Original paper

Study of Microwave Drying of Vegetables by Numerical Modeling. Influence of Dielectric Properties and Operating Conditions

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In the present work mass and energy transfer during microwave dehydration of vegetables were studied. Microwaves interact with the polar molecules of food enabling its heating and dehydration. This interaction is affected by the change of food properties due to temperature increase and water content reduction. In certain products, the dependence of dielectric properties with temperature is affected by a change in the food structure as a consequence of the chemical change of certain components and of the water loss. Lambert's law, that considers an exponential decay of incident microwave power, was applied to model these interactions. Additionally, two consecutive stages must be considered: initial heating, followed by intensive evaporation at constant temperature. The model was successfully validated for data published in literature related to slabs of microwave dehydrated potatoes and carrots, considering different processing times, power densities, pressure and sample size.

Keywords: microwave drying, dielectric properties, numerical modeling, vegetables.

Introduction

When electromagnetic energy of microwaves interacts with food, the thermal response mainly depends on the dielectric properties (dielectric constant and loss factor). These properties depend on several factors, some from the irradiated food and others related to the characteristics of the incident electric field. Among these factors the frequency of the electric field applied, the temperature of the material, density, composition and product structure could be mentioned. The temperature increase produces a reduction as much on the dielectric constant as on the dielectric loss factor, generally at 2450 MHz, leading to lower heat dissipation in the food. Certain foods (potato and garlic) present a modification on the dependence of their dielectric properties with temperature. This effect is mainly observed on the variation of the dielectric constant, in certain temperature ranges (Sipahioglu and Barringer, 2003). This modification on the behavior may be attributed to the structural modifications suffered by certain components of the food, such

as starch that probably gelatinizes at those temperature ranges producing a deviation on the behavior expected in fruits and vegetables.

Many research works have been devoted to microwave dehydration (MWD) of food materials (Bouraoui *et al*., 1994; Hebbar *et al*., 2003; Cui *et al*., 2005), in particular some of them to MWD of vegetable products (Tohi *et al*., 2002; Cui *et al*., 2003; Wang *et al*., 2004; Wang and Xi, 2005; Wu *et al*., 2007) that cover radish, carrot, potato, garlic and eggplant. With respect to the modeling of the MWD process, some works have been published considering different approaches. Among them Soysal Y. (2004) considered the empirical method using Page model, Dadali *et al*. (2007) employed the diffusional theory (Fick's second law) to obtain the moisture loss evolution and Sanga *et al*. (2002) studied the coupled moisture and energy transport using a mass and heat transfer model. Although several research works have been dedicated to model the MWD process none of them have considered the change in

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dielectric properties due to the modification in composition and structure of vegetable products.

The present work is focused on mass and energy transfer due to the interaction between the food and the microwaves. This interaction is affected by the change in the food properties due to temperature increase and moisture content reduction. Lambert's law was applied to model this interaction with the aim of obtaining the distribution of the absorbed microwave energy within the samples. This law is incorporated into the energy balance as a source term to obtain the temperature profiles under different operating conditions during microwave dehydration.

Materials and Methods

Mathematical model for microwave dehydration Two consecutive stages are considered in modeling: (1) initial heating with weak evaporation and (2) intense evaporation. Stage 1 involves food heating until the entire product reaches the equilibrium temperature T_{equi}, temperature achieved when the power absorbed is equilibrated with the energy spent in vaporization (Arballo *et al.*, 2010). To describe heat transfer, an energy balance must be developed that considers a source term of internal heat generation due to the energy supplied by microwaves (Campañone and Zaritzky, 2005). The microscopic resulting energy balance is:

$$V\rho C_p \frac{\partial T}{\partial t} = V \frac{\partial}{\partial x}\left(k\frac{\partial T}{\partial x}\right) + P \qquad \cdots\cdots \text{Eq. 1}$$

where V is the product volume (m^3), ρ is density (kg/m^3), Cp specific heat capacity (J/(kg ℃)), T temperature (℃), t time (s), x spatial position (m), k thermal conductivity (W/(m ℃)) and P is the power generated by microwave absorption (W). Initial and boundary conditions must be considered to complete modeling. Firstly, uniform humidity and temperature are considered in the entire product. In addition, convection and evaporation conditions are considered in the product frontier.

The power absorbed during the microwave heating is represented by the term P. The heat generation is a function of temperature at each point of the material. In this work, Lambert Law was considered (Lin *et al.*, 1995):

$$P = P_0 e^{(-2a\,(L-x))} \qquad \cdots\cdots \text{Eq. 2}$$

where P_0 is the absorbed microwave power on the surface (W), L is the half thickness of the slab (m) and α is the attenuation factor (1/m), function of the dielectric constant (ε'), the loss factor (ε'') and microwave wavelength (λ):

$$a = \frac{2\pi}{\lambda}\sqrt{\frac{\varepsilon'\left[(1+\tan^2\delta)^{1/2}-1\right]}{2}} \qquad \cdots\cdots \text{Eq. 3}$$

$$\tan\delta = \frac{\varepsilon''}{\varepsilon'} \qquad \cdots\cdots \text{Eq. 4}$$

To predict moisture profiles during heating, a microscopic mass balance is needed:

$$\frac{\partial C_w}{\partial t} = \frac{\partial}{\partial x}\left(D\,\frac{\partial C_w}{\partial x}\right) \qquad \cdots\cdots \text{Eq. 5}$$

where C_w is the water concentration (kg/m^3) and D is the moisture diffusivity (m^2/s).

Uniform initial conditions and convective and evaporative boundary conditions complete the formulation of mass balance (Arballo *et al.*, 2012a).

The Stage 2 of microwave dehydration starts when the entire product reaches T_{equi} and appears intense evaporation. This stage finishes at the end of the constant temperature period. In relation to energy transfer, temperature is considered to be in an equilibrium value within the food. At this stage the absorbed power is considered by taking into account the dielectric properties of the dehydrated food (α_d):

$$P = P_0 e^{(-2a_d\,(L-x))} \qquad \cdots\cdots \text{Eq. 6}$$

Furthermore, the model considers the operating mode of the microwave oven: continuous application or intermittent.

During the final stage, water evaporation occurs volumetrically within the food. The vapor generation is calculated considering that all volumetric absorbed microwave power (Q, W/m^3) is utilized to vaporization:

$$m_v = L_{vap}\int_0^V Q\,dV \qquad \cdots\cdots \text{Eq. 7}$$

where m_v is the velocity of removed water (kg/s) and L_{vap} is the latent heat of vaporization (J/kg).

Numerical solution In stage 1 energy and mass transfer balances (Equations 1 and 5) with their initial and boundary conditions form a system of nonlinear differential equations that have to be solved using a numerical method. Crank-Nicolson finite difference method was used for solving the final equation system. In stage 2 moisture content for each time step was calculated using equation 7 (Arballo *et al.*, 2012b). The numerical solution to obtain temperatures and moisture profiles were coded in Matlab 7.2 (Mathworks, Natick, MA, USA).

Results and Discussion

Application of the microwave dehydration model to potato slices

Case 1: Absorbed microwave power density 5.47 W/g The microwave dehydration (MWD) model was applied to experimental data of potato dehydration with microwaves. The trials were conducted in a microwave oven with 700 W of nominal power and the air temperature was 18 ℃, the analyzed samples corresponded to potato slabs of 15 mm thick (Bouraoui *et al.*, 1994). The process parameters and the physical and electromagnetic properties of food which were used in the mathematical modeling are shown in Table 1.

In the specific case of potato, dielectric properties must be specially evaluated; taking into account the modifications that food suffers due to the change of starch structure as a result of thermal processing (Sipagioglu and Barringer, 2003). Fig. 1a shows the variation of the dielectric constant (ε') and the loss

Table 1. Parameters and properties for vegetables microwave drying model

Variable	Potato	Carrot
Density (kg/m^3)	1085[a]	1079[b]
Thermal conductivity (W/(m K))	0.6835[a]	0.552[b]
Heat capacity (J/(kg K))	3600[a]	3792[b]
Moisture diffusivity (m^2/s)	$3.07\ 10^{-10}$ [b]	$2.6\ 10^{-10}$
Permitivity, ε' (T<62.78)	$50.7697+0.0263\ T-0.0013\ T^2$	$77.94-0.2068\ T$
(62.78<T<70.06)	$267.0001-7.3227\ T+0.0609\ T^2$	---
(T>70.06)	$18.8947+0.8982\ T-0.0058\ T^2$	---
Dielectric loss factor, ε"	$17.79-0.1357\ T+0.001370\ T^2$	$21.68-0.1040\ T+0.0016\ T^2$
Attenuation factor, α	$63.2884-0.4919\ T+0.0055\ T^2\ (T<62.78)$	$63.4587-0.2775\ T+0.0054\ T^2$
	$-37.2846+2.9674\ T-0.0241\ T^2\ (62.78<T<70.06)$	---
	$81.0523-0.9642\ T+0.0079\ T^2\ (T>70.06)$	---
Attenuation factor for stage 2, α_d	43	90
Initial temperature (℃)	20	15
Equilibrium temperature (℃)	103	30
Air temperature (℃)	18	30
Air velocity (m/s)	0.51	1
Vacuum pressure (kPa)	---	3
Diameter (mm)	50	40
Thickness (mm)	15	4
Microwave power density (W/g)	4.38^{c}-5.49^{d}	1.49[e]
Initial moisture (kgwater/kg (wet basis))	0.75	0.88
Relative humidity (kgwater/kg (wet basis))	0.65	0.62

[a] Lamberg and Hallstrom (1986); [b] Srikiatdena and Roberts (2008); [c,d,e] Experimental data extracted from (c) Durance and Yaghmaee (2011), (d) Bouraoui et al. (1994) and (e) Cui et al. (2005).

factor (ε") with the temperature increase obtained from the corresponding correlations (Table 1). By observing the curve of the dielectric constant, a discontinuity between 62 and 70 ℃ can be clearly visible due to the starch denaturation.

From the equations of the dielectric constant (permitivity) and loss factor as a function of temperature (Table 1), attenuation factor (α) was calculated using the equation 3 for each specific range of temperature (Fig. 1b). Correlations obtained for attenuation factor as a function of temperature were incorporated to the computer code to carry out the simulations.

Predicted moisture and temperature profiles obtained from the numerical solution of the energy and mass transfer equations (Equations 1 and 5) during 200 s of heating were compared to moisture and temperature experimental data. Fig. 2a and b show the experimental and simulated temperature and moisture as function of time during MWD of potato. It may be observed that average experimental temperatures (Fig. 2a) obtained by Bouraoui *et al.* (1994) validate the previous assumption of the existence of two stages in MWD. A first stage of fast heating until 83 s may be verified and afterwards the temperature stays constant (T_{equi}) during the following 120 s.

Regarding the evolution of moisture content (Fig. 2b), two distinct stages may be observed as well, an initial stage in which evaporation is weak or almost non-existent, and a second stage in which evaporation is intense. It may be clearly observed that the developed mathematical model simulates the two forementioned stages accurately accomplishing a proper prediction of dehydration times.

Case 2: Absorbed microwave power density 4.38 W/g The MWD model was also applied to the dehydration process of potato, which was subject to a microwave power density of 4.38 W/g during 300 s. Moisture and temperature profiles were simulated and compared to experimental data of water content and average temperature at each processing time (Durance and Yaghmaee, 2011). Fig. 3a and b show the thermal histories and the evolution of experimental moisture content and those simulated, during MWD of potato. Table 1 shows the employed parameters and properties for the numerical simulations.
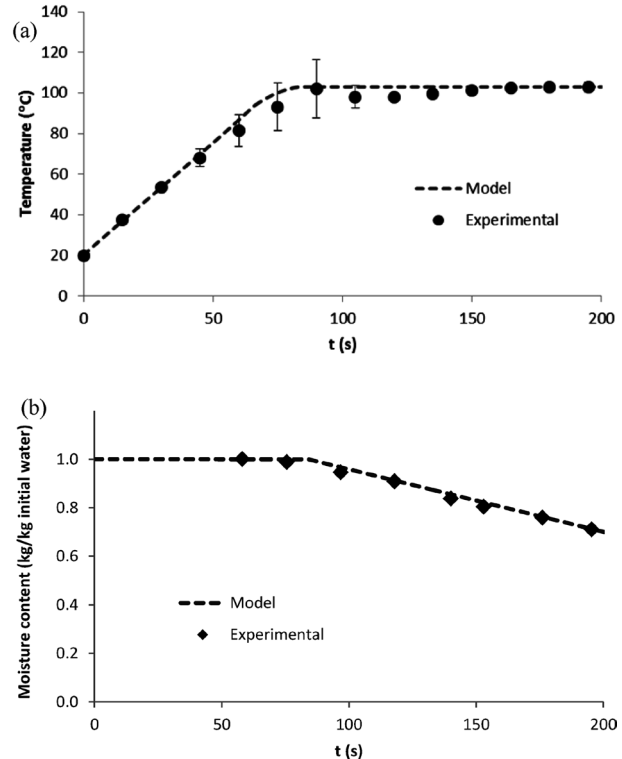
Analyzing the time necessary to reach the equilibrium temperature, Fig. 3a shows that from 90 s of heating the food material started intense evaporation. This effect is confirmed by the moisture evolution (Fig. 3b) which shows that from 90 s the water loss rate increases significantly remaining high until 300 s.

Regarding the application of the mathematical model to the experimental data it may be observed (Fig. 3a) that until 50 s the curve of mean temperatures is properly predicted and
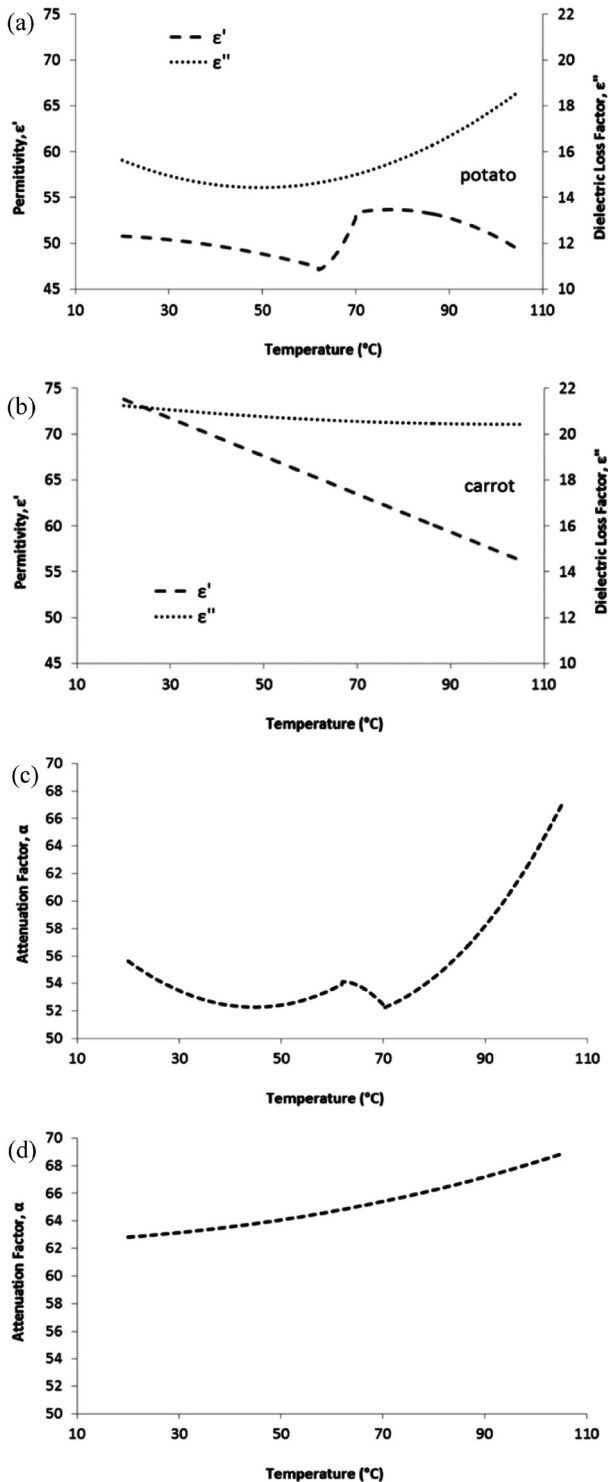
Fig. 1. Variation of dielectric properties of vegetables with temperature: Dielectric constant and loss factor of (a) potato and (b) carrot; attenuation factor of (c) potato and (b) carrot. (Microwave frequency applied 2450 MHz).

Fig. 2. Predicted and experimental (a) temperature and (b) moisture content during MWD of potato (microwave power density 5.47 W/g and air temperature 18 ℃). (Simulated values from numerical solution of Equations 1 and 5 and experimental data extracted from Bouraoui *et al*., 1994).

afterwards it deviates noticeably until 150 s. These deviations between simulations and experimental data may be due to the appearance of hot and cold spots within the food. They are produced by a non-homogenous distribution of the electromagnetic field generated by the application of microwaves; similar results were obtained in previous studies made by the authors (Sungsoontorn *et al*., 2011; Arballo *et al*., 2012a).

Despite of these deviations on the prediction of temperature profiles, the simulations of humidity reduction with time (Fig. 3b) follow with great accuracy the evolution of dehydration process.

In addition, considering the effect of microwave power density, it may be observed comparing Fig. 2a and 3a that the simulations properly predict the modification of the temperature profiles due to the effect of the increase of microwave power density from 4.38 W/g (Fig. 3a) to 5.48 W/g (Fig. 2a). As a result, the times needed to reach the balance temperature were 90 s and 82 s, respectively; showing, as could be expected, that at higher power density higher heating rate.

Application of the microwave dehydration model to carrot slices Table 1 shows the parameters and properties necessary for the application of the mathematical model to MWD of carrot. Considering the dielectric properties of carrot (Fig. 1b), the loss factor and permittivity present important differences in comparison with potato (Fig. 1a). Both dielectric properties in
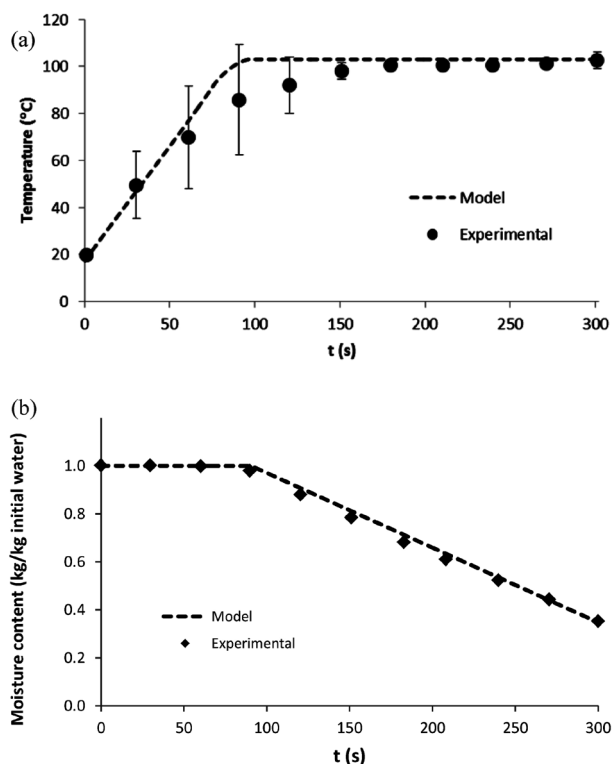
Fig. 3. Predicted and experimental (a) temperature and (b) moisture content during MWD of potato slabs (power density 4.38 W/g). (Simulated values from numerical solution of Equations 1 and 5 and Experimental data extracted from Durance and Yaghmaee, 2011).
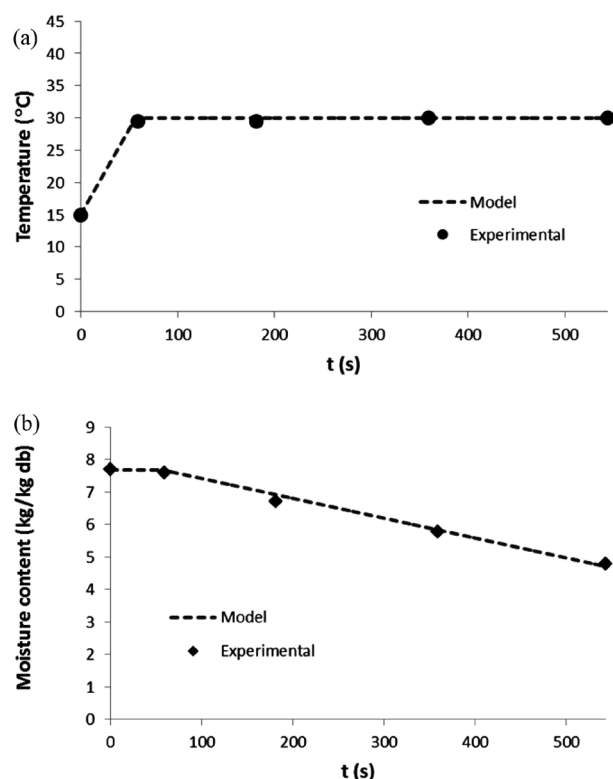
Fig. 4. Predicted and experimental (a) temperature and (b) moisture content during MWD of carrot slabs. (Simulated values from numerical solution of Equations 1 and 5 and Experimental data extracted from Cui *et al*., 2005).

carrot show a continuous progression of values as function of temperatures without a transition zone. In addition, it can be mentioned that the values of the loss factor (ε'') decrease with increasing temperature, and in the same way the permittivity (ε') decreases linearly with the evolution of the temperature, taking values between 74 to 57 for temperatures between 20 to 100°C, respectively.

The trials were conducted in a microwave oven of 359 W nominal power and the air temperature was 30 ℃. The analyzed samples corresponded to product slabs 4 mm thick. Simultaneously to the thermal process the samples were subjected to a vacuum pressure of 3 kPa (Cui *et al*., 2005).

In this way, moisture content and temperature profiles were obtained for 550 s of heating and compared to moisture and temperature experimental curves. Fig. 4a and b show the thermal histories and the experimental humidity evolution and those simulated during MWD of carrot under vacuum process conditions.

As can be seen in Fig. 4a the balance temperature was established in 30 ℃, due to the vacuum pressure applied, which produces a relevant reduction on the boiling point of water. Therefore, the temperature that initialized the intense evaporation process decreased dramatically from 103 ℃ in

dehydrated potato at atmospheric pressure, to 30 ℃ with the vacuum application in carrot.

Considering the quality of predictions it may be observed that the model adapted satisfactorily to the established vacuum conditions and the temperature profiles followed with total accuracy the evolution of experimental data until 550 s. Likewise, it can be appreciated in Fig. 4b that the simulations of moisture content evolution accurately predict experimental data obtained by Cui *et al*. (2005).

Conclusions

The mathematical model of microwave dehydration (MWD) was successfully validated for different vegetables and processing conditions (microwave power, pressure and size). The dependence of dielectric properties with temperature was properly evaluated achieving a high accuracy in the prediction of the mean temperature evolution of the product with time.

In this way, the developed model may be used to predict weight and water loss in a wide range of operating conditions during the MWD process of vegetables.

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