificantly from each other, ca. by 1 K on average.

4. ESTIMATION OF MODEL PARAMETERS

The initial value problem based on the set of kinetics (Eqs. (1) and (2)) was solved by the Adams-Bashforth non-self-starting multistep method. Selection of this method is motivated by good convergence and stability in long-term simulations.

The estimation method of model parameters is based on the inverse problem, which concept consists in solution of direct problem and applying optimization techniques (Stasiak et al, 2015). The solution of the inverse problem is compared directly with the curves of experimental kinetics of drying, and the best fitting of the numerical and experimental curves is searched. The kinetics consist of the drying and the temperature evolution curves, respectively. In the mathematical model (Eqs. (1) and (2)) four parameters describing the drying process, namely, the effective coefficients of convective heat h_T and mass h_m transfer, the additional heat source $(a_U \chi_U P_U)$, as well as the critical moisture content X_{cr} are introduced. Therefore, the multi-parameters and multi-objective optimization problem was formulated and solved. The objective function is defined as a sum of the squares of the normalized residuals of the experimental and numerical values of the moisture content and temperature

$$f(h_m, h_T, a_U \chi_U P_U, X_{cr}) = \sum_{i=1}^{N} \left[\left(\frac{X_{num,i} - X_{\exp,i}}{X_{\max} - X_{\min}} \right)^2 + \left(\frac{T_{num,i} - T_{\exp,i}}{T_{\max} - T_{\min}} \right)^2 \right] \tag{8}$$

The differences of the experimental maximum and minimum values of the moisture content and the temperature are used to get the same range of the residuals in the defined objective function. Rosenbrock (1960) optimization method is used for estimation of the model parameters. The method is then referred to optimization problem in which the objective function is inexpensive to compute and the derivative either does not exist or cannot be computed efficiently. The simulations should be stopped when the improvement of the error function is not observed.

5. EFFECTIVENESS OF ULTRASONIC DRYING

The proposed method for determination of the model parameters is exemplified with convective drying and ultrasound assisted convective drying of strawberry samples. Figures 4 and 5 present a comparison of the theoretical (Model) and experimental (Experiment) (Figs. 2 and 3) drying curves and the curves of material temperature evolution.

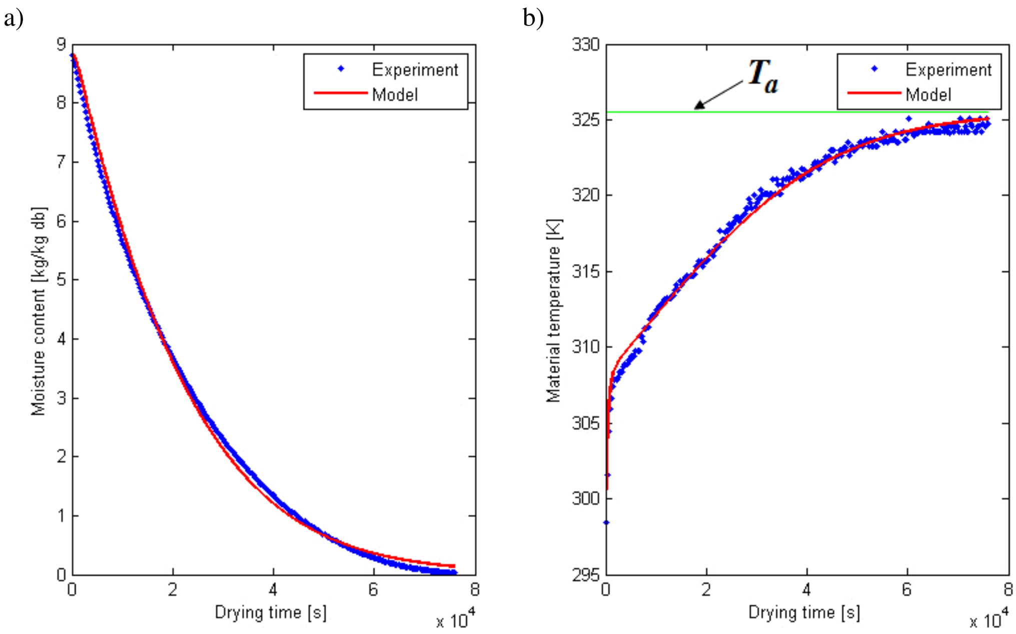

Fig. 4. Comparison of theoretical and experimental drying: a) curves for CV test, b) material temperature

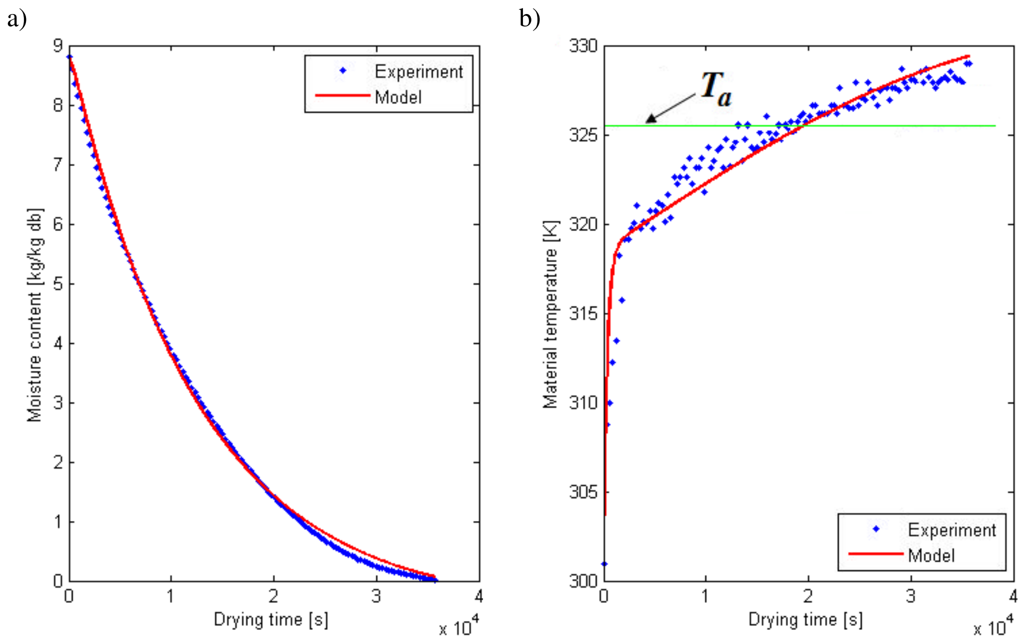

Fig. 5. Comparison of theoretical and experimental drying: a) drying curves for CV-US test, b) material temperature

As follows form Figs. 4 and 5, a very good adjustment of numerical drying curves as well as the material temperature curves to the experimental presented in Figs. 2 and 3 was achieved. Thus, the real drying processes have been successfully simulated with the proposed mathematical model of drying kinetics.

The drying rate, D_r [kg/s], expresses the speed of moisture decrease in drying material as a function of time, that is

$$D_r(t) = m_s \frac{dX}{dt} = -A_m h_m \ln \frac{\varphi|_{\partial B}\, p_{vs}(T)}{\varphi_a p_{vs}(T_a)} \tag{9}$$

The average drying rate, $D_{r,ave}$, is determined as

$$D_{r,ave}(t) = \frac{1}{t_{eq}} \int_0^{t_{eq}} D_r(t)\, dt \tag{10}$$

where t_{eq} is the drying time at which the moisture content reached equilibrium with the surroundings X_{eq}. The drying time for pure convective drying (i.e. without ultrasonic assistance) is denoted as $t_{eq} = t_{eq}^{CV}$, and that with ultrasonic assistance as $t_{eq} = t_{eq}^{CVUS}$.

The drying rate enhancement D_rE and the ratio of drying rate enhancement AD_rE are used to evaluate the effect of ultrasound assisted drying. They are expressed as follows:

$$D_rE = D_{r,ave}^{CVUS} - D_{r,ave}^{CV} \qquad \text{and} \qquad AD_rE = \frac{D_{r,ave}^{CVUS} - D_{r,ave}^{CV}}{D_{r,ave}^{CV}} \cdot 100\% \tag{11}$$

Figure 6 illustrates the variation of drying rate in time for convective drying (a) and for convective drying assisted with ultrasound (b).

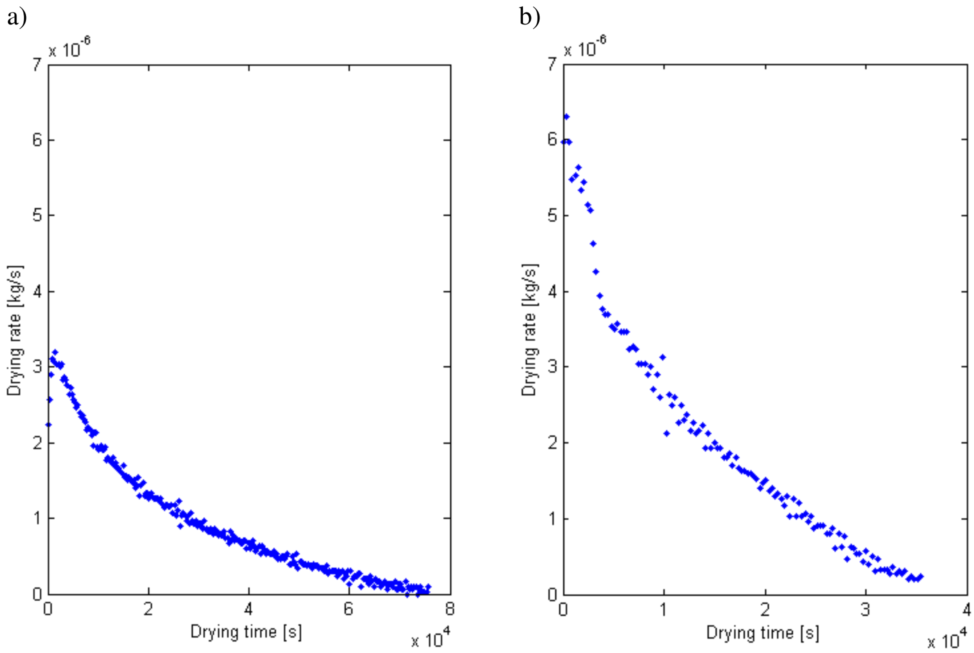

Fig. 6. Comparison of drying rate for: a) CV drying, b) for CV-US drying

As can be seen in Fig. 6, at the very beginning of the CV-US process the drying rate of strawberries is about twice higher than that in the CV drying. Similarly, the total drying time of the CV-US is twice shorter as compared with the CV drying. The average drying time for convective drying equals $t_{eq} = t_{eq}^{CV} = 1258$ min and for ultrasound assisted convective drying it is $t_{eq} = t_{eq}^{CVUS} = 600$ min. Thus, the average drying rates for the CV and CV-US processes calculated from Eq. (10) are $D_{r,ave}^{CV} = 14.90$ g/h and $D_{r,ave}^{CVUS} = 27.16$ g/h.

Drying rate enhancement D_rE and the ratio of drying rate enhancement AD_rE were used to evaluate the effectiveness of ultrasound assisted convective drying:

$$D_rE = D_{r,ave}^{CVUS} - D_{r,ave}^{CV} = 27.16 - 14.90 = 12.26 \text{ g/h} \tag{12}$$

$$AD_rE = \frac{D_{r,ave}^{CVUS} - D_{r,ave}^{CV}}{D_{r,ave}^{CV}} \cdot 100\% = \frac{12.26}{14.90} \cdot 100\% = 82\% \tag{13}$$

Taking into account the above results, one can state that ultrasound enhancement of convective strawberries drying significantly accelerated the drying process, as the ratio of drying rate amounts to 82%. These results correspond to those reported by Kowalski and Pawłowki (2015), where the ratio of drying rate enhancement AD_rE in the case of apple drying amounted to 85.9%.

To describe the *heating effect* (T), *vibration effect* (v) and the *synergistic effect* (s) quantitatively, i.e. components of ultrasound action (C), a number of equations derived by Kowalski and Pawłowski (2015) were used:

$$CD_rE_{T,eff} = \frac{A_m h_m}{D_r E} \ln \frac{p_{vs}(T_m + \Delta T_m)}{p_{vs}(T_m)} \cdot 100\% = \frac{20.8 \cdot 0.612}{12.26} \ln \frac{15741}{12960} \cdot 100\% = 20.17\% \tag{14}$$

$$CD_rE_{v,eff} = \frac{A_m \Delta h_m}{D_r E} \ln \frac{\varphi \mid_{\partial B}}{\varphi_a} \cdot 100\% = \frac{20.8 \cdot 0.292}{12.26} \ln \frac{0.325}{0.075} \cdot 100\% = 72.64\% \tag{15}$$

$$CD_rE_{s,eff} = \frac{A_m \Delta h_m}{D_r E} \ln \frac{p_{vs}(T_m + \Delta T_m)}{p_{vs}(T_a)} \cdot 100\% = \frac{20.8 \cdot 0.292}{12.26} \ln \frac{15741}{13613} \cdot 100\% = 7.19\% \tag{16}$$

where the average surface of 8 strawberry halves A_m equals 0.0208 m^2, the average relative air humidity φ_a is 0.075, the h_m coefficients for CV and CV-US processes are 0.612 and 0.904 kg/m^{2}h, and Δh_m is 0.292 kg/m^{2}h, respectively. The vapour partial pressures p_{vs} at saturated state (Strumiłło, 1983) are, respectively:

- $p_{vs} = 13613$ Pa for air temperature $T_a = 52$ °C,
- $p_{vs} = 12960$ Pa for material temperature $T_m = 51$ °C in CV test,
- $p_{vs} = 15741$ Pa for material temperature $T_m + \Delta T_m = 55$ °C in CV-US test.

On the basis of the above calculations it can be concluded that the *vibration effect* has contributed the most to an increase in drying efficiency.

6. CONCLUDING REMARKS

The results of convective drying enhanced by ultrasound presented in this article have shown significant improvement of drying kinetics as well as selected quality indicators as far as it concerns drying of biological materials, e.g. strawberries. Although the convective-ultrasound drying is not very energy-effective (total energy profit is up to only 6.4%) as compared to convective drying, it is beneficial from the drying time and product quality point of view.

Ultrasound action contributes the most to the *vibration effect*, less to *heating effect*, and less significantly to *synergistic effect*. However, the *vibration effect* is the most dominant factor of the mass transfer growth during drying, so it decides about the effectiveness of drying assisted with ultrasound. The estimated coefficients allowed to determine the percentage effectiveness of the above mentioned effects. Analysis of the obtained results proved that an increase in drying efficiency is mainly due to pulsed vibrations caused by ultrasounds.

It is interesting to note that in convective drying with ultrasound assistance an extra effect may appear that contributes to the drying efficiency. This extra effect, termed as the *synergistic effect*, can be positively provided when the *heating effect* is significant, that is, when the temperature of the drying material becomes greater than its surroundings. This may occur by intensive absorption of ultrasonic waves or by additional volumetric heat supply, e.g. by microwave heating. One can expect that such emerging drying technology could be suitable for drying of biological materials and would find application in the industry, thus raising competitiveness by increasing productivity and decreasing energy consumption, and would contribute to the concept of sustainable development.

SYMBOLS

a_U	ultrasound absorption coefficient, –
A	sample surface, m^2
c_l	specific heat for liquid, $J \cdot kg^{-1}K^{-1}$
c_s	specific heat for solid, $J \cdot kg^{-1}K^{-1}$
h_m	mass transfer coefficient, $kg \cdot sm^{-4}$
h_T	heat transfer coefficient, $W \cdot K^{-1}m^{-2}$
l	latent heat of evaporation, $J \cdot kg^{-1}$
p_v	vapour partial pressure, Pa
p_{vs}	saturated vapour partial pressure, Pa
P_U	power of ultrasonic generator, W
R	gas constant for vapour, $J \cdot kg^{-1}K^{-1}$
t	time, s
T	temperature, K
T_a	air temperature, K
$X = m_m/m_s$	molar ratio of vapour, –

Greek letters

$\varphi = (p_v/p_{vs})\big|_T$	humidity, –
φ_a	air relative humidity, –
χ_U	ultrasound working efficiency, –
α_V	volumetric shrinkage coefficient, –

Subscripts

a	ambient air
cr	critical
CV	convective
$CVUS$	convective with ultrasound
eq	equilibrium
m	moisture
o	initial
v	volume
T	thermal

Superscripts

s	solid
v	vapour

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