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FULL LENGTH ARTICLE

Investigation of microwave dryer effect on energy efficiency during drying of apple slices

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Abstract Characteristics of thin layer microwave drying of apple were evaluated in a laboratory scale microwave dryer at 2450 MHz. The drying experiments were carried out at 200, 400 and 600 W. The experimental data were fitted to nine drying models. The models were compared using the coefficient of determination (R^2), root mean square error (RMSE) and reduced chi-square (χ^2). The Midilli et al. model best described the drying curve of apple slices. The effective moisture diffusivity was determined by using Fick's second law and was observed to lie between 3.93×10^{-7} and 2.27×10^{-6} m^2/s for the apple samples. 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 12.15 W/g. The highest energy efficiency was recorded for the samples dried at 600 W as 54.34% and lowest at 200 W as 17.42%.

1. Introduction

Apple represents the fourth most important horticultural crop for human nutrition in the world and the apple is an important raw material for many food products. Apple is the pomaceous fruit of the apple tree, species *Malus domestica* of the rose family (Rosaceae) (Forsline et al., 2010). Drying is probably the oldest method of food preservation and it is one of the most common processes used to improve food stability. Drying preserves foods by removing enough moisture from food and reduces microbiological activity and minimizes physical and chemical changes during storage to prevent decay and spoilage (Doymaz and Ismail, 2011; VijayaVenkataRaman et al., 2012). Apple drying is a highly energy-consuming process. Also, the drying methods have significant effects on the dried apple quality such as nutritional values, color, shrinkage and other organoleptic properties. So far, many works have been performed to study hot air, tray dryer with and without air circulation, fluidized bed, and superheated steam drying of apple pieces of various shapes (Doymaz, 2010; Huang et al., 2011; Schössler et al., 2012; Wang et al., 2007; Zlatanović et al., 2013). Hot air convection drying is one of the oldest methods and the most widely used method of drying. Over 85% of industrial dryers are of the convective type with hot air. One

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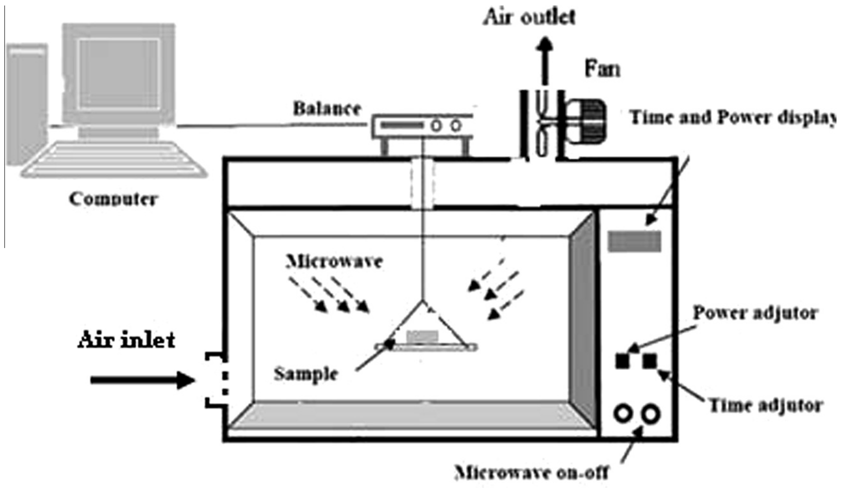

Figure 1 A schematic diagram of microwave–convective oven dryer.

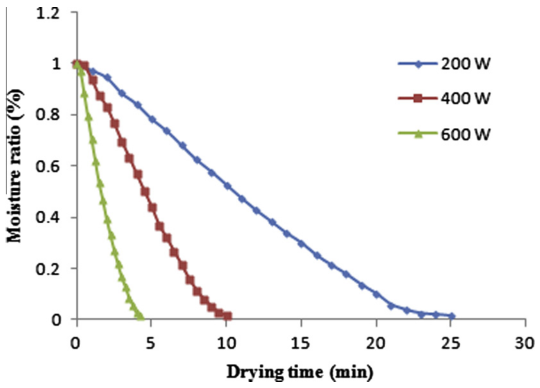

Figure 2 Variation of the moisture content with drying time at various microwave powers.

of the disadvantages of these dryers is high energy consumption. Due to these difficulties, more rapid, safe and controllable drying methods are required (Kavak Akpinar et al., 2005; Motevali et al., 2011). 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. Recently the development of inexpensive and reliable microwave sources has been of increasing attraction to applications in the drying process (Balbay et al., 2012; Darvishi et al., 2013; Kahyaoglu et al., 2012). A two-stage drying process involving an initial forced-air convective drying followed by a microwave final drying has been reported to give better product quality with considerable saving in energy and time (Maskan, 2000). It has also been suggested in the drying of apple slices, mushroom (Funebo and Ohlsson, 1998) and raisin (Kostaropoulos and Saravacos, 1995), that microwave energy should be applied in the falling rate period or at a low moisture content to finish drying. One of the most important aspects of drying technology is the modeling of the drying process. The objective of this study is to analyse and model the drying kinetics of apple slices using the microwave in different conditions of drying and describe the influence of microwave output power on energy efficiency.

2. Materials and methods

2.1. Materials

Cultivar of Golab apple was used in the present study which was purchased from the local market in Tehran, Iran and was stored in the refrigerator at a temperature of 4 ± 1 °C until the experiments were carried out. The initial moisture content of the samples was found about 86.2 ± 1.5% (w.b.), and was determined by drying in an air convection oven at 105 ± 1 °C till the weight did not change any more (Wang et al., 2007). For each experiment, apple samples (about 54 ± 0.5 g with 5 mm of sample thickness) were placed in a glass dish.

2.2. Drying equipment and drying procedure

Fig. 1 shows the diagram of the microwave drying system. An experimental microwave oven (M945, Samsung Electronics Ins.) with a maximum output of 1000 W at 2450 MHz was used for the drying experiments. The oven has a fan for air flow in the drying chamber and cooling of the magnetron. The moisture from the drying chamber was removed with this fan by passing it through 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 three microwave powers of 200, 400, and 600 W. The moisture losses of samples were recorded at 60 s intervals during the drying process by a digital balance (GF-600, A & D, Japan) and an accuracy of ±0.01 g. Drying process was done until the moisture content about 5% on a wet basis was achieved. All measurements were carried out in triplicate.

2.3. Theoretical considerations

2.3.1. Modeling of the thin-layer drying

One of the most important aspects of drying technology is the modeling of the drying process. In this study, the experimental drying data of apple slices at different microwave powers were

Table 1 Mathematical models given for drying curves.

No.	Model name	Model	References
1	Newton	$MR = \exp(-kt)$	Motevali et al. (2010)
2	Page	$MR = \exp(-kt^n)$	Motevali et al. (2010)
3	Modified page	$MR = \exp(-(kt)^n)$	Wang et al. (2007)
4	Wang and Singh	$MR = 1 + a.t + bt^2$	Wang and Singh (1978)
5	Henderson and Pabis	$MR = a.\exp(-kt)$	Chhinnan (1984)
6	Logarithmic	$MR = a.\exp(-kt)+c$	Dandamrongrak et al. (2002)
7	Modified Henderson and Pabis	$MR = a\exp(-kt)+(1-a)\exp(-kbt)$	Sharma et al. (2005)
8	Modified page equation-II	$MR = \exp(-c(t/L^2)^n)$	(Diamante and Munro (1991))
9	Midili et al.	$MR = a.\exp(-kt^n)+b.t$	Midilli et al. (2002)

fitted into 9 commonly used thin-layer drying models, listed in Table 1.

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

$$MR = \frac{M_t - M_e}{M_0 - M_e} \tag{1}$$

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 [H_2O]/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 (Akgun and Doymaz, 2005). Therefore, Eq. (2) was used to describe the thin layer drying kinetics of samples (Senadeera et al., 2003).

$$MR = \frac{M_t}{M_0} \tag{2}$$

The terms used to evaluate goodness of fit of the tested models to the experimental data were the coefficient of determination (R^2); root mean square error (RMSE) and the reduced chi-square (χ^2) between the experimental and predicted moisture ratio values. The statistical parameters were calculated using equations: (Ertekin and Yaldiz, 2004):

$$R^2 = 1 - \frac{\sum_{i=1}^{N}(MR_{pre,i} - MR_{exp,i})^2}{\sum_{i=1}^{N}(\overline{MR_{pre,i}} - MR_{exp,i})^2} \tag{3}$$

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

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

where MR_{exp} is the experimental dimensionless moisture ratio, MR_{pre} is the predicted dimensionless moisture ratio, N is the number of experimental data points, and z is the number of parameters in the model. The model is said to be good if R^2 value is high and, χ^2 and RMSE values are low (Ertekin and Yaldiz, 2004).

Drying rate was defined as:

$$DR = \frac{M_{t+\Delta t} - M_t}{\Delta t} \tag{6}$$

where $M_{t+\Delta t}$ is moisture content at time $t + \Delta t$ (kg [H_2O]/kg dry mater), t is the time (min) and DR is the drying rate (kg [H_2O]/kg dry mater.min).

2.3.2. Effective diffusivities

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:

$$\frac{\partial M}{\partial t} = D_{eff}\frac{\partial^2 M}{\partial x^2} \tag{7}$$

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

$$MR = \frac{8}{\pi^2}\sum_{n=0}^{\infty}\frac{1}{(2n+1)^2}\exp\left(-(2n+1)\pi^2\frac{D_{eff}t}{4L^2}\right) \tag{8}$$

where D_{eff} is the effective diffusivity (m^2/s), and L is the half-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 a good estimate of the solution, which is expressed in logarithmic forms as follows (Tütüncü and Labuza, 1996):

$$\ln(MR) = \ln\left(\frac{8}{\pi^2}\right) - \left(\frac{\pi^2}{4L^2}D_{eff}t\right) \tag{9}$$

The 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:

$$Slope = \frac{\pi^2 D_{eff}}{4L^2} \tag{10}$$

2.3.3. Modeling drying data

Three replications of each experiment were performed according to a preset microwave power and time schedule, and the data given are an average of these results. Non-linear regression analyses were down by using a statistical computer program to obtain each parameter value of every model. The statistical results from models are summarized in Table 1.

Where: k, n, a, and b are the model constants.

2.3.4. Activation energy

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 Eq. (11) can be effectively used as follows (Özbek and Dadali, 2007):

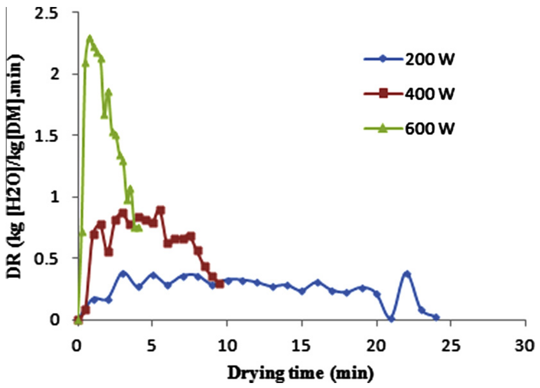

Figure 3 Variation of drying rate with drying time for the apple.

$$D_{\text{eff}} = D_0 \ \exp\left(-\frac{E_a m}{P}\right) \tag{11}$$

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).

2.3.5. *Drying efficiency*

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 (Soysal et al., 2006).

$$\eta = \frac{m_w \times \lambda_w}{P \times t} \tag{12}$$

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).

3. Results and discussion

3.1. *Drying curves*

The moisture content versus drying time curves for microwave drying of apple samples as affected by various microwave powers are shown in Fig. 2. The time required to dry apple samples from an initial moisture content of 74 ± 1.5% (w.b.) to the final moisture content of 4 ± 1% (w.b.) was 25, 10 and 4.25 min at 200, 400 and 600 W, respectively. Drying microwave power

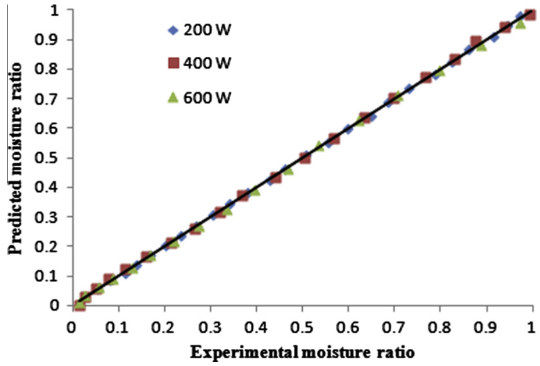

Figure 4 Comparison of experimental and calculated moisture ratio values using Midilli et al. model.

Table 2 Results of statistical analysis on the modeling of moisture contents and drying time for the microwave–convective dried apple slices.

No.	Power (W)	Model constants				R^2	χ^2	RMSE
1	200	$k = 0.07819$				0.8764	0.007691	0.08764
	400	$k = 0.1852$				0.908	6.48×10^{-5}	0.1038
	600	$k = 0.4983$				0.9456	0.005	0.0783
2	200	$k = 0.01476$	$n = 1.653$			0.9952	0.000515	0.02318
	400	$k = 0.04592$	$n = 1.827$			0.9968	3.53×10^{-4}	0.01977
	600	$k = 0.3267$	$n = 1.558$			0.9979	2.27×10^{-4}	0.016
3	200	$k = 0.07802$	$n = 1.653$			0.9952	0.00515	0.02318
	400	$k = 0.1852$	$n = 1.827$			0.9968	3.53×10^{-4}	0.01977
	600	$k = 0.4878$	$n = 1.558$			0.9979	2.24×10^{-4}	0.016
4	200	$a = -0.05077$	$b = 0.0003359$			0.9949	0.0005437	0.02382
	400	$a = -0.1145$	$b = 0.0009769$			0.9886	0.0012	0.03742
	600	$a = -0.3476$	$b = 0.02562$			0.9933	0.0011	0.02739
5	200	$a = 1.135$	$k = 0.08951$			0.9522	0.0050	0.07281
	400	$a = 1.158$	$k = 0.2159$			0.9397	0.01067	0.08618
	600	$a = 1.124$	$k = 0.5608$			0.9652	0.0036	0.06454
6	200	$a = 2.35$	$c = -1.305$	$k = 0.0251$		0.9971	3.34×10^{-4}	0.01845
	400	$a = 2.749$	$c = -1.685$	$k = 0.05114$		0.9934	7.34×10^{-4}	0.02923
	600	$a = 1.591$	$c = -0.5354$	$k = 0.2637$		0.9958	4.61×10^{-4}	0.0231
7	200	$a = 2.35$	$c = -1.305$	$k = 0.0251$		0.9898	0.006471	0.0343
	400	$a = 2.749$	$c = -1.685$	$k = 0.05114$		0.9836	0.00183	0.04626
	600	$a = 1.591$	$c = -0.5354$	$k = 0.2637$		0.9958	4.61×10^{-4}	0.0231
8	200	$L = 0.04975$	$c = 0.001456$	$n = 0.7622$		0.847	0.0162	0.1331
	400	$L = 2.239$	$c = 0.8734$	$n = 1.827$		0.9968	3.53×10^{-4}	0.02031
	600	$L = 1.115$	$c = 0.4589$	$n = 1.56$		0.9979	2.27×10^{-4}	0.01653
9	**200**	$\boldsymbol{a = 1.001}$	$\boldsymbol{b = -0.0063}$	$\boldsymbol{k = 0.0156}$	$\boldsymbol{n = 1.426}$	**0.9995**	$\boldsymbol{5.29 \times 10^{-5}}$	**0.007776**
	400	$\boldsymbol{a = 1.004}$	$\boldsymbol{b = -0.00986}$	$\boldsymbol{k = 0.05092}$	$\boldsymbol{n = 1.655}$	**0.9994**	$\boldsymbol{3.12 \times 10^{-5}}$	**0.008946**
	600	$\boldsymbol{a = 1.009}$	$\boldsymbol{b = -0.01829}$	$\boldsymbol{k = 0.3244}$	$\boldsymbol{n = 1.696}$	**0.9997**	$\boldsymbol{3.51 \times 10^{-5}}$	**0.006905**

Table 3 Effective diffusivity values for microwave drying of apple.

P (W)	Effective moisture diffusivity (m^2/s)
200	3.93×10^{-7}
400	9.48×10^{-7}
600	2.27×10^{-6}

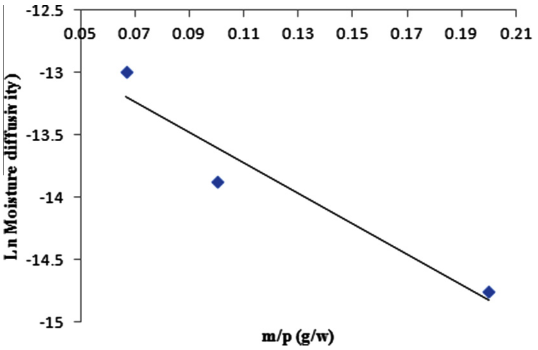

Figure 5 Arrhenius-type relationship the values of $\ln(D_{eff})$ versus sample amount/power.

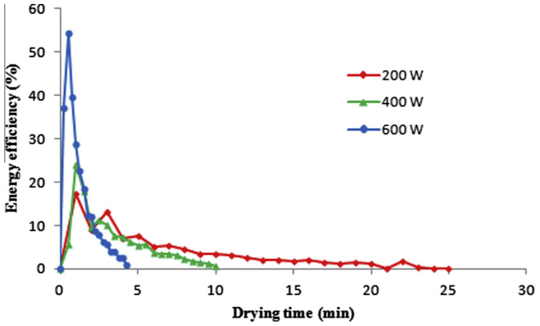

Figure 6 Energy efficiency versus drying time for microwave drying of apple samples.

had an important effect on drying time. The results indicated that mass transfer within the sample was more rapid during higher microwave power heating because more heat was generated within the sample creating a large vapor pressure difference between the center and the surface of the product due to characteristic microwave volumetric heating.

Fig. 3 shows how the drying rate of apple 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 0.382, 0.898 and 2.299 kg [H_2O]/kg dry mater/min, when the microwave powers of 200, 400 and 600 W 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.

3.2. Modeling drying data

Non-linear regression was used to obtain each parameter value of every model. The statistical results from models are summarized in Table 2. In all cases, the statistical parameter estimations showed that R^2, χ^2 and RMSE values ranged from 0.847 to 0.9997, 3.12×10^{-5} to 0.0162, and 0.006905 to 0.1331, respectively. Based on highest value of R^2, and lowest values of χ^2 and RMSE, it can be concluded that Midilli et al. model gave better results than the other models. Thus, it was selected to represent the thin layer drying characteristics of apple slices. As it is seen, the R^2, χ^2 and RMSE values for Midilli et al. model ranged from 0.9994 to 0.9997, 3.12×10^{-5} to 5.29×10^{-5} and 0.006905 to 0.008946, respectively. Based on the multiple regression analysis, the Midilli et al. model, the constants and coefficients were as follows:

$$k = 0.0031 \exp(0.0076P) \quad R^2 = 0.984 \tag{13}$$

$$n = 1.33 \exp(0.0004P) \quad R^2 = 0.853 \tag{14}$$

$$a = 2 \times 10^{-5}P + 0.9967 \quad R^2 = 0.98 \tag{15}$$

$$b = -3 \times 10^{-5}P + 0.0005 \quad R^2 = 0.948 \tag{16}$$

Fig. 4 compares experimental data with those predicted with the Midilli et al. model for apple slices at 200, 400 and 600 W. There was a very good agreement between the experimental and predicted moisture ratio values, which closely band around a 45° straight line. The Midilli et al. model has also been suggested by others to describe the infrared drying of tomato (Celma et al., 2008), fluidized bed drying of olive pomace (Arslan and Ozcan, 2011; Meziane, 2011), sun, oven, and microwave oven drying of savory leaves, and thin layer drying of potato, apple, and pumpkin slices (Akpinar, 2006).

3.3. Effective moisture diffusivity

The determined values of effective moisture diffusivity (D_{eff}) for different microwave powers are given in Table 3. The values lie within the general range of 10^{-6} to 10^{-11} m^2/s for food materials. It can be seen that the values of D_{eff} 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. 5.612×10^{-9} to 1.317×10^{-8} m^2/s for fluidized bed drying of apples (VijayaVenkataRaman et al., 2012), 4.606×10^{-6} to 7.065×10^{-6} m^2/s freeze-drying of apple cubes with far-infrared (Kahyaoglu et al., 2012), 3.17×10^{-7} to 15.45×10^{-7} m^2/s for thin-layer drying of apple slices in length of continuous band dryer (Wang et al., 2007), and 2.90×10^{-8} to 4.88×10^{-8} m^2/s, 7.04×10^{-8} to 24.22×10^{-8} m^2/s, and 3.15×10^{-8} to 5.36×10^{-8} m^2/s for convective, microwave and combined drying of apple cylinders, respectively (Wang et al., 2007).

The activation energy was calculated by plotting the natural logarithm of D_{eff} versus sample amount/power (m/P) as presented in Fig. 5. The plot was found to be a straight line in the range of microwave power studied, indicating Arrhenius dependence. Then, the dependence of the effective diffusivity of apple samples on the microwave power can be represented by the following equation:

$$D_{\text{eff}} = 4 \times 10^{-6} \exp(-12.15\frac{m}{P}) \quad R^2 = 0.924 \tag{17}$$

The activation energy for apple samples was found to be 12.15 W/g.

3.4. Energy efficiency

Fig. 6 shows the variation of energy efficiency with drying time for microwave drying of apple 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 the reflected power increased. The best result with regard to energy efficiency was obtained from 600 W microwave power levels among all microwave power. Average energy efficiency of apple samples ranged from 17.42% to 54.34% for the output microwave power.

4. Conclusion

Characteristics of the microwave drying of apple (about 54 ± 0.5 g with 5 mm of sample thickness) were determined. Microwave drying period of samples lasted between 25 and 4.25 min at the microwave powers at 200 and 600 W, respectively. This study indicated that based on non-linear regression analysis, the Midilli et al. model gave excellent fitting to the drying experimental data of apple slices. The drying time of apple slices decreases and the effective diffusivity increases as the microwave output power increases. The values of effective diffusivity for microwave drying of apple ranged from 3.93×10^{-7} to 2.27×10^{-6} m^2/s and activation energy was found to be 12.15 W/g. The changes of moisture content have been described by using the Midilli et al. model. We concluded that 600 W is the optimum microwave power level in the microwave drying of apple with respect to drying time and energy efficiency. The models and parameters found in this study can be applied to industrial designs and operational guides for the microwave drying of apple slices.

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