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Research Article

EFFECTS OF MICROWAVE POWERS ON DRYING KINETICS AND ENERGY EFFICIENCY OF TOMATO SAMPLES

***M. Abolhasani[1] and M. Ansarifar[2]**
[1]*Biosystems Engineering Department, Shiraz University, Shiraz, Iran*
[2]*Biosystems Engineering Department, Ferdowsi University of Mashhad (FUM)*
**Author for Correspondence*

ABSTRACT
Drying experiments of thin layer tomato samples were carried out by using microwave drying. The drying experiments were carried out at 200, 300, 400 and 500 W. The drying rate of tomato samples was changed with increased drying time under various microwave powers. The drying rates increased with the increasing microwave power levels. Dying processes were completed between 3.5-9.25 min for tomato samples depending on the microwave power level. Moisture transfer from tomato samples was described by applying the Fick's diffusion model and effective moisture diffusion coefficients were calculated. Within the range of microwave power values, 200–500 W, effective moisture diffusivities were found to be9.83×10^{-7} to $24.7\times10^{-7} m^2/s$. The microwave power dependence of the effective diffusivity coefficient followed an Arrhenius-type relationship. The activation energy for the moisture diffusion was determined to be 10.1 W/g. The highest energy efficiency was recorded for the samples dried at 500W and lowest at 200 W.

Keywords: *Microwave Powers, Drying Kinetics, Energy Efficiency, Tomato Samples*

INTRODUCTION
Tomato is rapidly perishable within a few days after harvest (Darvishi *et al*., 2012), due to the high moisture contents (typically greater than 85 g 100 g-1). In addition, it has a very short shelf-life, since it loses its quality within only a few days (Liu and Wang, 2012). As a result, it is necessary to find a method to extend their shelf life, and hot-air drying is reported as the cheapest method to protect tomato and the packed dried product can prolong its quality more than one year (Yapara *et al*., 1990). The objective of drying is to remove water to a level at which microbial spoilage and deterioration reactions are greatly minimized. Moreover, moisture transportation and distribution in products are key factors for the development of the product quality. To control the quality development, understanding of the moisture content at a certain time of the product is required (Jin *et al*., 2011). The drying time of the convective technique can be shortened by using higher temperatures which increase moisture diffusivity (Maroulis *et al*., 1995) and by cutting the material into small pieces (Madamba *et al*., 1996). Increased drying temperature entails higher costs and may cause biochemical changes that degrade the dried product quality; whereas subdividing the material is an additional process that results, especially under industrial conditions, in mass losses and lowering of the product quality (Watada *et al*., 1996).
The drying time can be greatly reduced (Sharma and Prasad, 2004) and the quality of finished product insured (Yongsawatdigul and Gunasekaran, 1996) by applying the microwave energy to the dried material. Furthermore, commonly used hot air techniques are limited by high energy consumption, long drying times, low energy efficiency and high costs, which is not desirable for the food industry. Due to these difficulties, more rapid, safe and controllable drying methods are required. Also, it is necessary to dry the product with minimum cost, energy and time. In microwave drying, drying time is shortened due to quick absorption of energy by water molecules, causes rapid evaporation of water, resulting in high drying rates of the food. As little research has been performed effect of microwave power on energy consumption and drying efficiency in microwave drying method (McMinn *et al*., 2003), the present research is focused on this issue. The aim of this study was to describe the influence of microwave output power on drying kinetics, moisture diffusion and energy efficiency of tomato samples under microwave oven.

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MATERIALS AND METHODS

Tomato samples were purchased from local market of Tehran, Iran. Samples were washed with distilled water, and then samples with mean thickness of 5 mm were selected. The initial moisture content of the samples found about 84.1±1% (w.b.), and was determined by drying in an air convection oven at 103±1 °C till the weight did not change any more (Hatamipour *et al*., 2007). A domestic microwave oven (M945, Samsung Electronics Ins) with maximum output of 1000 W at 2450 MHz was used for the drying experiments. The oven has a fan for air flow in drying chamber and cooling of magnetron. The moisture from drying chamber was removed with this fan by passing it through the openings on the right side of the oven wall to the outer atmosphere. The microwave dryer was operated by a control terminal which could control both microwave power level and emission time. Experiments were performed at four microwave powers of 200, 300, 400 and 500 W. The moisture losses of samples were recorded at 15s intervals during the drying process by a digital balance (GF-600, A & D, Japan) and an accuracy of ±0.01 g. For measuring the weight of the samples during experimentation without taking them out of the oven, the tray with sample was suspended on the balance with a nylon wire through a ventilation hole in the center of chamber ceiling. Drying was carried out until the final moisture content reaches to a level less than 1% (w.b.) (Krokida *et al*., 2003). All measurements were carried out in triplicate.

The moisture ratio (MR) was calculated using the following equation:

$$\mathrm{MR} = \frac{\mathrm{M_t} - \mathrm{M_e}}{\mathrm{M_0} - \mathrm{M_e}} \quad (1)$$

Where, MR is the moisture ratio (dimensionless); M_t, M_e and M_0 are the moisture content at any time, the equilibrium moisture content, the initial moisture content (kg[H2O]/kg dry mater), respectively. The values of M_e are relatively small compared to M_t and M_0, hence the error involved in the simplification by assuming that M_e is equal to zero is negligible. The Midilli's model is an empirical modification of the simple exponential model to overcome its shortcomings. It was successfully used to describe the drying characteristics of a variety of biological materials. Therefore, the semi-empirical Midilli's equation (Eq. (2)) was used to describe the thin layer drying kinetics of samples (Aghbashlo *et al*., 2009):

$$\mathrm{MR} = \frac{\mathrm{M_t}}{\mathrm{M_0}} = \mathrm{a}\exp(-\mathrm{kt^n}) + \mathrm{bt} \quad (2)$$

Where, k is the drying constant (1/min); a and b are constant coefficients and n is the dimensionless exponent. Statistical test using the coefficient of determination (R^2), reduced chi-square (χ^2) and root mean square error (RMSE) were calculated to evaluate the goodness of fit of the model. The statistical parameters were calculated using equations (Zarein *et al*., 2013):

$$\mathrm{R}^2 = 1 - \frac{\sum_{i=1}^{N}\left(MR_{pre,i} - MR_{exp,i}\right)^2}{\sum_{i=1}^{N}\left(MR_{pre,i} - \overline{MR}_{exp,\iota}\right)^2} \quad (3)$$

$$\chi^2 = \frac{\sum_{i=1}^{N}\left(\mathrm{MR_{pre,i}} - \mathrm{MR_{exp,i}}\right)^2}{\mathrm{N} - \mathrm{z}} \quad (4)$$

$$\mathrm{RMSE} = \left(\frac{\sum_{i=1}^{N}\left(\mathrm{MR_{pre,i}} - \mathrm{MR_{exp,i}}\right)^2}{\mathrm{N}}\right)^{1/2} \quad (5)$$

Where, MR_{exp} is the experimental dimensionless moisture ratio, MR_{pre} is the predicted dimensionless moisture ratio by Midilli model, N is the number of experimental data points, and z is the number of parameters in model. The model is said to be good if R^2 value is high and, χ^2 and RMSE values are low (Zarein *et al*., 2015).

Drying rate was defined as:

$$\mathrm{DR} = \frac{\mathrm{X_{t+\Delta t}} - \mathrm{X_t}}{\Delta \mathrm{t}} \quad (6)$$

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Where, $M_{t+\Delta t}$ is moisture content at time t+Δt (kg [H2O]/kg dry mater), t is the time (min) and DR is the drying rate (kg [H2O]/kg dry mater.min). Fick's second law of diffusion equation, symbolized as a mass-diffusion equation for drying agricultural products in a falling rate period, is shown in the following equation:

$$\frac{\partial M}{\partial t} = D_{eff}\frac{\partial^2 M}{\partial x^2} \qquad (7)$$

By using appropriate initial and boundary conditions, Crank (Crank, 1975) gave the analytical solutions for various geometries and the solution for slab object with constant diffusivity is given as:

$$MR = \frac{8}{\pi^2}\sum_{n=0}^{\infty}\frac{1}{(2n+1)^2}\exp\left(-(2n+1)\pi^2\frac{D_{eff}t}{L^2}\right) \qquad (8)$$

Where, D_{eff} is the effective diffusivity (m^2/s), and L is the thickness of samples (m), n is a positive integer. For long drying times, only the first term (n=0) in the series expansion of the above equation can give good estimate of the solution as follows:

$$MR = \frac{8}{\pi^2}\exp\left(-\pi^2\frac{D_{eff}t}{L^2}\right) \qquad (9)$$

Eq. (9) is evaluated numerically for Fourier number, ($F_0 = (D_{eff}\times t)/L^2$), for diffusion and can be rewritten as Eq. (10)

$$MR = \frac{8}{\pi^2}\exp(-\pi^2 F_0) \qquad (10)$$

Thus:

$$F_0 = -0.1013\ln(MR) - 0.0213 \qquad (11)$$

The effective moisture diffusivity was calculated using Eq. (12) as:

$$D_{eff} = \frac{F_0}{(\frac{t}{L^2})} \qquad (12)$$

The average diffusion coefficients are typically determined by plotting experimental drying data in terms of ln (MR) versus drying time (t), because the plot gives a straight line with a slope as $\pi^2 D_{eff}/4L^2$ (Ozbek and Dadali, 2007). In as much as temperature is not precisely measurable inside the microwave drier, the activation energy is found as modified from the revised Arrhenius equation. In this method it is assumed as related to effective moisture diffusion and the ratio of microwave output power to sample weight (m/p) instead of to air temperature. Then Equation (9) can be effectively used as follows (Soysal *et al*., 2006):

$$(D_{eff})_{ave} = D_0\exp\left(-\frac{E_a m}{P}\right) \qquad (13)$$

Where, E_a is the activation energy (W/g), m is the mass of raw sample (g), D_0 is the pre-exponential factor (m^2/s) and P is the microwave power (W).

The microwave drying efficiency was calculated as the ratio of heat energy utilized for evaporating water from the sample to the heat supplied by the dryer (Darvishi and Zarein, 2012).

$$\eta = \frac{m_w \times \lambda_w}{P \times t} \qquad (14)$$

Where, η is the microwave-convective drying efficiency (%);P is the microwave power (W); m_w is the mass of evaporated water (kg), and λ_w is the latent heat of vaporization of water (2257 kJ/kg).

RESULTS AND DISCUSSION

The moisture content versus drying time curves for microwave drying of tomato samples affected by various microwave powers are shown in Figure 1. The time required to dry tomato samples from initial moisture content of 84.1±1% (w.b.) to the final moisture content of 1±0.2% (w.b.) was 9.25, 5.25, 4 and 3.5 min at 200, 300, 400 and 500 W, respectively. Drying microwave power had an important effect on drying time. The results indicated that mass transfer within the sample was more rapidly during higher microwave power heating because more heat was generated within the sample creating a large vapor

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pressure difference between the center and the surface of the product due to characteristic microwave volumetric heating.

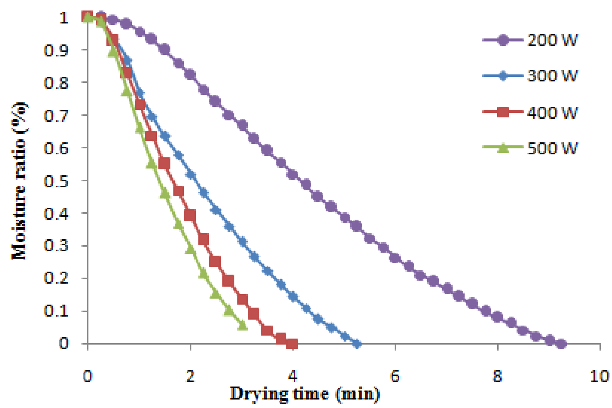

Figure 1: The Variation of the Moisture Ratio with Drying Time at Various Microwave Powers

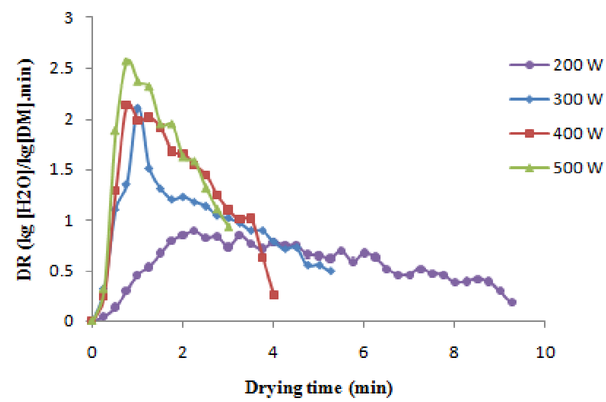

Figure 2: Variation of Drying Rate with Drying Time for Tomato Samples

Figure 2 shows how the drying rate of tomato samples was changed with increased drying time under various drying conditions. The drying rates increased with the increasing microwave power levels. The maximum drying rates were approximately 0.889, 2.105, 2.130 and 2.566 kg [H2O]/kg dry mater min, when the microwave powers of 200, 300, 400 and 500W were applied, respectively. The moisture content of the material was very high during the initial phase of the drying which resulted in a higher absorption of microwave power and higher drying rates due to the higher moisture diffusion. As the drying progressed, the loss of moisture in the product caused a decrease in the absorption of microwave power and resulted in a fall in the drying rate.
The moisture content data obtained from the drying experiments was fitted to the Midilli model. The statistical results from the model such as R^2, χ^2 and RMSE values are shown in Table 1. As it is seen, the highest value of R^2 and lowest values of χ^2 and RMSE obtained as 0.9995, 4.2989×10^{-5} and 0.0091, respectively.

Table 1: Results of Statistical Analysis on the Modeling (Midilli's Model) of Moisture Content and Drying Time for Tomato Samples

P (W)	Model Constants		R^2	$\chi^2 \times 10^{-5}$	RMSE
200	a= 1.021 k= 0.1789	b= -0.02936 n= 1.239	0.9974	4.2989	0.0178
300	a= 1.019 k= 0.2344	b= -0.02544 n= 1.301	0.9992	9.1476	0.0103
400	a= 1.015 k= 0.2886	b= -0.02135 n= 1.578	0.9995	6.7688	0.0091
500	a= 1.016 k= 0.3875	b= -0.01893 n= 1.567	0.9994	7.6214	0.0099

Based on the multiple regression analysis, the Midilli model, the constants and coefficients were as follows:

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$k = 0.108\exp(0.002P)\ R^2 = 0.996$

$n = 0.779 + 0.002P - 2 \times 10^{-6}P^2 R^2 = 0.864$

$a = 1.032 - 7 \times 10^{-5}P + 8 \times 10^{-8}P^2 R^2 = 0.892$

$b = -0.04 + 6 \times 10^{-5}P - 4 \times 10^{-8}P^2 R^2 = 0.997$

Plots of calculated versus experimental dimensionless moisture content are shown in Figure 3. As can be observed in this figure, good agreement between the former variables is observed.

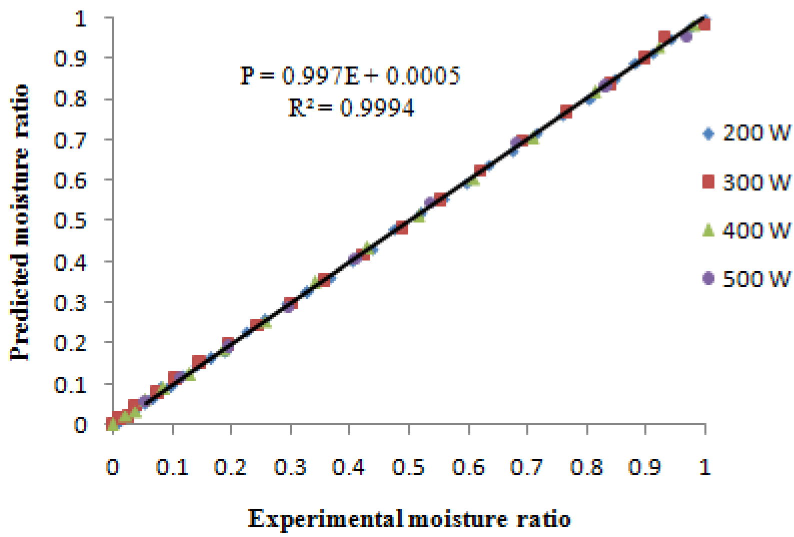

Figure 3: Comparison of Experimental and Calculated Dimensionless Moisture Content Values by the Midilli's Model

The determined values of average effective diffusivity $(D_{eff})_{ave}$ for different microwave powers are given in Table. 2. The values lie within the general range of 10^{-6}–10^{-11} m^2/s for food materials. It can be seen that the values of $(D_{eff})_{ave}$ decreased with increasing moisture content (d.b.) and increased with increasing microwave power. This might be explained by the increased heating energy, which would increase the activity of the water molecules leading to higher moisture diffusivity when samples were dried at higher microwave power.

Table 2: Effective Diffusivity Values for Microwave Drying of Tomato Samples

P(W)	**Average Effective Diffusivity ×10^{-7} (m^2/s)**
200	9.83
300	16.3
400	20.7
500	24.7

The activation energy was calculated by plotting the natural logarithm of $(D_{eff})_{ave}$ versus sample amount/power (m/P) as presented in Figure 4. The plot was found to be a straight line in the range of microwave power studied, indicating Arrhenius dependence. Then, the dependence of the average effective diffusivity of tomato samples on the microwave power can be represented by the following equation:

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$$D_{eff} = 4 \times 10^{-6} \exp\left(-10.1 \frac{m}{P}\right) \quad (15)$$

The activation energy for tomato samples was found to be 10.1 W/g.

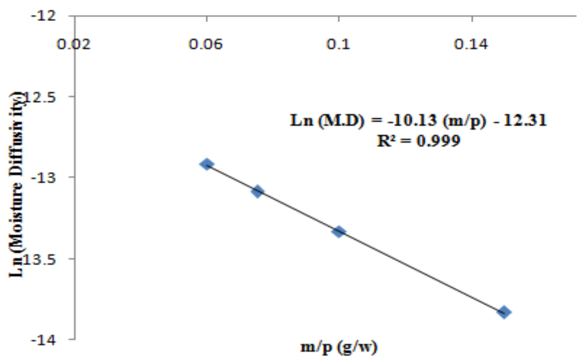

Figure 4: Arrhenius-Type Relationship the Values of Ln $(D_{eff})_{ave}$ Versus Sample Amount/Power

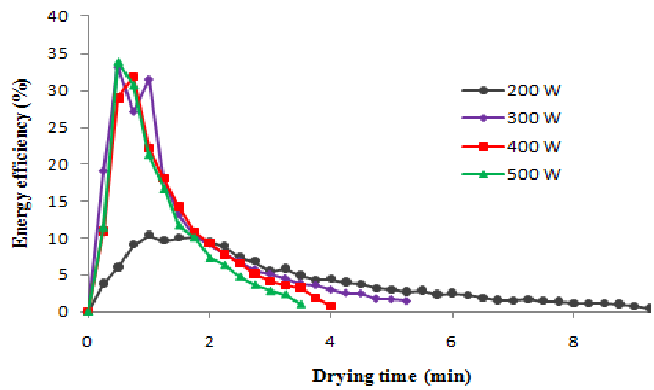

Figure 5: Energy Efficiency Versus Drying Time for Microwave Drying of Tomato Samples

Figure 5 shows the variation of energy efficiency with drying time for microwave drying of tomato samples. The energy efficiency was very high during the initial phase of the drying which resulted in a higher absorption of microwave power. Following moisture reduction, the energy absorbed by the product decreased and reflected power increased. The best result with regard to energy efficiency was obtained from 500W microwave power levels among all microwave power. Average energy efficiency of tomato samples ranged from 10.34 to 33.86% for the output microwave power.

Conclusion

Characteristics of the microwave drying of tomato samples (with mean thickness samples of 5 mm) were determined. Microwave drying period of samples lasted between 9.25 and 3.5 min at the microwave powers at 200 and 500 W, respectively. The changes of moisture content have been described by using Midilli's model. It has been concluded that microwave power of 500 W is the optimum microwave power level in the microwave drying of tomato samples with respect to drying time and energy efficiency. The values of effective diffusivity for microwave drying of tomato samples ranged from 9.83×10^{-7} to 24.7×10^{-7} m^2/s and activation energy was found 10.1 W/g. Energy efficiency increases with the increase of microwave drying power and moisture content from 10.34 to33.86% for microwave powers of 200 W and 500 W, respectively.

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