Mathematical modeling of microwave-assisted convective heating and drying of grapes

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Abstract: This research studied the processing performance and product quality of Thompson seedless grapes dried using microwave-assisted convective hot air drying as well as the effect of blanching and dipping pretreatments. Two pretreatment methods were compared, dipping into 2% ethyl oleate (V/V) and 5% potassium carbonate solution (m/V) at 40℃ for 3 minutes and steam blanching at 90℃ for 140 s, to accelerate drying rate and inactivate PPO aiming to improve drying rate and product color. Pretreated grapes were dried in a microwave-assisted convective dryer at 0.25 W/g specific power and 60℃ air temperature. In this study dielectric and physical properties of grapes were calculated using descriptive equations for fruits and vegetables. Semi-theoretical models were used to describe the drying curves of both pretreated and untreated grapes. Center and near surface temperature profile of grapes was obtained using fiber optic probes. Experimental center temperature was modeled using one dimensional heat equation and was simulated using Partial Differential Equation toolbox of Matlab. The results showed that the maximum difference between experimental and predicted values were 4℃ which occurred at the initial heating up period. It has been observed that dipping into solution had no effect on drying rate whereas steam blanching significantly reduced the drying time and produced product with desirable color.

Keywords: Microwave, drying, grapes, mathematic modeling, thin-layer, curve fitting
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1 Introduction

Grapes are one of the fruit crops most widely grown throughout the world[1]. They are grown on six continents in 62 different countries, each with a minimum of 12,000 acres (5,000 hm^2) in production, supplying grapes to commercial trade[2]. United States and Turkey are the largest raisin producers in the world and account for about 80 percent of global production[3].

Mass production of dried raisins is often accomplished through the use of convective dryers[4]. The dryers use hot air resulting in slow heat transfer rate, long drying time and undesirable brown color of finished products. The main problem in grape drying has been slow drying rate due to waxy layer at skin and the browning reactions that took place due to polyphenol oxidase (PPO) enzyme. Dipping in hot water or the use of chemicals such as sulphur, NaOH, and ethyl or methyl oleate emulsions are some of pretreatments widely used for grape drying to increase drying rate and improve the color quality of raisins[5,6]. Blanching can serve a variety of functions, such as destruction of enzymatic

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activity and improvement of drying rate in some fruits prior to further processing. It may be applied either by immersing food in hot water or by spraying steam onto the food[7].

The ability of microwave radiation to penetrate the materials can lead to controlled, precise heating, which improves the drying rate of food materials[8]. Microwave heating in food processing applications is promising, but successful application of microwave heating relies on a complete understanding of the interaction between microwaves and foods, and on the ability to predict and provide a desired heating pattern in foods for specific applications[9]. Microwave drying has been applied to several agricultural products: American Ginseng roots[10], apple[11], banana[12], carrot[13], kiwifruits[14], mushroom[15], parsley[16], and potato[17]. However, volumetric heating from microwave energy may create a water film on the surface due to lower ambient air temperature surrounding the product and if not dealt with in a suitable manner, may lead to electrical surface conduction and damage the product[18]. Thus in order to remove surface moisture, microwave energy is generally combined with other technologies such as hot air, infrared or vacuum. The combined use of microwave and convective drying not only greatly enhances the drying rate but may also improve the final product quality[15].

According to Zhang and Datta[18] microwave heating performance of foods inside ovens is affected by several factors, such as the strength and distribution of electromagnetic fields where the food is placed, reflection of electromagnetic waves from the food and propagation of the waves inside the food as characterized by the food properties and geometry. Therefore, it is important to study and predict the drying and heating characteristics of grapes under microwave-assisted convective drying.

The objectives of this research were to (1) develop a mathematical model for predicting the center temperature profile of grapes during microwave-assisted convective drying taking moisture dependent dielectric properties and total absorbed microwave power into account; (2) describe the drying curves of pretreated and untreated grapes using semi-theoretical models and (3) investigate the effect of microwave-assisted convective drying on the color of dried grapes.

2 Mathematical modeling of heat and mass transfer

2.1 Heat transfer modeling

In order to explain the heating profile of grapes during microwave-assisted convective drying, a mathematical model was proposed by applying one-dimensional heat transfer equation in cylindrical coordinates when the grape was assumed as an infinite cylinder. Heat supplied by microwaves was considered as internal heat generation and heat transferred from/to convective air was taken as boundary condition. After the near surface temperature of grapes reached 55℃, it was observed that the increase in center temperature of grapes was faster than that near surface temperature. To understand the mechanism of microwave heating of grapes at the hottest point to prevent the overheating of the product, only the center temperature was modeled during microwave-assisted convective drying of grapes. Moisture transfer was modeled by using the semi-theoretical Lewis model which was derived from simplification of general solution of Fick's second law[19]. During microwave-assisted convective drying of grapes, heat loss due to water vapor loss was taken into consideration as evaporative heat loss term.

To develop the mathematical models used to predict the moisture content and temperature profile during microwave-assisted convective drying of grapes, the following assumptions were made:

1) The initial temperature and moisture of grape were uniform.

2) The length/diameter of the grapes used in the experiments was 1.60±0.14 and since lateral area of grapes was much larger than the top and the bottom, the grapes were assumed as infinite cylinders with heat transfer only in radial direction.

3) Heat losses due to radiation were not considered.

4) Since the radius of the grape was longer than the penetration depth of microwaves, the electric field strength within the grape was assumed to be non-uniform.

The general approach made by Datta[20] was adopted during the establishment of the heat transfer model as shown in following one-dimensional equation (1) in Cartesian coordinates:

$$\underbrace{\rho \cdot C_p \cdot \frac{\partial T}{\partial t}}_{\substack{\text{rate of}\\ \text{energy}\\ \text{accumulation}}} + \underbrace{\rho \cdot C_p \cdot u \cdot \frac{\partial T}{\partial x}}_{\substack{\text{convective}\\ \text{energy flow}}} = \underbrace{k_T \cdot \frac{\partial^2 T}{\partial x^2}}_{\substack{\text{diffusive}\\ \text{energy}}} + \underbrace{\dot{Q}}_{\substack{\text{microwave}\\ \text{heat generation}}} - \underbrace{\frac{\dot{m}_{w,loss} \cdot h_{fg}}{V}}_{\substack{\text{energy used}\\ \text{in internal}\\ \text{evaporation}}} \qquad (1)$$

Where $\dot{Q}$ (W/m^3) is volumetric heat generation, T is temperature at position x and time t, u is velocity of air (m/s), k_T is thermal conductivity, W/(m·K), ρ is density, (kg/m^3), C_p is specific heat, J/(kg·K), $m_{w,loss}$ is the water vapor loss, (kg/s), h_{fg} is enthalpy of vaporization, (J/kg) and V is the volume of grapes, (m^3). The convective energy flow term in equation (1) was taken into consideration as boundary condition. $m_{w,loss}$ in equation(1), which refers to the amount of water vapor evaporated from the grape, was calculated using thin-layer equations, which take into account different mass transfer modes and structural changes such as shrinkage.

Partial Differential Equation (PDE) toolbox of Matlab was used for the heat transfer simulation. In this toolbox Generic Scalar type of equation was selected and the partial differential equation was specified to be parabolic type. Therefore, general equation for transient heat conduction in cylindrical coordinates is as follows:

$$\rho \cdot C_p \cdot \frac{\partial T}{\partial t} = \frac{1}{r} \cdot \frac{\partial}{\partial r}\left(k_T \cdot r \cdot \frac{\partial T}{\partial r}\right) + \dot{Q} - \frac{\dot{m}_{w,loss} \cdot h_{fg}}{V} \tag{2}$$

Where r is radius (m) of grapes. In this study due to constant temperature of heating air, the Neumann boundary condition was selected. Boundary conditions were expressed as follows:

$$\begin{aligned} k_T \cdot \frac{\partial T}{\partial r} &= h \cdot (T - T_\infty), \qquad r = R \\ \frac{\partial T}{\partial r} &= 0, \qquad r = 0 \end{aligned} \tag{3}$$

Where h and T_∞ were convective heat transfer coefficient, W/(m^2 •K) and temperature (℃) of heated air, respectively. The velocity of the hot air in the microwave oven was 1.9 m/s and the convective heat transfer coefficient, h, was calculated as 29.73 W/(m^2 • K) using equation (4).

$$Nu = \frac{h \cdot D}{k_T} = 0.683 \cdot \mathrm{Re}^{0.466} \cdot \mathrm{Pr}^{1/3} \tag{4}$$

During microwave heating of biological materials the increase in temperature (ΔT) can be calculated from equation (5)[21]:

$$\rho \cdot C_p \cdot \frac{\Delta T}{\Delta t} = 5.563 \times 10^{-11} f \cdot E_0^2 \cdot \varepsilon'' \tag{5}$$

Where E_0 (V/m) is electric field intensity inside the cavity and f (Hz) is frequency, which are functions of the equipment. It should be noted that the right part of the equation is equal to microwave energy deposition whereas the left side of the equation assumes that heating is uniform within the material. To find the electric field within the microwave cavity, calorimetric method was used. In this method the average microwave power received by a drying sample is assumed to be approximately the same as the power received by the distilled water. In order to prevent any evaporative heat loss at high temperatures, 600 mL distilled water was heated from 5℃ to 20℃ using 150 W microwave power. Temperature data were collected every 30 s and the temperature rise with time ($\Delta T/\Delta t$) was found as (0.025±0.001)℃/s by linear curve fitting of the data points (R^2=0.99). Using equation (5) electric field intensity within the cavity, E_0, was found to be 248.29 V/m.

Predictive equations for dielectric properties of fruits and vegetables at 2450 MHz are given as follows[22]:

$$\varepsilon' = 2.14 - 0.104T + 0.808X_w \tag{6}$$

$$\varepsilon'' = 3.09 - 0.0638T + 0.213X_w \tag{7}$$

Where ε' and ε'' are dielectric constant and dielectric loss factor, respectively, T is temperature (℃) and X_w is the percentage of moisture in wet basis.

When exposed to an electromagnetic field, the amount of thermal energy converted in food is proportional to the value of the loss factor ε''. The decay in electric field strength (E_0) along the radius of grapes can be calculated using equation (8):

$$E(r) = E_0 \cdot e^{-\alpha \cdot r} \tag{8}$$

Where α is the attenuation factor. The degree of decay is determined by an attenuation factor (equation (9)), which in turn is a function of the material[23]:

$$\alpha = \frac{2\pi}{\lambda_0} \cdot \left[\frac{1}{2} \cdot \varepsilon' \cdot \left(\sqrt{1 + \left(\frac{\varepsilon''}{\varepsilon'}\right)^2} - 1\right)\right]^{\frac{1}{2}} \tag{9}$$

Where λ_0 is the free space wavelength.

The incident electric field, E_0, decays exponentially within the grape. In order to obtain the average electric field within the grape, the integral average of electric field is calculted as follows:

$$E_{average} = \frac{\int_0^r E_0 \cdot e^{-\alpha \cdot r} \cdot dr}{\int_0^r dr} \tag{10}$$

Where radius, r, was 10.3 (mm) and attenuation factor, α, was 48.50 (Np/m). Average electric field within the grape was calculated as 195.39 V/m.

Due to its simplicity, Lewis model below can be used to describe the change of moisture ratio with time:

$$MR = \frac{M(t) - M_e}{M_0 - M_e} = e^{-k \cdot t} \quad (11)$$

Where *MR* is the moisture ratio, $M(t)$ is moisture content (d.b.), M_e is equilibrium moisture content (d.b.), M_0 is initial moisture content (d.b.) and k is drying constant (min^{-1}). The equilibrium moisture content was assumed to be zero for microwave drying[12,16,24]. Taking the time derivative of equation (11) and replacing $M(t)$ with $m_w(t)/m_s$ the equation (12) gives moisture loss of the grapes by evaporation:

$$\dot{m}_{w,loss} = \frac{\mathrm{d}m_w(t)}{\mathrm{d}t} = -(k/60) \cdot e^{-(k/60) \cdot t} \cdot (M_0 - M_e) \cdot m_s \quad (12)$$

Where $m_w(t)$ is the time dependent water mass content (kg) and m_s is the solid mass content (kg) of grape.

Thus the change of percentage moisture content with time can be expressed as:

$$\frac{\mathrm{d}X_w}{\mathrm{d}t} = \frac{m_{w,i} - \dot{m}_{w,loss}}{m_i - \dot{m}_{w,loss}} \times 100 \quad (13)$$

Where m_i and $m_{w,i}$ were the initial weight of grape and initial weight of moisture in the grape, respectively. Replacing the right part of equation (5) with the frequency (Hz) of the microwaves, the average electric field (V/m) within the grape and the time derivative of dielectric loss factor (equation (7)) gives:

$$\dot{Q} = 1108.30 \cdot \frac{\mathrm{d}X_w}{\mathrm{d}t} \quad (14)$$

Replacing the water vapor loss term in energy used in internal evaporation and microwave heat generation in equation (2) with equation (12) and (14), respectively, then equation (2) becomes as equation (15) and is then solved by using PDE toolbox of Matlab which uses finite element method to solve partial differential equations.

$$\rho \cdot C_p \cdot \frac{\partial T}{\partial t} = \frac{1}{r} \cdot \frac{\partial}{\partial r}\left(k_T \cdot r \cdot \frac{\partial T}{\partial r}\right) + 1108.30 \cdot \frac{\mathrm{d}X_w}{\mathrm{d}t} - \frac{\left(-(k/60) \cdot e^{-(k/60) \cdot t} \cdot (M_0 - M_e) \cdot m_s\right) \cdot h_{fg}}{V} \quad (15)$$

2.2 Mass transfer modeling

During microwave-assisted convective drying of untreated and dipped grapes, a heating rate, a constant drying rate and two falling rate periods were observed. However, the microwave-assisted convective drying of steam blanched grapes mainly took place in the falling rate period which was preceded by a heating rate period. Mass transfer during constant-rate and falling-rate periods involves liquid and vapor diffusion mechanisms and can be described by Fick's second law[25]. As proposed by Midilli[26] semi-theoretical models are adequate for design and analysis of drying processes. Several authors used the semi-theoretical thin-layer equations to describe the drying curves of fruits and vegetables. Page equation was used by Margaris and Chiaus[27] to describe drying curve of Sultana grapes and by Doymaz[19] for black grapes. Ertekin and Yaldiz[28] observed that Midilli equation best described the hot air drying of eggplants. Doymaz[29] found that experimental data of hot air drying of mulberries showed a better fit to Logarithmic model. The Midilli equation was proposed by Midilli[26] to describe the solar drying of pollen, pistachio and mushroom. Roberts[30] observed that hot air drying kinetics of grape seeds can be described by Lewis and Handerson and Pabis model by less than 10% error where the error in prediction by Lewis model was less than 5%. Thus some semi-theoretical thin-layer models, derived from general solution of Fick's second law by simplification, have been widely used in literature were also chosen to describe the drying curves of microwave-assisted convective drying of grapes (Table 1).

3 Materials and methods

3.1 Grapes

Thompson seedless grapes (*Vitis vinifera*) were bought from a local store in California, and were stored in plastic bags in a refrigerator at 4℃ until drying. Individual berries were sized using a caliper. The average diameter of the grapes which were used for drying was (18.34±1.50) mm and the average moisture content was (80.25±1.91)% (w.b.). Grapes were washed with tap water and their surfaces were dried with a paper towel.

Density (ρ), specific heat (C_p) and thermal conductivity (k_T) of the grapes were calculated by using equations (16), (17) and (18), respectively and found as 1077.932 kg/m^3, 3.395 kJ/(kg·K) and 0.479 W/(m·K), respectively.

$$\rho = \frac{1}{\sum \frac{x_i}{\rho_i}} = \frac{1}{\frac{x_C}{1600} + \frac{x_P}{1320} + \frac{x_F}{920} + \frac{x_A}{2420} + \frac{x_W}{1000}} \quad (16)$$

$$C_p = 1.6x_C + 2.0x_P + 2.0x_F + 1.1x_A + 4.2x_W \quad (17)$$

$$k_T = k_{T,water} \cdot \frac{C_{p,grape}}{C_{p,water}} \quad (18)$$

Where in equations (16) and (17), x is mass fraction of the respective component and the subscripts *C*, *P*, *F*, *A* and W denotes carbohydrate, protein, fat, ash and water, respectively. The carbohydrate, protein, fat, ash and water content of grapes were taken as 18.10, 0.72, 0.16, 0.48 and 0.81, respectively[35].

3.2 Microwave-assisted convective drying

The schematic of the combined hot air and microwave drying system is given in Figure 1. The microwave oven was powered by a 2450 MHz magnetron with continuous variable power control from 0-2,500 W (GAE Inc., Modesto, CA). The magnetron was connected to the oven cavity using WR-284 waveguide components. The oven cavity measured 0.88 m × 0.88 m × 0.88 m and had two-mode stirrers operating at 30 and 35 r/min. Both the cavity and mode stirrers were made of aluminum. Input and reflected power were measured using power meters (Model 435B, Hewlett Packard Corp., Santa Clara, CA) connected to a directional coupler in the waveguide. The microwave oven was designed to ensure uniform heating within the cavity[36]. The input specific power was 0.25 W/g, and 3 fiber optic probes (Model 790 Thermometry System, Luxtron Corporation, Santa Clara, CA) were used to monitor center and near surface temperatures of a grape, and the entering air temperature. Weight loss was monitored by taking the grapes out and measuring the weight using a balance (Mettler TE 30, 0.01 kg accuracy).

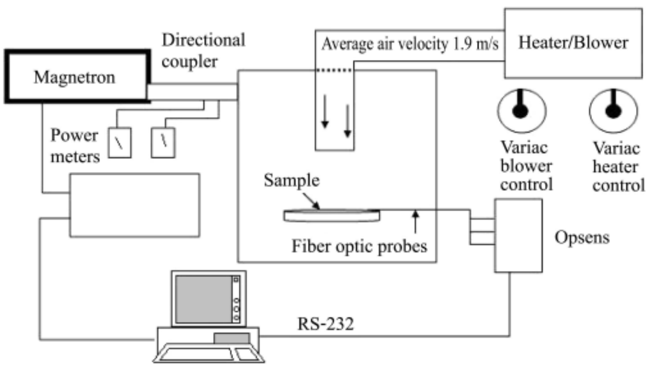

Figure 1 Set up of microwave-assisted convective drying system

3.3 Pretreatments

The grapes were either dipped into 2% ethyl oleate (V/V) and 5% potassium carbonate (m/V) mixture at 40℃ for 3 min or blanched in a steam blancher (Dixie Canner, Athens, GA, USA) at 90℃ for 140 seconds. The grapes that were not pretreated were referred as control.

3.4 Color analysis

Surface color of the samples from each treatment was measured using Minolta Spectrophotometer (CM-508d, Minolta Co. Ltd., Japan). The reported color values are the average values of 10 readings of each sample measured. Color was expressed in CIE values as L^* (whiteness/darkness), a^* (redness/greenness) and b^* (yellowness/blueness). Total color change and Hue angle were calculated using equation (19) and (20), respectively.

$$\Delta E = \sqrt{(L_0 - L_r)^2 + (a_0 - a_r)^2 + (b_0 - b_r)^2} \qquad (19)$$

$$Hue^\circ = \begin{cases} \tan^{-1}\left(\dfrac{b}{a}\right)\cdot\dfrac{180}{\pi}, & a > 0, b > 0 \\ \tan^{-1}\left(\dfrac{b}{a}\right)\cdot\dfrac{180}{\pi} + 180, & a < 0, b > 0 \end{cases} \qquad (20)$$

Where subscript "0" and "r" refer to the color of the fresh grapes and raisins, respectively. A large ΔE value indicates a great color change from the original reference state. The hue angle represents color by a positive number between 0° and 360°, where 0° is red-purple, 90° is yellow, 180° is bluish-green and 270° is blue. It is widely used in the evaluation of color parameters of fruits[14].

3.5 Statistical analysis

Non-linear regression analyses were performed to thin-layer mass transfer models (Table 1) regarding moisture ratio versus time data, using Matlab software (Natick, MA). Three criteria were adopted to evaluate the goodness of fit in each model: the R^2 (regression coefficient), *SSE* (Sum of Squares Due to Error) and *RMSE* (Root Mean Square Error).

$$SSE = \sum_{i=1}^{N}\left(MR_{\exp,i} - MR_{predict,i}\right)^2 \qquad (21)$$

$$RMSE = \left[\frac{1}{N}\sum_{i=1}^{N}\left(MR_{\exp,i} - MR_{predict,i}\right)^2\right]^{1/2} \qquad (22)$$

Where $MR_{exp,i}$ is the experimental moisture ratio; $MR_{predict,i}$ is the predicted moisture ratio; N is the number of experimental points. For both *SSE* and *RMSE* a value closer to 0 indicates a better fit.

4 Results and discussion

4.1 Drying kinetics

Our previous experiments showed that specific powers higher than 0.25 W/g did not result in raisins of acceptable quality. Center temperature of grapes at specific powers of 0.5 W/g and 1 W/g rose over 85° and 100℃, respectively, which are not considered as safe drying temperatures for grapes. Thus specific power of 0.25 W/g was used for microwave-assisted drying and the simulation of center temperature profile of grapes. This is in agreement with Tulasidas[37] who observed that specific power levels higher than 0.3 W/g (15 W to 50 g of samples) was unsuitable for grapes.

The drying kinetics of microwave-assisted convective drying of untreated and pretreated grapes is shown in Figure 2. The authors' previous experiments showed that dipping grapes into ethyl oleate and potassium carbonate solution at 40℃ for 3 minutes prior to hot air drying at 60℃ reduced the drying time by 41.1%, until 20% moisture content in wet basis. Similar findings were reported by Pangavhane et al.[38] for hot air drying of Thompson seedless grapes. However, the dipping pretreatment did not improve drying rate during microwave-assisted hot air drying, which is consistent with the research by Tulasidas[37] who observed that dipping grapes into 3% ethyl oleate and 2.5% potassium carbonate at 40℃ for 3 minutes was not effective in reducing the drying time for microwave drying. However, steam blanching that reduced the hot air drying time of grapes by 76.4% also significantly reduced the drying time of microwave-assisted convective drying of grapes. There was 66.7% of reduction in drying time of steam blanched grapes compared to untreated samples to 20% moisture content in wet basis.

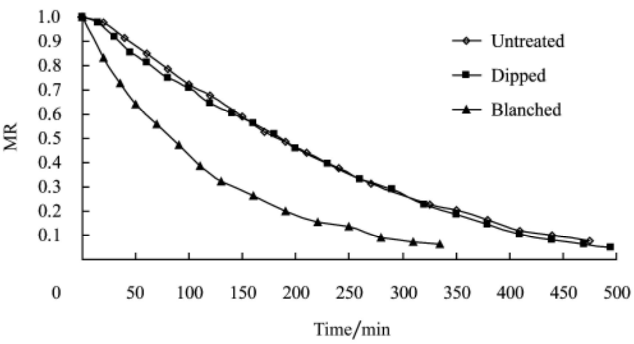

Figure 2 Drying curves of grapes with different pretreatments under microwave-assisted convective drying (0.25 W/g specific power at 60℃ air temperature)

Drying curves of microwave-assisted convective drying of both untreated and pretreated grapes at 0.25 W/g specific power and 60℃ convective air temperature could be accurately described by the thin-layer models given in Table 1. The constants of the thin-layer models applied to both pretreated and untreated grapes are presented in Table 2 and R^2, *RMSE* and *SSE* values are given in Table 3. A two-way ANOVA test for each criterion and treatment in Table 3 revealed that there were no significant differences ($P>0.05$) between R^2 and *SSE* values of pretreated and untreated grapes; however, there were significant differences ($P<0.05$) between the R^2, *RMSE* and *SSE* values of proposed models. It was observed that the Midilli equation gave the highest average value for R^2 and lowest average values for SSE and *RMSE* for untreated and pretreated grapes among the proposed models. It was therefore concluded that microwave-assisted convective drying of grapes can be best described by Midilli equation.

Table 1 Thin-layer models used for predicting the drying rate of grapes

Model	Mathematical expression	References
Lewis	$MR = \exp(-kt)$	(Lewis[31])
Page	$MR = \exp(-kt^n)$	(Page[32])
Henderson and Pabis	$MR = a\exp(-kt)$	(Henderson and Pabis[33])
Logarithmic	$MR = a\exp(-kt)+c$	(Yaldiz[34])
Midilli et. al.	$MR = a\exp(-kt^n)+bt$	(Midilli[25])

Table 2 Parameters of thin-layer models used for predicting the drying rate of grapes treated with different methods and dried with 0.25 W/g specific power and 60℃ convective air temperature

Model	Untreated	Dipped	Steam Blanched
Lewis	k=0.004	k=0.004	k=0.008
Page	k_1=0.00067 n=1.331	k_1=0.001 n=1.281	k_1=0.009 n=0.968
Henderson and Pabis	a=1.084 k=0.005	a=1.062 k=0.005	a=0.989 k=0.008
Logarithmic	a=1.346 k=0.003 c=-0.304	a=1.347 k=0.003 c=-0.330	a=0.983 k=0.008 c=0.007
Midilli et al.	a=1.009 k_1=0.001 n=1.260 b_2=-7.1·10^{-5}	a=1.001 k_1=0.002 n=1.119 b_2=-0.00023	a=0.998 k_1=0.010 n=0.961 b_2=-1.8·10^{-5}

Table 3 Statistical analysis results of thin-layer models used for predicting the drying rate of grapes treated with different methods and dried with 0.25 W/g specific power and 60℃ convective air temperature

Model	Untreated	Dipped	Steam Blanched
Lewis	R^2=0.973 *RMSE*=0.050 *SSE*=0.046	R^2=0.97 *RMSE*=0.047 *SSE*=0.047	R^2=0.999 *RMSE*=0.008 *SSE*=0.001
Page	R^2=0.999 *RMSE*=0.008 *SSE*=0.001	R^2=0.996 *RMSE*=0.020 *SSE*=0.008	R^2=0.999 *RMSE*=0.006 *SSE*=0.000
Henderson and Pabis	R^2=0.985 *RMSE*=0.038 *SSE*=0.024	R^2=0.983 *RMSE*=0.040 *SSE*=0.033	R^2=0.999 *RMSE*=0.007 *SSE*=0.000
Logarithmic	R^2=0.997 *RMSE*=0.016 *SSE*=0.004	R^2=0.998 *RMSE*=0.012 *SSE*=0.002	R^2=0.999 *RMSE*=0.007 *SSE*=0.000
Midilli et al.	R^2=0.999 *RMSE*=0.006 *SSE*=0.000	R^2=0.998 *RMSE*=0.011 *SSE*=0.002	R^2=0.999 *RMSE*=0.007 *SSE*=0.000

4.2 Temperature profiles and model validation

The penetration depth of grapes, like most of the biological materials, increased with decreasing moisture content. At the beginning of drying the penetration depth of the grapes was calculated as 8.1 mm and the radius of grape used in simulation was 10.3 mm. Thus unlike Souraki[39], the attenuation effect for grapes was taken into consideration since the microwave energy will decrease significantly until it reaches center. According to Lyons[40] during initial heating period when the solid material contains very high proportions of water, some moisture may be removed from the solid as liquid, due to filtrational flow driven by the total pressure gradient. This phase of drying precedes the constant or falling rate period of drying and is termed ‘liquid movement period’ [41]. It was observed that in the first 20 min of drying moisture content of grapes reduced only 0.38% (w.b.). Thus it was assumed that for the first 20 minutes, evaporative heat loss was negligible. This assumption is also in agreement with Boldor[42]. The experimental and predicted temperature profiles of grapes are shown in Figure 3. Maximum temperature difference between predicted and experimental temperature was approximately 4℃ occurred during initial heating up period. However after initial heating up period the difference was less than 1℃. It was also observed that after 110 min of drying the difference was slightly over 1℃ and gradually increased. The error in prediction of center temperature of grapes can be due to omitting shrinkage during drying and also from the accuracy of prediction of moisture content change of grapes described by Lewis model. Below 56% moisture content (w.b.) the experimental temperature values showed a sudden increase, which is shown by an arrow, which could not be estimated by the model proposed. This increase could be due to increase in sugar concentration which caused grapes to absorb more microwave energy. It is known that sugars modify the dielectric behavior of water. As proposed by Datta et al.[43] the increase in sugar concentration can either increase or decrease the loss factor of sugar solutions depending on temperature. This has also been reported by Padua[44] who observed that increased levels of sucrose caused the agars to absorb microwave energy more efficiently. At the temperatures above 40℃ the loss factor may increase with the increase of concentration since more hydrogen bonds will be stabilized by the presence of more hydroxyl groups of sugars. This phenomenon was also consistent with the previous observations such that when the hot air was insufficient to remove the diffusing grape juice charred spots occurred on grape surface. Also it was seen that as of 240 minutes, grapes’ moisture content reduced to 1.30 (d.b.) and second falling rate period initiated. With moisture content being a significant factor in how a food couples with microwave energy and converts it to heat, it was assumed that the increase in temperature at the center was due to the significant reduction in moisture content. The reduced moisture content results in reduced dielectric properties which will increase the penetration depth of microwaves that might cause significant focusing effects due to the shape of grapes. This focusing effects may result in the deposition of microwave energy coupled at the center that might become a significant factor in the enhanced heating of the center of grapes.

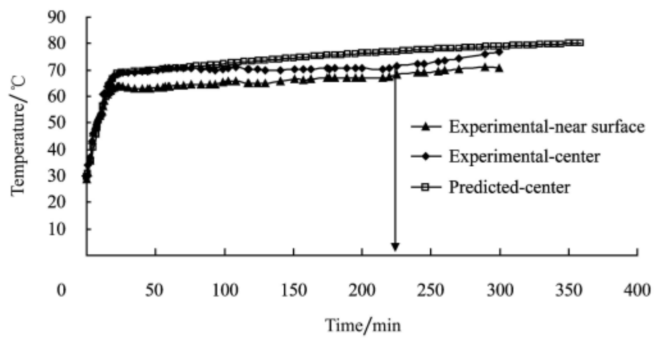

Figure 3 Experimental and predicted heating temperature curves of grapes during microwave-assisted convective drying

4.3 Color changes

The L^*, a^*, b^* and Hue° value of fresh grapes were 45.29±0.87, -1.96±0.31, 8.11±1.97 and 104.11±3.51, respectively. The color values of finished products dried with microwave-assisted convective drying are shown in Table 4. It is seen that there is no significant difference between the ΔE values of untreated, dipped and blanched grapes which might mean that rather than the pretreatment phase the microwave-assisted convective drying phase dominated the color change of grapes. However, blanching grapes prior to microwave-assisted convective drying improved the L^*-value and increased the Hue° value. It can therefore be concluded that pretreatment with steam before microwave-assisted convective drying improved the color properties thus raisins produced this way had the shiniest appearance. Initial a^* values of grapes were negative, indicating greenness and it was observed that regardless of the drying methods the final a^* value were positive which indicated a shift to redness. According to Clydesdale[45] during heat treatment the bright green chlorophylls generally degrade to a dull olive-brown which might be the cause of the shift from a negative to a positive *a** value. The highest hue angle and *L** values were obtained for steam blanched grapes which makes them shinier and more yellowish. It should also be noted that the hue angle values of untreated and dipped samples were almost the same, which makes them appear to have similar color to an observer.

Table 4 Final color values of grapes dried with 0.25 W/g specific power and 60℃ convective air temperature

Drying Method	*L**	*a**	*b**	ΔE	Hue°
Untreated	38.86±1.64	6.11±1.14	23.64±1.95	18.81±2.87	75.51±2.49
Dipped	34.71±1.16	5.74±1.86	20.86±2.54	18.40±1.93	74.44±5.88
Steam Blanched	40.68±2.31	4.39±2.13	27.35±3.28	21.17±3.33	80.91±4.31

5 Conclusions

The temperature predicted using the proposed heat transfer model generally matches well with the experimental data which indicates that the heat transfer model can be used for temperature prediction of grapes under microwave assisted convective drying. For mass transfer, among the proposed semi-theoretical models Midilli equation best described the drying curves of microwave-assisted convective drying of grapes. Unlike hot air drying of grapes, it was observed that there was no difference in drying rate of the microwave-assisted convective drying of chemically dipped and untreated grapes. However, similar to hot air drying, steam blanching significantly improved the microwave-assisted convective drying rate of grapes. Steam blanched grapes had desirable yellowish shinier appearance compared to the dipped and untreated grapes.

Nomenclature

a	Dimensionless constant
b	Drying Constant, min^{-1}
C_p	Specific heat capacity, J/(kg·K)
d.b.	Dry basis
D	Diameter of grape, m
d_p	Penetration depth, m
E	Electric field strength within the grape, V/m
E_0	Electric field strength in free space, V/m
f	Frequency, Hz
h	Convective heat transfer coefficient, $W/(m^2 \cdot K)$
h_{fg}	Latent heat, J/kg
k	Drying constant, min^{-1}
k_T	Heat conduction coefficient, W/(m·K)
M	Moisture content of grape, (d.b.)
M_0	Initial moisture content of grape, (d.b.)
M_{eq}	Equilibrium moisture content of grape, (d.b.)
MR	Moisture ratio
m_s	Solid content of grape, kg
m_w	The weight of evaporating water during drying, kg
Nu	Nusselt number
Pr	Prandtl number
Q	Microwave heat generation, W/m^3
R	Radius of grape, m
Re	Reynolds number
T	Temperature, ℃
t	time, s
w.b.	Wet basis
X_w	Percentage moisture content of grape, (w.b.)
α	Attenuation factor, Np/m
ε'	Dielectric constant
ε''	Dielectric loss factor
ρ	Density, kg/m^3

[References]

[1] Baydar N G, Ozkan G, Sagdic O. Total phenolic contents and antibacterial activities of grape (Vitis vinifera L.) extracts. Food Control, 2004; 15(5): 335－339.

[2] Petrucci V E, Clary C D. A Treatise on raisin production, processing and marketing. California: Malcolm Media Press. 2002.

[3] Raisin Situation and Outlook in Selected Countries. FAS Attache Report. http:// www.fas.usda.gov/htp/horticulture/ dried% 20fruits/ 01-31-05 %20Dried %20 Fruit % 20 (Raisins).pdf. Accessed on [2008-07-30].

[4] Nijhuis H H, Torringa H M, Muresan S, Yuksel D, Leguijt C, Kloek W. Approaches to improving the quality of dried fruits and vegetables. Trends in Food Science & Technology, 1998; 9(1): 13－20.

[5] Doymaz I, Pala M. The effects of dipping pretreatments on air-drying rates of the seedless grapes. Journal of Food Engineering, 2002; 52(4): 413－417.

[6] Pangavhane D R, Sawhney R L, Sarsavadia P N. Effect of various dipping pretreatment on drying kinetics of Thompson seedless grapes. Journal of Food Engineering, 1999; 39(2): 211－216.

[7] Fellows, P. Blanching in food processing technology: principles and practice. Second edition, Cambridge: Midway Technology Limited. 2000.

[8] Saltiel C, Datta A K. Heat and mass transfer in microwave processing. Advances in Heat Transfer, 1998; 32: 1－94.

[9] Tang J, Hao F, Lau M. Microwave heating in food processing, in advances in bioprocess engineering (Advances in Agricultural Science and Technology). editors Yang H, Tang J, London: World Scientific Publishing. 2002; pp. 1－44.

[10] Ren G, Chen F. Drying of American Ginseng (Panax quinquefolium) roots by microwave-hot air combination. Journal of Food Engineering, 1998; 35(4): 433－443.

[11] Andres A, Bilbao C, Fito P. Drying kinetics of apple cylinders under combined hot air-microwave dehydration. Journal of Food Engineering, 2004; 63: 71－78.

[12] Maskan M. Microwave/air and microwave finish drying of banana. Journal of Food Engineering, 2000; 44: 71－78.

[13] Wang J, Xi Y S. Drying characteristics and drying quality of carrot using a two-stage microwave process. Journal of Food Engineering, 2005; 68(4): 505－511.

[14] Maskan M. Drying, shrinkage and rehydration characteristics of kiwifruits during hot air and microwave drying. Journal of Food Engineering, 2001; 48: 177－182.

[15] Torringa E, Esveld E, Scheewe I, Berg R, Bartels P. Osmotic dehydration as a pre-treatment before combined microwave-hot-air drying of mushrooms. Journal of Food Engineering, 2001; 49(2/3): 185－191.

[16] Soysal Y. Microwave drying characteristics of parsley. Biosystems Engineering, 2004; 89(2):167－173.

[17] Srikiatden J, Roberts J S. Measuring moisture diffusivity of potato and carrot (core and cortex) during convective hot air and isothermal drying. Journal of Food Engineering, 2006; 74(1): 143－152.

[18] Zhang H, Datta A K. Electromagnetics of Microwave Heating: Magnitude and uniformity of energy absorption in an oven, in Handbook of Microwave Technology for Food Applications, editors Datta A K, Anantheswaran R C, New York: Marcel Dekker Inc. 2001: 33－67.

[19] Doymaz I. Drying kinetics of black grapes treated with different solutions. Journal of Food Engineering, 2006; 76(2): 212－217.

[20] Datta A K. Fundamentals of Heat and moisture transport for microwaveable food product and process development, in Handbook of Microwave Technology for Food Applications, editors Datta A K, Anantheswaran R C, New York: Marcel Dekker Inc. 2001: 115－172.

[21] Nelson S O. Review and assessment of radio-frequency and microwave energy for stored-grain insect control. Trans ASAE, 1996; 39(4): 1475－1484.

[22] Delgado A E, Sun D W, Rubiolo A C. Thermal physical properties of foods, in thermal food processing: New Technologies and Quality Issues, editors Sun D W, Florida: CRC Press Taylor & Francis Group. 2006: 3－34.

[23] Von Hippel, A. Dielectrics and waves. New York: Wiley, 1954.

[24] McMinn W A M. Thin-layer modelling of the convective, microwave, microwave-convective and microwave-vacuum drying of lactose powder. Journal of Food Engineering, 2006; 72(2): 113－123.

[25] Babalis S J, Papanicolaou E, Kyriakis N, Belessiotis V G. Evaluation of thin-layer models for describing drying kinetics of figs (Ficus carica). Journal of Food Engineering, 2006; 75(2): 205－214.

[26] Midilli A, Kucuk H, Yapar Z, A new model for single-layer drying. Drying Technology, 2002; 20(7): 1503－1513.

[27] Margaris D P, Ghiaus A G, Experimental study of hot air dehydration of Sultana grapes. Journal of Food Engineering, 2007; 79(4): 1115－1121.

[28] Ertekin C, Yaldiz O. Drying of eggplant and selection of a suitable thin layer drying model. Journal of Food Engineering, 2004; 63(3): 349－359.

[29] Doymaz I. Drying kinetic of white mulberry. Journal of Food Engineering, 2004; 61(3): 341－346.

[30] Roberts J S, Kidd D R, Padilla-Zakour O. Drying kinetics of grapes seeds. Journal of Food Engineering, 2008; 89(4): 460－465.

[31] Lewis W K. The rate of drying of solid materials. Industrial Engineering Chemistry, 1921; 13(5): 427–442.

[32] Page G E. Factors influencing the maximum rates of air drying shelled corn in thin layers. M. Sc. Thesis, Lafayette: Purdue University, 1949.

[33] Henderson S M, Pabis S. Grain drying theory I: Temperature effect on drying coefficient. Journal of Agriculture Research Engineering, 1961; 6: 169－174.

[34] Yaldiz O, Ertekin C, Uzun H I. Mathematical modeling of thin layer solar drying of sultana grapes. Energy, 2001; 26(5): 457－465.

[35] Nutrient Data Library, Available: http://www.nal.usda.gov/fnic/foodcomp/search/. Accessed on [2008-07-30].

[36] Roberts J S, Tong C H. The development of an isothermal drying apparatus and the evaluation of the diffusion model on hygroscopic porous material. International Journal of Food Properties, 2003; 6(1): 165－180.

[37] Tulasidas T N, Raghavan, G S V, Norris E R. Effects of dipping and washing pretreatments on microwave drying of grapes. Journal of Food Process Engineering, 1996; 19(1): 15－25.

[38] Pangavhane D R, Sawhney R L, Sarsavadia, P N. Effects of various dipping pretreatment on drying kinetics of Thompson seedless grapes. Journal of Food Engineering, 1999; 39(2): 211－216.

[39] Souraki B A, Andres A, Mowla D. Mathematical modeling of microwave-assisted inert medium fluidized bed drying of cylindrical carrot samples, Chemical Engineering and Processing: Process Intensification, 2008, Article in Press.

[40] Lyons D W, Hatcher J D, Sunderland J E. Drying of a porous medium with internal heat generation. International Journal of Heat and Mass Transfer, 1972; 15: 897.

[41] Metaxas A C, Meredith R J, Industrial microwave heating, editors Johns A T, Ratcliff G, Platss J R, London: Peter Peregrinus Ltd. 1998. p. 357.

[42] Boldor D, Sanders T H, Swartzel K R, Farkas B E. A model for temperature and moisture distribution during continuous microwave drying. Journal of Food Process Engineering, 2005, 28(1):68－87.

[43] Datta A K, Sumnu G, Raghavan G S V. Dielectric properties of foods, in Engineering Properties of Foods, editors Rao M A, Rizvi, S S H, Datta A K, Florida: CRC Press Taylor & Francis Group. 2005. pp. 501－557.

[44] Padua G W. Microwave heating of agar gels containing sucrose. Journal of Food Science, 1993; 58(6): 1426－1428.

[45] Clydesdale E M. Color: origin, stability, measurement, and quality, in Food Storage Stability, editors Taub I A, Singh R P, Florida: CRC Press LLC. 1998. pp. 175－191.