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ORIGINAL ARTICLE

Energetic and exergetic performance analysis and modeling of drying kinetics of kiwi slices

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Abstract This work focused on the effects of the moisture content, slices thickness and microwave power on aspects of energy and exergy, drying kinetics, moisture diffusivity, activation energy, and modeling of the thin layer drying of kiwi slices. Results showed that energy and exergy efficiency increased with increasing microwave power and decreasing slice thickness while values of energy efficiency (15.15–32.27 %) were higher than exergy efficiency (11.35–24.68 %). Also, these parameters decreased with a decrease in moisture content. Specific energy consumption varied from 7.79 to 10.02, 8.59 to 10.77 and 9.57 to16.20 to MJ/kg water evaporated for 3, 6 and 9 mm, respectively. The values of exergy loss were found to be in the range of 5.90 and 14.39 MJ/kg water and decreased as the microwave power increased and slice thickness decreased. Effective diffusivity increased with decreasing moisture content and increasing microwave power and slice thickness. Average effective moisture diffusivity of kiwi slices changes between 1.47×10^{-9} and 39.29×10^{-9} m^2/s within the given variables range. Activation energy (17.96–21.38 W/g) showed a significant dependence on the moisture content. Although the Midilli model showed the best fit, Page's model was selected, since it had almost a similar performance but the model is simpler with two parameters instead of four.

Keywords Energy · Exergy · Modeling · Microwave drying · Moisture diffusivity · Kiwi slices

Nomenclature

A, B, C, D	Constant of Eq. (23)
C_p	Heat capacity (J/kg K)
D_{em}	Effective moisture diffusivity (m^2/s)
Dr	Drying rate (kg water/kg dry matter.min)
E_a	Activation energy for moisture diffusivity (W/g)
E_{loss}	Specific energy loss (J/kg water)
E_{sc}	Specific energy consumption (J/kg water)
EX	Exergy (J)
ex	Specific exergy (J/kg water)
EX_{abs}	Exergy absorbed (J)
EX_{in}	Exergy input (J)
ex_{loss}	Specific exergy loss (J/kg water)
ex_{exap}	Exergy of evaporation water (J/kg water)
EX_{ref}	Exergy reflected (J)
EX_{tra}	Exergy transmitted (J)
F(M)	Function of moisture content
F_0	Fourier number (dimensionless)
F_{ave}	Average value of F(M)
h_m	Mass transfer coefficient (m/s)
L	Half thickness of slice (m)
m	Mass (kg)
m_0	Initial mass of sample (kg)
m_d	Mass of dry sample (kg)
m_{wt}	Mass of water evaporated (kg)
M	Moisture content (kg water/kg dry matter)
M_0	Initial moisture content (kg water/kg dry matter)
M_{cr}	Critical moisture content (begin falling rate period) (kg water/kg dry matter)
M_e	Equilibrium moisture content (kg water/kg dry matter)

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MR	Moisture ratio (dimensionless)
M_t	Moisture content at any time (kg water/kg dry matter)
P	Microwave power (W)
P_{abs}	Microwave power absorbed (W)
P_{in}	Microwave power emitted by the magnetron (W)
P_{ref}	Microwave power reflected (W)
P_{tra}	Microwave power transmitted (W)
R^2	Coefficient of determination (−)
t	Time (s)
t_{cr}	Time of begin fall rate period (s)
T	Temperature (K)
T_0	Ambient temperature (K)
η_{en}	Energy efficiency (%)
η_{ex}	Exergy efficiency (%)
λ_k	Latent heat of sample (J/kg)
λ_{wf}	Latent heat of free water (J/kg)
RMSE	Root mean square error (−)
χ^2	Chi-square (−)

Subscripts

ave	Average
in	Input
out	Output
pd	Dry product
wp	Wet product
w	Water evaporate
cr	Critical point

Introduction

Kiwifruits have very short shelf-life because of softening and vitamin loss during storage even at refrigerated conditions (Mohammadi et al. 2008; Dalvand et al. 2013). Fresh kiwifruits are usually dehydrated to extend their shelf life and, therefore, can provide a good alternative to fresh fruits, allowing the availability of out of season fruits (Maskan 2001; Doymaz 2008).

The drying kinetics of food is a complex phenomenon and requires simple representations to predict the drying behavior, and for optimizing the drying parameters. Drying is the most energy intensive process in the food industry. One of the key issues of drying technology is to reduce the cost of energy sources to increase the efficiency of drying facilities for a good quality of dried products (Doymaz 2011; Darvishi et al. 2014a; Alibas 2007). Due to the high prices of energy, environmental concerns as acid rain and stratospheric ozone depletion, global warming, increased world population and decreasing fossil fuel recourses, the optimum application of energy and the energy consumption management methods are vital.

From the thermodynamics point of view, exergy analysis has appeared to be an essential tool for system design, analysis and optimization of thermal systems (Prommas et al. 2010, Dincer and Sahin 2004). Exergy is defined as the maximum amount of work which can be produced by a stream of matter, heat or work as it comes to equilibrium with a reference environment (Akpinar et al. 2005; Dincer 2002). The exergy method can help further the goal of more efficient energy resource use because it enables the locations, types and true magnitudes of losses to be determined (Liu et al. 2008, Prommas et al. 2012).

Convective drying in hot air is still the most popular method applied to reduce the moisture content of fruits and vegetables. Nevertheless, this method has a number of disadvantages such as very long-lasting drying period, high energy consumption, contamination problems, low energy efficiency and high costs which is not a desirable situation for the food industry (Alibas 2007; Ozbek and Dadali 2007, Al-Harahsheh et al. 2009). The desire to reduce the above problems, as well as to achieve fast and effective thermal process lead to the use of microwave and dielectric heating method for food drying (Bondaruk et al. 2007; Orsat et al. 2007). Microwave drying has several advantages such as higher drying rate, shorter drying time, decrease energy consumption, and better quality of the dried products (Sarimeseli 2011; Wang et al. 2007; Soysal et al. 2006).

An important aspect of designing drying technology is the mathematical modeling of the drying processes and equipment. Accurate modeling allows design engineers to choose the most suitable operating conditions and then size the drying equipment and drying chamber accordingly to meet the desired operating conditions (Darvishi et al. 2014a; Al-Harahsheh et al. 2009). The main transport property incorporated in most drying models is effective moisture diffusivity (McMinn et al. 2003; Haghi and Amanifard 2008). Knowledge of accurate D_{em} is very important for modeling processes during which simultaneous mass transfer take place. The moisture diffusion of a food material characterizes its intrinsic mass transport property of moisture which includes molecular diffusion, liquid diffusion, vapour diffusion, surface diffusion, capillary flow, hydrodynamic flow and other possible mass transport mechanisms (Pathare and Sharma 2006; Aboltins 2013; Celma et al. 2011).

Therefore, the objectives of this work were (1) energy and exergy analyses, (3) to calculate drying kinetics, moisture diffusivity, activation energy, (3) to fit the experimental data to seven thin-layer drying models and estimate the constants, and (4) to analyses their behaviours as function of moisture content, slice thickness and microwave power during drying process.

Materials and methods

Sample preparation

Freshly harvested kiwifruits were obtained, samples were rinsed and sliced in three different thicknesses of 3, 6 and 9 mm using a cutting machine. Kiwi slices had an initial moisture content of 83.5 ± 1 % wet basis (5.08 ± 0.05 kg water/kg dry matter), which was determined by vacuum drying at 65 °C for 24 h (Mohammadi et al. 2009). The determination was performed in triplicate.

Drying detail

Figure 1 shows the diagram of the microwave drying system. Drying studies were carried out with a domestic digital microwave oven (M945, Samsung Electronics Ins) with the technical feature of 230 V, 50 Hz and 1000 W. The oven is fitted with a controller to adjust the microwave output power and the time of processing. 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. Weight loss was recorded at 30 s intervals during drying for determination of drying curves by a digital balance (GF-600, A & D, Japan) in the measurement range of 0–600 g and an accuracy of 0.001 g. The temperature of sample was measured by IR temperature sensor (accuracy of ±1.5 °C). Experiments were performed at four microwave powers of 200, 300, 400 and 500 W, and three slice thicknesses of 3, 6 and 9 mm with power cycles of 30 s on/5 s off. Samples were dried to around 10 % moisture content (wet basis). Drying runs were done in triplicate and average values are reported.

Energy analyses

The conservation of mass and energy for the control volume (microwave cavity) of microwave drying porous is shown in Fig. 2. General equation of mass conservation of moisture:

$$\sum m_{in} = \sum m_{out} \quad (1)$$

$$m_{wp} = m_{dp} + m_{wt} \quad (2)$$

The mass evaporated of water equation is written as:

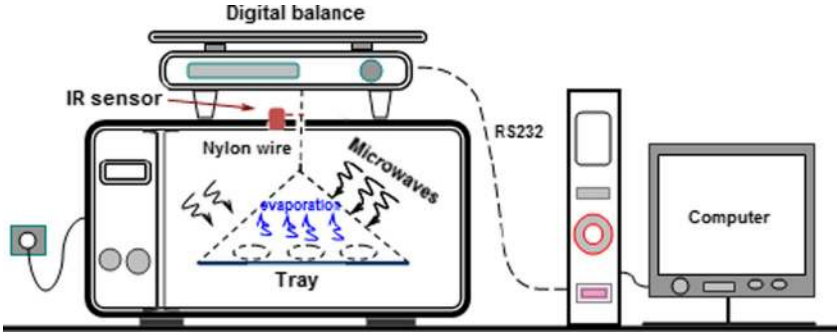
$$m_{wt} = m_d\,(M_0 - M_t) \quad (3)$$

The energy conservation of the sensible heat, latent heat and source heat of microwave is written as (Jindarat et al. 2011):

$$P_{in} = P_{abs} + \overbrace{P_{ref} + P_{tra}}^{\cong P_{loss}} \quad (4)$$

$$\overbrace{P_{in} \times t}^{\text{energy input}} = \overbrace{\left(\overbrace{(mC_pT)_{dp}}^{\text{energy of dry prodcut}} - \overbrace{(mC_pT)_{wp}}^{\text{energy of wet product}} \right) + \overbrace{\lambda_k m_w}^{\text{latent heat}}}^{\cong \text{energy absorption}} + \overbrace{E_{ref} + E_{tra}}^{\cong \text{energy loss}} \quad (5)$$

Fig. 1 Diagram of microwave drying system



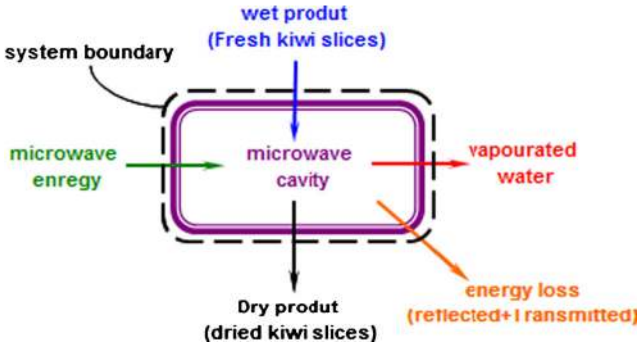


Fig. 2 Volume control of microwave system

Latent heat of kiwi samples was calculated according to the following Eq. (Hall 1975; Sharqawy et al. 2010):

$$\frac{\lambda_k}{\lambda_{wf}} = 1 + 23\exp(-40\ M_t) \quad (6)$$

An expression for the latent heat of vaporization of free water is given by Brooker et al. (1992):

$$\lambda_{wf} = 2503 - 2.386(T - 273) \quad (7)$$

The heat capacity is also a function of its moisture content and may be calculated by the Siebel's model (ASRHAE Fundamentals Handbook 1985):

$$C_p = 840 + 3350 \times \overbrace{\left(\frac{M_t}{1 + M_t}\right)}^{\text{mass fraction of water}} \quad (8)$$

Thermal drying efficiency is defined as follows:

$$\eta_{en} = \frac{\text{energy absorption}}{P_{in} \times t} \quad (9)$$

The specific energy loss is determined by (Darvishi et al. 2014a):

$$E_{loss} = \frac{E_{in} - E_{abs}}{m_w} \text{ or } E_{loss} = (1 - \eta_{en}) \times \frac{P_{in} \times t}{m_w} \quad (10)$$

The energy consumed for drying a kilogram of samples is calculated using Eq. (11):

$$E_{sc} = \frac{P_{in} \times t}{m_w} \quad (11)$$

Exergy analyses

The general exergy balance in microwave cavity was expressed as follows:

$$EX_{in} = EX_{abs} + \overbrace{EX_{ref} + EX_{tra}}^{\cong EX_{loss}} \quad (12)$$

$$\overbrace{P_{in} \times t}^{\text{exergy input}} = \overbrace{\left(\overbrace{(m \times ex)_{dp}}^{\text{exergy of dryprodcut}} - \overbrace{(m \times ex)_{wp}}^{\text{exergy of wet prodcut}}\right) + \overbrace{ex'_{exap} \times t}^{\text{exergy evaporation}}}^{\text{exergy absorption}} + \overbrace{EX_{ref} + EX_{tra}}^{\cong EX_{loss}} \quad (13)$$

The rate of exergy transfer due to evaporation in the chamber drying was:

$$ex'_{exap} = \left(1 - \frac{T_0}{T_p}\right) \times \dot{m}_{wv}\, \lambda_{wp} \quad (14)$$

where:

$$\dot{m}_{wv} = \frac{m_{t+\Delta t} - m_t}{\Delta t} \quad (15)$$

The specific exergy was determined using Eq. (16) as follows (Akpinar et al. 2006):

$$ex = C_p\left[(T - T_0) - T_0 \ln\left(\frac{T}{T_0}\right)\right] \quad (16)$$

The exergy efficiency for the any drying system as the ratio of exergy use (investment) in the drying of the product to exergy of the drying source supplied to the system (Dincer and Sahin 2004):

$$\eta_{ex} = 100 \times \left(\frac{\text{exergy absorption}}{\text{exergy input}}\right) \quad (17)$$

The specific exergy loss can be determined as follows (Darvishi et al. 2014a):

$$EX_{loss} = \frac{EX_{in} - EX_{abs}}{m_{wv}} \quad (18)$$

In this study the reference temperature and pressure were taken as the environment, $T_0 = 20$ °C (293.15 K) and $P_o = 101.325$ kPa.

Drying kinetics and modeling

The moisture ratio and drying rate of kiwi slices during drying experiments were calculated using the following equations:

$$MR = \frac{M_t - M_e}{M_0 - M_e} \quad (19)$$

$$Dr = \frac{M_{t+\Delta t} - M_t}{\Delta t} \quad (20)$$

The value of M_e is relatively small compared with $M_{t.}$ or M_0 (especially for microwave drying), hence the error involved in the simplification by assuming that M_e is equal to zero is negligible (Sarimeseli 2011; Al-Harahsheh et al. 2009). Drying curves were fitted to 7 thin-layer drying models, which are widely used in the scientific literature to describe the kinetics of the drying process. The selected thin-layer drying models are identified in Table 1. The models were fitted to the experimental data by direct least square. The three criteria of statistical parameters, the correlation coefficient (R^2), chi-square (χ^2) and the root mean square error (RMSE) were used to assess the goodness of fitting. The model was considered best when RMSE and χ^2 were at a minimum value and R^2 at a maximum value. These parameters can be calculated as follows:

$$\chi^2 = \frac{\sum_{i=1}^{N} \left(MR_{pre,i} - MR_{exp,i}\right)^2}{N - z} \quad (21)$$

$$RMSE = \left(\frac{\sum_{i=1}^{N} \left(MR_{pre,i} - MR_{exp,i}\right)^2}{N}\right)^{0.5} \quad (22)$$

Moisture diffusivity

The experimental drying data for the determination of diffusivity coefficients were interpreted by using Fick's second diffusion model.

$$\frac{\partial M}{\partial t} = \frac{\partial}{\partial x}\left(D_{em}\frac{\partial M}{\partial x}\right) \quad (23)$$

Assuming uniform initial moisture distribution, negligible external mass transfer resistance, constant slab thickness and final equilibrium moisture content close to zero, the solution of this equation proposed by Crank (1975) is:

$$\frac{M_t}{M_0} = \frac{8}{\pi^2}\sum_{n=0}^{\infty}\frac{1}{(2n+1)^2}\exp\left(-(2n+1)^2\,\pi^2\frac{D_{em}}{4L^2}t\right) \quad (24)$$

As applied to microwave drying of solids, this solution is valid only for the falling rate period when internal moisture diffusion controls the dehydration rate, which means for sample moisture content below the critical value (see Figs. 8 and 9). Eq. (25) for diffusivity determination, the initial moisture content must be set to the moisture critical value ($M_0 = M_{Cr}$) and time must be set to zero when the sample overall moisture content reaches the first critical value (Dissa et al. 2010).

$$\frac{M_t}{M_{Cr}} = \frac{8}{\pi^2}\sum_{n=0}^{\infty}\frac{1}{(2n+1)^2}\exp\left(-(2n+1)^2\,\pi^2\frac{D_{em}}{4L^2}(t - t_{cr})\right) \quad (25)$$

Table 1 Thin-layer drying models used for mathematical of drying of kiwi slices

No.	Model name	Model	References
1	Newton	$MR = \exp.(-kt)$	Doymaz (2008)
2	Henderson and Pabis	$MR = a\exp.(-kt)$	Lee and Kim (2009)
3	Wang and Singh	$MR = 1 + bt + at^2$	Sarimeseli (2011)
4	Page	$MR = \exp.(-kt^n)$	Ozkan et al. (2007)
5	Logarithmic	$MR = a\exp.(-kt) + b$	Darvishi et al. (2014a), b)
6	Midilli	$MR = a\exp.(-kt^n) + bt$	Rhim and Lee (2011)
7	Two order polynomial*	$Ln(MR) = c + bt + at^2$	Sharma and Prasad (2004)

*This model used when the variation of ln[MR] v.s drying time is nonlinear from

Moisture transport which involves diffusion of moisture in solid foods is a complex process. For most cases, the total effective diffusivity is the sum of the vapor phase diffusivity and the liquid phase diffusivity. However, for most materials, the vapor phase diffusion coefficient exhibits a maximum at low moisture contents. Also, the liquid phase diffusion coefficient increases with moisture content and eventually, at high moisture contents, becomes the dominant mechanism of diffusion. In the case reported here, however, the experimental logarithmic drying curve is not linear (Fig. 3). The non-linearity of the curves is indicative of the variation in moisture diffusivity with moisture content. This non-linearity in the relationship may be due to the reasons like shrinkage in the product, non-uniform distribution of initial moisture, variation in moisture diffusivity with moisture content and change in product temperature during drying (Sharma and Prasad 2004; Pathare and Sharma 2006; Celma et al. 2011; Hassini et al. 2007). Therefore, Eq. (25) is evaluated numerically for Fourier number, $\left[F_o = \frac{D_{em}}{4L^2}(t - t_{cr})\right]$ for diffusion and can be rewritten as (Pathare and Sharma 2006; Jain and Pathare 2007; Celma et al. 2011):

$$\frac{M_t}{M_{Cr}} = \frac{8}{\pi^2}\sum_{n=0}^{\infty}\frac{1}{(2n+1)^2}\exp\left(-(2n+1)^2\pi^2 F_o\right)$$
$$= \frac{8}{\pi^2}\left(\exp(-\pi^2 F_o) + \frac{1}{9}\exp(-9\pi^2 F_o) + \frac{1}{25}\exp(-25\pi^2 F_o) + \cdots\right) \quad (26)$$

Fourier number was calculated using fifteen series terms of Eq. (26) by using the Microsoft Excel SOLVER tool. The effective moisture diffusivity was calculated using Eq. (27):

$$D_{em} = \frac{4L^2 F_0}{(t - t_{cr})} \quad (27)$$

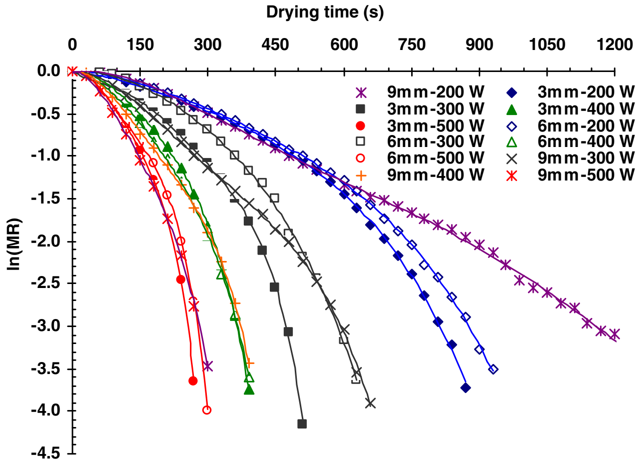


Fig. 3 Variation of ln(MR) with drying time for microwave kiwi slice drying

Activation energy

Direct factors affecting the changes in moisture diffusivity of a solid are the parameters of its thermodynamic state, i.e. drying air temperature and moisture content of the solid. Therefore, the correlation between the moisture diffusivity, m_0/P (initial mass of raw sample/microwave power instead of to air temperature) and moisture content of samples is used for calculation of the activation energy (Markowski et al. 2010; Ozbek and Dadali 2007; Zielinska and Markowski 2010).

$$D_{em} = D_0 \exp\left(-\frac{E_{ad}\, m_0}{P} + aM\right) \quad (28)$$

Statistical analysis

The experiments are carried out at three replications and the mean values of data are reported with standard deviation. The statistical evaluation was performed by using SPSS software Ver.18. The comparison of the results was made to analyze the effect of microwave power and slice thickness on selected properties by using ANOVA and post hoc (Duncan) tests. All statistical significance was determined at the 5 % significance level ($P \leq 0.5$). The average value of each parameter was calculated using the following expression (Celma et al. 2011):

$$F_{ave} = \frac{\int_{M_{initial}}^{M_{final}} F(M).dM}{\int_{M_{initial}}^{M_{final}} dM} \quad (29)$$

Results and discussion

Energy analyses

The effects of microwave power, moisture content and slice thickness on the energy efficiency ($P \leq 0.05$, Table 2) of microwave drying of kiwi slices are illustrated in Fig. 4. The energy efficiency rapidly increases and then slowly decreases with the reduction of moisture content. Apparently, during the initial drying phase, the microwave energy applied was used in raising the kiwi slices temperature and very little moisture was evaporated that lead to lower efficiency values. After a slow increasing tendency to about the moisture content of 3.8–3.5 kg water/kg dry matter, the microwave energy efficiency reached to its maximum value and was varied between 36 % and 51 % depending on the variables test. Then, it was almost remained constant up to the moisture contents of about 1.7 kg

Table 2 Analysis of variance (ANOVA) for effect of microwave power slice thickness on aspects of kiwi drying

Parameter	Source	Sum of Squares	df	Mean Square	F	Sig.
Time (min)	Corrected Model	858.41	11	78.04	53.90	0.00**
	Intercept	3296.67	1	3296.67	2277.13	0.00**
	Thickness	40.72	2	20.36	14.06	0.00**
	Power	776.19	3	258.73	178.71	0.00**
	Thickness × Power	41.50	6	6.92	4.78	0.00**
	Error	34.75	24	1.45		
	Total	4189.83	36			
	Corrected Total	893.16	35			
Energy efficiency (%)	Corrected Model	553.99	11	50.3	12.14	0.00**
	Intercept	21,161.52	1	21,161.52	5101.19	0.00**
	Thickness	194.14	2	97.07	23.40	0.00**
	Power	296.43	3	98.81	23.81	0.00**
	Thickness × Power	63.42	6	10.57	2.55	0.04**
	Error	99.56	24	4.15		
	Total	21,815.07	36			
	Corrected Total	653.55	35			
Specific energy loss (MJ/kg water)	Corrected Model	156.81	11	14.26	16.08	0.00**
	Intercept	2172.96	1	2172.96	2450.45	0.00**
	Thickness	49.53	2	24.76	27.93	0.00**
	Power	71.11	3	23.70	26.73	0.00**
	Thickness × Power	36.17	6	6.03	6.79	0.00**
	Error	21.28	24	0.89		
	Total	2351.05	36			
	Corrected Total	178.09	35			
Specific energy consumption (MJ/kg water)	Corrected Model	157.37	11	14.31	15.98	0.00**
	Intercept	3709.44	1	3709.44	4143.97	0.00**
	Thickness	49.86	2	24.93	27.85	0.00**
	Power	70.93	3	23.64	26.41	0.00**
	Thickness × Power	36.58	6	6.10	6.81	0.00**
	Error	21.48	24	0.89		
	Total	3888.30	36			
	Corrected Total	178.86	35			
Exergy efficiency (%)	Corrected Model	505.38	11	45.94	11.27	0.00**
	Intercept	19,223.82	1	19,223.82	4715.29	0.00**
	Thickness	181.87	2	90.93	22.30	0.00**
	Power	262.92	3	87.64	21.50	0.00**
	Thickness × Power	60.59	6	10.09	2.48	0.05*
	Error	97.85	24	4.08		
	Total	19,827.05	36			
	Corrected Total	603.22	35			
Specific exergy loss (MJ/kg water)	Corrected Model	157.404	11	14.31	11.05	0.00**
	Intercept	2235.87	1	2235.87	1726.22	0.00**
	Thickness	49.77	2	24.89	19.21	0.00**
	Power	70.93	3	23.64	18.25	0.00**
	Thickness × Power	36.70	6	6.12	4.72	0.00**
	Error	31.09	24	1.29		
	Total	2424.36	36			
	Corrected Total	188.49	35			

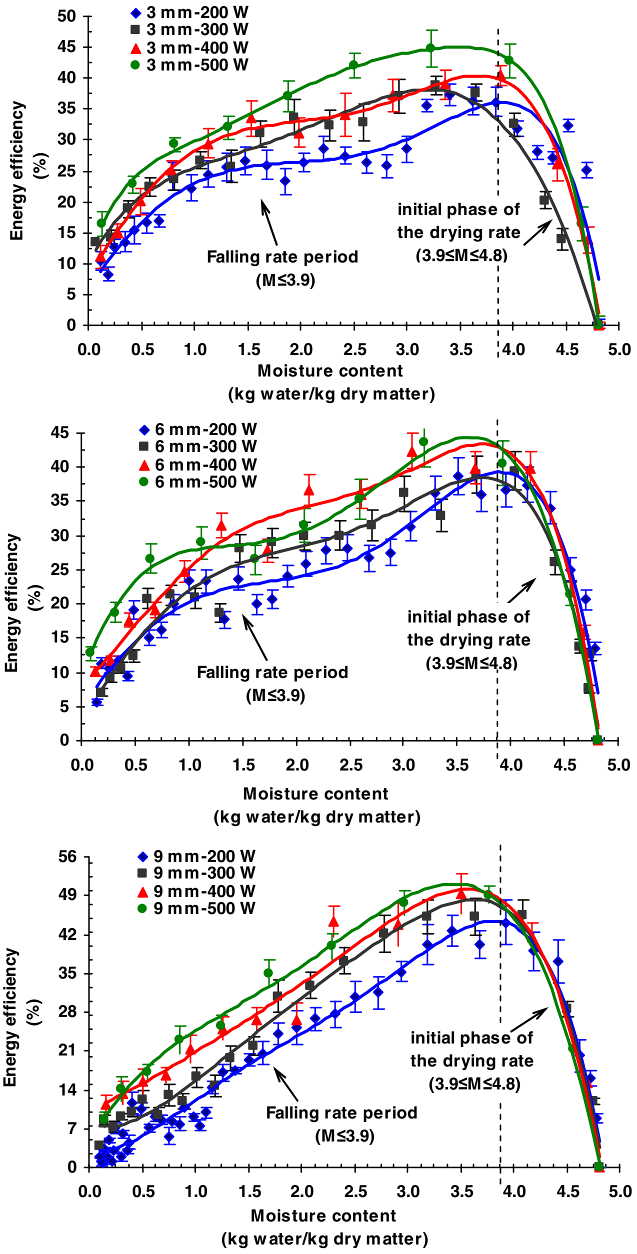


Fig. 4 Energy efficiency as a function of moisture content during drying of kiwi slices

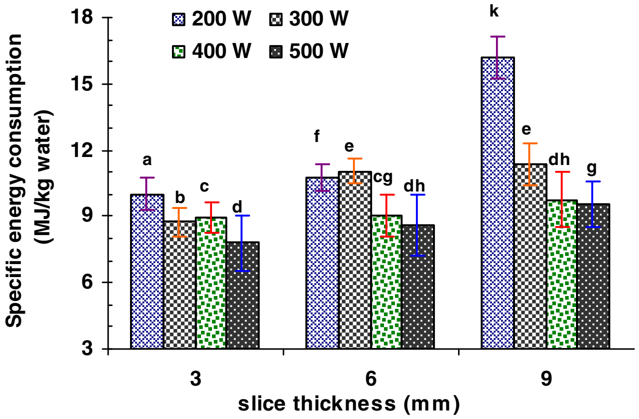


Fig. 5 Specific energy consumption during the microwave drying of kiwi slices

water/kg dry matter. Below these moisture contents, microwave drying efficiency decreased rapidly and reached to a value as low as 3.6 %. This could be attributed to the decrease in moisture content of the material at the later stages of the drying. This is due to the fact that the amount of microwave energy absorbed by the material is lower due to a lower moisture content which affects the bulk dielectric properties and the electric field strength inside the material (Soysal et al. 2006; Giri and Prasad 2007; Souraki et al. 2009). The values of the dielectric constant and loss factors are higher at a higher moisture content of the sample (Al-Harahsheh et al. 2009). Therefore, at the beginning of the process where the moisture content of the sample exceeds 83.5 % wet basis (5.08 kg water/kg dry matter), the sample will absorb more microwave power causing a very high internal heat generation which in turn produces higher diffusion and thus higher drying rate. As drying proceeds, moisture content within the sample decreases and thus decreasing the absorption of microwave power (Araszkiewicz et al. 2004; Darvishi et al. 2013; Soysal et al. 2006).

Besides, the energy efficiency is increasing with increasing microwave power and decreasing slice thickness and microwave power is more effective on efficiency ($P \leq 0.05$, Table 2). This was because of the dramatic reduction in the drying time

Table 3 Average values of energy and exergy efficiency of microwave drying process of kiwi slices

Parameter	L (mm)	Microwave power (W)			
		200	300	400	500
η_{en}(%)	3	24.39 (±1.71)	28.21 (±1.98)	27.57 (±1.72)	32.27 (±1.89)
	6	21.97 (±2.41)	22.70 (±1.21)	27.65 (±2.42)	29.12 (±1.63)
	9	15.15 (±0.93)	21.84 (±1.77)	25.73 (±2.35)	26.16 (±2.88)
η_{ex}(%)	3	17.91 (±1.26)	21.39 (±1.50)	20.96 (±1.62)	24.68 (±3.89)
	6	16.71 (±0.91)	17.54 (±0.89)	21.02 (±2.28)	22.28 (±2.32)
	9	11.35 (±0.83)	16.63 (±1.34)	19.56 (±2.55)	20.00 (±2.20)

with an increase in microwave power and decrease in slice thickness (Doymaz 2011; Sharma and Prasad 2006; Wang and Sheng 2006; Alibas 2007). The average values of energy efficiency are presented in Table 3. Statistical analyses showed that the slice thickness (high F-value) indicated more effect on the energy aspects than that microwave power (low F-value) ($P \leq 0.05$; Table 2). The $\eta_{,ave.}$ varied from 24.39–32.68 %, 21.97–29.12 %, and 15.15–26.20 % for 3, 6 and 9 mm over the microwave power range, respectively. In comparison with microwave power of 200 W, that of 500 W caused an increase in $\eta_{,ave.}$ by about 34–73 %.

It is evident from Fig. 5 that as microwave power was increased from 200 to 500 W, the specific energy consumption decreased from 10.02 to 7.79 MJ/kg water, 10.77 to 8.59 MJ/kg water and 16.20 to 9.57 MJ/kg water evaporated for 3, 6 and 9 mm, respectively. This was because of the dramatic reduction in the drying time with an increase in microwave power. At a given microwave power, specific energy consumption increased with increasing of slice thickness (Table 2, $P \leq 0.05$) about 61. 7 % for 200 W, 30.1 % for 300 W, 8.6 % for 400 W and 38.3 % for 500 W.

The difference between the energies input and absorb was called energy loss in this study. The increase in the microwave power applied was statistically significant (Table 2, $P \leq 0.05$) in the specific energy losses during drying. As the microwave power increased, specific energy losses decreased from 7.65 to 5.40 MJ/kg water for 3 mm, 8.40 to 6.20 MJ/kg water for 6 mm and 13.80 to 7.18 MJ/kg water for 9 mm, which indicated that 67.4–86.1 % of the energy given to the system was not used in drying the kiwi slice samples (Table 4). The best result with regard to energy aspects ($\eta_{ave} = 32.27$ %, $E_{sc} = 7.79$ MJ/kg water, $E_{loss} = 5.32$ MJ/kg water) was obtained from 500 W and 3 mm slice thickness.

Exergy analyses

The exergy analysis of thin layer drying process of kiwi slices was performed by using data obtained from the experiments. The change in the exergetic efficiency depending on the

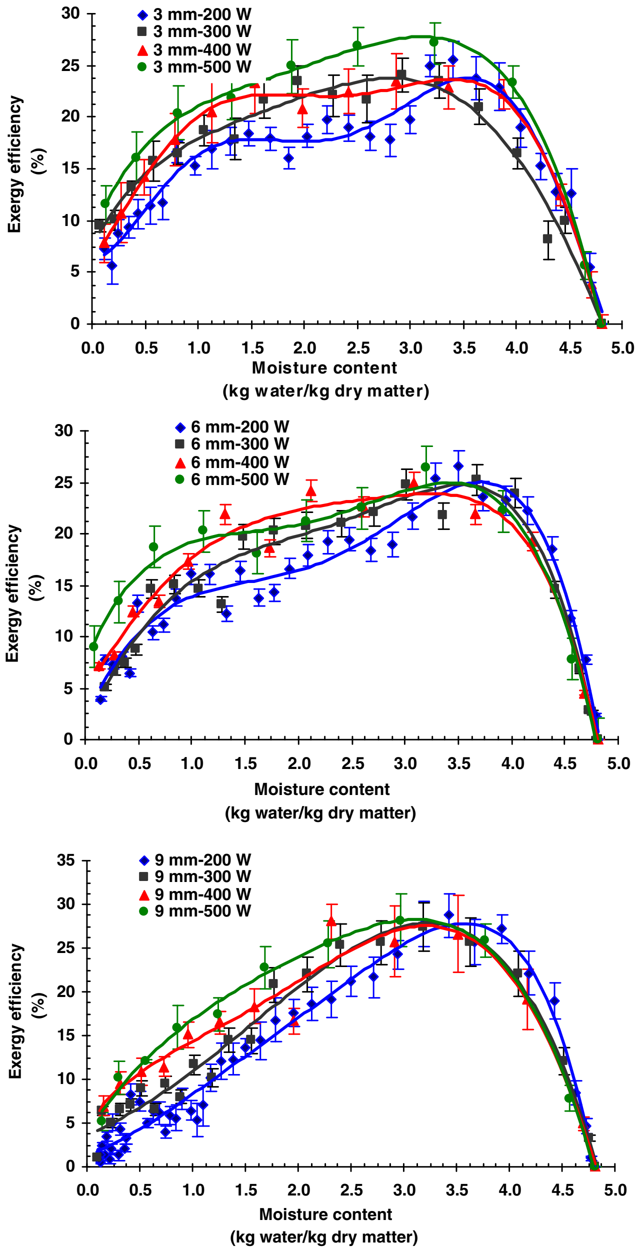


Fig. 6 Exergy efficiency as a function of moisture content during drying of kiwi slices

Table 4 values of specific energy and exergy loss of microwave drying process of kiwi slices

Parameter	L (mm)	Microwave power (W)			
		200	300	400	500
E_{loss} (MJ/kg water)	3	7.58 (±0.70)	6.28 (±0.61)	6.51 (±0.69)	5.32 (±1.21)
	6	8.29 (±0.58)	8.41 (±0.61)	6.52 (±0.97)	6.16 (±1.38)
	9	13.77 (±0.97)	8.86 (±0.91)	7.23 (±1.24)	7.06 (±1.04)
ex_{loss} (MJ/kg water)	3	8.23 (±0.99)	6.87 (±0.86)	7.10 (±0.98)	5.90 (±1.71)
	6	8.94 (±0.82)	9.00 (±0.80)	7.11 (±1.37)	6.74 (±1.96)
	9	14.39 (±1.37)	9.44 (±1.29)	7.82 (±1.76)	7.64 (±1.47)

moisture content, microwave power and slice thickness was represented in Fig. 6. The exergy efficiency was found to be high at the initial stage of the drying process but it decreases ($p \leq 0.05$) during the drying from inside the kiwi samples until the end of the drying process. These curves show that the exergetic efficiency of the microwave kiwi drying increased with the increase of microwave power and decrease of slice thickness ($P \leq 0.05$; Table 2). This can be explained by the fact that the surface moisture evaporates very quickly due to high heat and mass transfer coefficients in high microwave power and low slice thickness, resulting in decreased drying time and consequently lower exergy consumption.

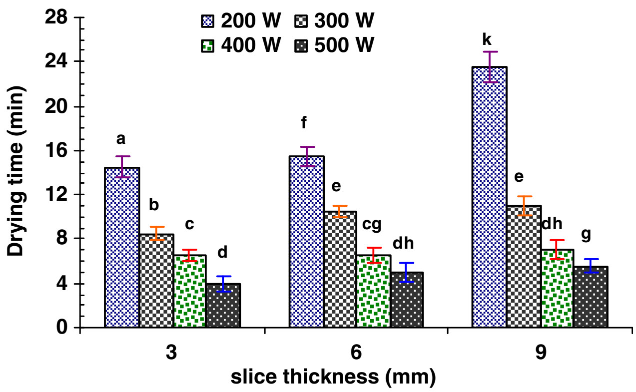


Fig. 8 Variation of drying time of kiwi slices at various slice thickness and microwave power levels

The average values of exergy aspects presented in Tables 3 and 4. The exergy efficiency for microwave drying of kiwi slices for the conditions studied was in the range of 11.35–24.68 % (Table 3) while the energy efficiency was higher for the same conditions ($P \leq 0.05$). These results were similar with the results in the literature (Akpinar et al. 2006; Corzo et al. 2008; Erbay and Icier 2009; Bozkurt 2009). The energy efficiency values mainly showed the heat losses to the environment and energy losses caused by irreversibility. Since exergy efficiency predicted strongly depended on dead state assumptions made on analyses, the dead state conditions should be set to the reference environment to obtain appropriate results in the performance analyses. The exergy efficiency was determined by taking account of only useful energy output for microwave drying process while the energy efficiency was found by total energy change (Bozkurt and Icier 2010). The decrease in the treatment times and more homogeneous heating due to lower thickness of the kiwi samples provided the minimization of energy losses or equivalently entropy generation, which meant the increase in the exergetic efficiency of the system. The minimum value of exergy efficiency was 11.35 % (at 200 W and

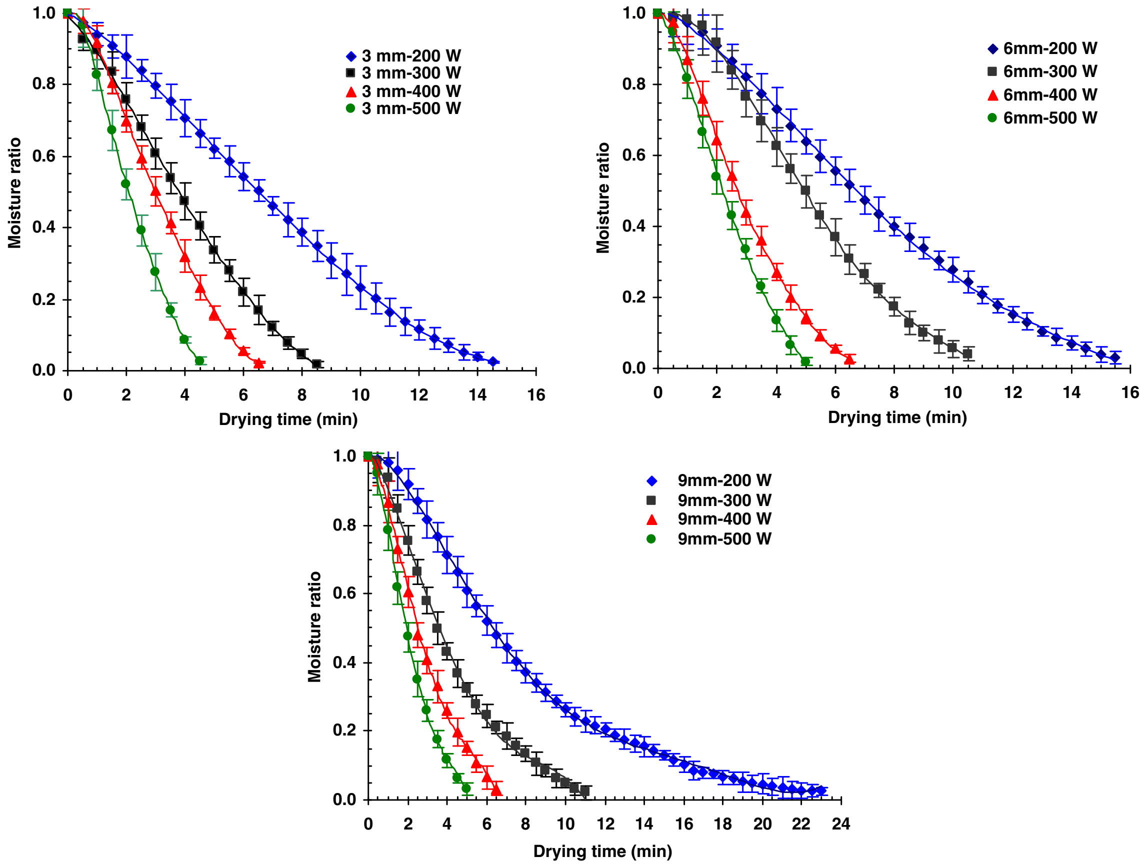


Fig. 7 Drying curves of kiwi slices at various microwave powers and slice thicknesses

9 mm) while maximum value of exergy efficiency of 24.68 % was obtained at a microwave power of 500 W with thickness of 2 mm. A linear regression analysis on the exergy efficiency with the processing variables resulted in the following relationship:

$$\eta_{ex,ave} = 14.17 + 0.037P - 0.911L - 3.24 \times 10^{-5}P^2 - 0.028L^2 + 0.002PL \quad R^2 = 0.923 \tag{30}$$

The specific exergy loss values varied between 5.90 and 14.39 MJ/kg water, and significantly decreased as the microwave power increased and slice thickness decreased (Table 2, $P \leq 0.05$). These results are in closing adverse with the findings of Darvishi et al. (2014a) for microwave drying white mulberry. These situations can be explained by the effect of drying time. An analysis of variance showed that the effect of drying time on exergy loss is more the effect of microwave power ($P \leq 0.05$). The drying time is longer under low microwave power levels and high slice thickness hence results in an increase in entering exergy to the drying chamber. For this reason, it was observed that as the microwave power decreased and slices thickness increased the energy losses increased, in other words, microwave exergy efficiency values decreased.

Drying kinetics and modeling

The variations of the moisture ratio as against drying time are shown in Fig. 7 for microwave drying of kiwi slices. The microwave power and slice thickness had a significant effect on the moisture content of the kiwi samples as expected ($p \leq 0.05$). It is clear that the moisture content decreases continuously with drying time. The moisture ratio had a steeper decreasing slope with increasing microwave power as well as decreasing slice thickness. According to the results in Fig. 8, the slice thickness and microwave power level had a significant effect on the drying time of the kiwi slices as expected ($P < 0.05$; Table 2). The results showed that drying time decreased when the microwave power level increased and slice thickness decreased. The drying time required to reach the final moisture content of samples were 4–14.5 min, 5–15.5 min, and 5.5–23.5 min at the slice thickness levels of 3, 6 and 9 mm, respectively. This increase in the drying time with increasing slice thickness was due to the effect the exposed surface area resulting in increased diffusion path of moisture out of the kiwi slices during microwave drying (Doymaz 2011; Sacilik et al. 2006; Falade et al. 2007; Lee and Kim 2009). Mohammadi et al. (2009) investigated the drying of kiwi slices using a convective dryer at 40–80 °C air temperature, 1.5 m/s air velocity, 4 mm slice thickness and recorded drying times up to 3 h. Maskan (2001) reported that the drying time required to drying of kiwi slices (4.55 to 0.01 kg water/kg dry matter) was 30 min at the microwave power level of 210 W and 5 mm slice thickness. Doymaz (2008) dried kiwi slices in fixed bed dryer (50–60 °C, 2.4 m/s, 8 mm) and found their drying time as 6.5–9.7 h, which are very high compared those obtained at the experimental ranges used in this study.

The variation of drying rate with drying time which explains the microwave drying behavior of kiwi slice is given in Fig. 9. The microwave power absorption by the product depends on its moisture content (Darvishi et al. 2013). The moisture content of kiwi slices was relatively high during the initial phase of the drying which resulted in higher absorption of the microwave and led to an increased product temperature and, therefore, higher drying rate due to 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. It is apparent that increasing microwave output power and a decrease in slice thickness substantially increases the drying rate and thus decreasing drying time. This indicates 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 centre and the surface of the product due to characteristic microwave volumetric heating. Such an influence of microwave power and slice thickness on the drying rate was noted in earlier researches (Lee and Kim 2009; Evin 2011; Sarimeseli 2011;

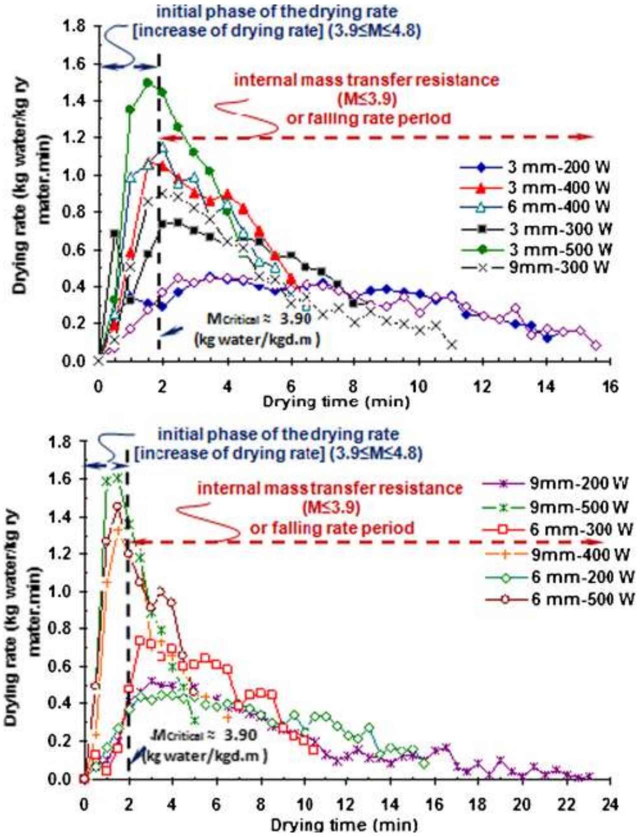


Fig. 9 Variation of drying rate with drying time under microwave drying process of kiwi slices

Darvishi et al. 2014a; Al-Harahsheh et al. 2009; Wang et al. 2007; Ozkan et al. 2007).

Non-linear regression analyses were performed to thin-layer drying models (Table 1) regarding moisture ratio versus drying time data. The statistical results from models are summarised in Tables 5, 6 and 7. In all cases, the R^2, χ^2 and RMSE values range from 0.8001 to 0.9996; 0.00005 to 0.14663 and 0.00651 to 0.36328, respectively. The Midilli model can be considered the most suitable drying model with the highest R^2 and lowest RMSE and χ^2 values for all microwave powers and slice thicknesses. The level of RMSE and χ^2 as well as R^2 for the Midilli and Page models were always very close to each other. Although the Midilli model showed the best fit among the selected models, the Page model was selected as the appropriate model for this research because it is simple with two parameters while Midilli model has four parameters. It was observed that the value of drying rate constant (k) increased with the increase in microwave power and decrease in slice thickness. The higher k values confirm the elevated moisture removal rates and indicate an enhancement of drying potential (Evin 2011; Darvishi et al. 2014b; McMinn 2006).

Moisture diffusivity

The changes of the D_{em} with moisture content for various microwave powers and slice thicknesses were illustrated in Fig. 10. The values for D_{em} increased with a decrease in moisture content and increase in microwave power and slice thickness. As seen in Fig. 10, all curves have two parts (positive or acceptable values and negative or not acceptable values). It has been accepted that the drying characteristics of biological products in falling rate period can be described by using Fick's diffusion equation (Wang et al. 2007). According to Fig 9, the falling rate period occurred when moisture contents were lower than 3.9 kg water/kg dry matter, while the drying rate increased when moisture contents varied between 3.90 and 4.81 kg water/kg dry matter.

Table 5 Statistical results of different thin-layer drying models for kiwi slices (L = 3 mm)

Model	P (W)	Model constants	R^2	χ^2	RMSE
Newton	200	K = 0.1748	0.8378	0.01887	0.13506
	300	K = 0.3126	0.8001	0.02135	0.14200
	400	K = 0.4001	0.8199	0.02774	0.16050
	500	K = 0.5717	0.8174	0.02818	0.15926
Henderson and Pabis	200	a = 1.641, k = 0.2251	0.8988	0.03675	0.18520
	300	a = 1.698, k = 0.4034	0.8598	0.05377	0.21862
	400	a = 1.726, k = 0.5214	0.8863	0.06187	0.23029
	500	a = 1.675, k = 0.7347	0.8782	0.06900	0.23495
Wang and Singh	200	a = 0.0014, b = −0.0815	0.9947	0.05852	0.23371
	300	a = 0.0038, b = −0.1413	0.9959	0.00252	0.04734
	400	a = 0.0062, b = −0.1662	0.9858	0.01387	0.10902
	500	a = −0.0117, b = −0.2380	0.9858	0.02687	0.14661
Page	200	k = 0.0318, *n* = 1.671	0.9954	0.00050	0.02151
	300	k = 0.0806, *n* = 1.652	0.9943	0.00065	0.02412
	400	k = 0.0912, *n* = 1.860	0.9981	0.00026	0.01486
	500	k = 0.1785, *n* = 1.849	0.9982	0.00027	0.01473
Midilli	200	a = 0.9900, k = 0.0345, *n* = 1.501, b = −0.0093	0.9996	0.00005	0.00651
	300	a = 0.9856, k = 0.0786, *n* = 1.472, b = −0.0175	0.9995	0.00006	0.00695
	400	a = 1.0154, k = 0.1041, *n* = 1.648, b = −0.0129	0.9994	0.00009	0.00803
	500	a = 1.0061, k = 0.1753, *n* = 1.724, b = −0.0155	0.9993	0.00014	0.00912
Logarithmic	200	a = 2.587, k = 0.0362, b = −1.546	0.9966	0.00038	0.01840
	300	a = 2.669, k = 0.0584, b = −1.640	0.9968	0.00039	0.01812
	400	a = 3.073, k = 0.0672, b = −2.006	0.9915	0.00124	0.03121
	500	a = 3.228, k = 0.0893, b = −2.169	0.9906	0.00157	0.03318
Two order polynomial	200	c = −0.1372, b = 0.0459, a = −0.0187	0.9914	0.14663	0.36328
	300	c = −0.1950, b = 0.1401, a = −0.0639	0.9749	0.03829	0.17864
	400	c = −0.1033, b = 0.1279, a = −0.0999	0.9904	0.01519	0.10926
	500	c = −0.0960, b = 0.1832, a = −0.2040	0.9865	0.02448	0.13092

Table 6 Statistical results of different thin-layer drying models for kiwi slices (L = 6 mm)

Model	P (W)	Model constants	R^2	χ^2	RMSE
Newton	200	K = 0.1629	0.8600	0.01740	0.12985
	300	K = 0.2282	0.8507	0.02726	0.16130
	400	K = 0.4137	0.8738	0.01887	0.13239
	500	K = 0.5478	0.8070	0.02463	0.14963
Henderson and Pabis	200	a = 1.611, k = 0.2083	0.9192	0.02941	0.16604
	300	a = 1.672, k = 0.2999	0.9227	0.04178	0.19489
	400	a = 1.593, k = 0.5172	0.9252	0.03914	0.18316
	500	a = 1.709, k = 0.7011	0.8649	0.07017	0.23960
Wang and Singh	200	a = 0.0018, b = −0.0792	0.9906	0.01011	0.09734
	300	a = 0.0024, b = −0.0941	0.9745	0.02726	0.15741
	400	a = 0.0121, b = −0.2035	0.9885	0.01193	0.10112
	500	a = 0.0133, b = −0.2412	0.9924	0.00656	0.07326
Page	200	k = 0.0293, n = 1.669	0.9981	0.00015	0.01200
	300	k = 0.0475, n = 1.701	0.9924	0.00012	0.01044
	400	k = 0.1326, n = 1.670	0.9989	0.00014	0.01099
	500	k = 0.1886, n = 1.682	0.9958	0.00057	0.02153
Midilli	200	a = 0.9956, k = 0.0295, n = 1.607, b = −0.004	**0.9994**	0.00007	0.00802
	300	a = 1.0305, k = 0.0417, n = 1.733, b = −0.006	0.9984	0.00023	0.01378
	400	a = 0.9899, k = 0.1194, n = 1.689, b = −0.005	0.9989	0.00016	0.01068
	500	a = 1.001, k = 0.1893, n = 1.652, b = −0.003	0.9967	0.00057	0.01913
Logarithmic	200	a = 2.032, k = 0.0486, b = −0.963	0.9956	0.00043	0.01983
	300	a = 3.338, k = 0.0388, b = −2.243	0.9853	0.00197	0.04123
	400	a = 1.831, k = 0.1355, b = −0.768	0.9926	0.00105	0.02870
	500	a = 2.364, k = 0.1181, b = −1.318	0.9949	0.00078	0.02381
Two order polynomial	200	c = −0.0811, b = 0.0149, a = −0.0144	0.9939	0.00425	0.06314
	300	c = −0.0200, b = 0.0203, a = −0.0305	0.9990	0.00109	0.03147
	400	c = −0.0519, b = 0.0005, a = −0.0797	0.9954	0.00634	0.07370
	500	c = −0.1495, b = 0.2129, a = −0.1828	0.9795	0.03556	0.17058

At initial stages of the falling rate period, for which the sample contains a high quantity of moisture, the physical mechanism that governs the moisture transport is liquid diffusion. As drying progresses, the sample surface gets progressively dried. Hence, a porous structure is formed and at the same time, the transport of moisture might be in vapour form. The pores in the surface structure of the sample are widened as a result of the increase of water vapour pressure inside them. This effect takes place in the final stage of the drying process. The higher microwave power can accelerate the water molecules present in the samples to evaporate faster, thus providing a faster decrease of the material moisture content and the corresponding higher value of effective moisture diffusivity (Thuwapanichayanan et al. 2011; Singh and Pandey 2011; Rhim and Lee 2011). As expected, the D_{em} value of kiwi slice increased with the increase in slice thickness due to the effect of the surface hardening of the product. Nguyen and Price (2007) found that the occurrence of surface hardening of thin slabs was faster than those of thick slabs because the moisture evaporation rate of thin slabs was higher. A rapid surface hardening of thin slabs then hindered the moisture transfer during the drying process, which caused the D_{em} value of thin slabs to be lower than that of thick slabs. Similar results were also reported by several researchers (Poomjai et al. 2011; Jenas and Das 2007; Shiby and Mishra 2007).

The average values of moisture diffusivity are presented in Table 8. Results showed that the effect of slice thickness on the moisture diffusivity was higher than the effect of microwave power ($P \leq 0.05$). The average moisture diffusivity values of dried samples at microwave power level of 200–500 W were varied in the range of 1.47–4.93 × 10^{-9} m^2/s; 5.83–18.02 × 10^{-9} m^2/s; and 12.35–39.39 × 10^{-9} m^2/s for 3, 6, 9 mm slice thickness, respectively. The effective moisture diffusivity values of kiwi slices under microwave drying conditions are found to be within the general range of 10^{-12} to 10^{-6} m^2/s for food materials and agricultural crops

Table 7 Statistical results of different thin-layer drying models for kiwi slices (L = 9 mm)

Model	P (W)	Model constants	R^2	χ^2	RMSE
Newton	200	K = 0.1490	0.9713	0.00667	0.08083
	300	K = 0.2787	0.9247	0.00989	0.09725
	400	K = 0.4297	0.9016	0.01619	0.12260
	500	K = 0.5867	0.9165	0.01868	0.13031
Henderson and Pabis	200	a = 1.379, k = 0.1693	0.9905	0.00601	0.07591
	300	a = 1.482, k = 0.3312	0.9575	0.01613	0.12135
	400	a = 1.575, k = 0.5237	0.9435	0.03485	0.17282
	500	a = 1.589, k = 0.7076	0.9554	0.04456	0.19094
Wang and Singh	200	a = 0.0025, b = −0.0915	0.9880	0.00226	0.04653
	300	a = 0.0085, b = −0.1627	0.9885	0.01269	0.10764
	400	a = 0.0165, b = −0.2291	0.9881	0.01352	0.10766
	500	a = 0.0289, b = −0.3059	0.9874	0.01098	0.09479
Page	200	k = 0.0511, *n* = 1.393	0.9965	0.00032	0.01747
	300	k = 0.1074, *n* = 1.444	0.9975	0.00028	0.01612
	400	k = 0.1645, *n* = 1.546	0.9979	0.00029	0.15818
	500	k = 0.2417, *n* = 1.596	0.9990	0.00015	0.01095
Midilli	200	a = 1.003, k = 0.0514, *n* = 1.407, b = 0.0008	0.9972	0.00027	0.01547
	300	a = 1.013, k = 0.1154, *n* = 1.421, b = 0.0005	0.9981	0.00028	0.01512
	400	a = 0.999, k = 0.1584, *n* = 1.555, b = −0.0015	0.9978	0.00036	0.01600
	500	a = 0.997, k = 0.2358, *n* = 1.604, b = −0.0098	0.9990	0.00122	0.02783
Logarithmic	200	a = 1.195, k = 0.1158, b = −0.0802	0.9914	0.00086	0.02832
	300	a = 1.275, k = 0.1733, b = −0.1875	0.9920	0.00096	0.02895
	400	a = 1.421, k = 0.2051, b = −0.3477	0.9912	0.00132	0.03220
	500	a = 1.403, k = 0.2730, b = −0.3347	0.9887	0.00172	0.03536
Two order polynomial	200	c = 0.1042, b = −0.1126, a = −0.0024	0.9982	0.00165	0.03928
	300	c = −0.0153, b = −0.0976, a = −0.0212	0.9919	0.01173	0.10098
	400	c = −0.0259, b = −0.0804, a = −0.0633	0.9944	0.01042	0.09049
	500	c = −0.0123, b = −0.1136, a = −0.1122	0.9976	0.00392	0.05339

(Evin 2011; Erbay and Icier 2010). The values of D_{em} are comparable with the reported values of 1.743–2.241 × 10^{-10} m^2/s mentioned for kiwi slice hot air drying at 50–60 °C, 2.4 m/s and 8 mm slice thickness (Doymaz 2008); 3–17.2 × 10^{-10} m^2/s for kiwi slice convective drying at 30–90 °C (Simal et al. 2005). The D_{em} values for microwave drying are higher than the value determined for hot air drying by other researchers. Similar results were reported by Al-Harahsheh et al. (2009) for tomato pomace; Darvishi et al. (2014a) for white mulberry; Arslan and Ozcan (2010) for red bell-pepper; McMinn et al. (2003) for potato slab; Evin (2011) for Gundelia tournefortii, and Darvishi et al. (2013) for pepper. A linear regression analysis on the average moisture diffusivity with the processing variables resulted in the following relationship:

$$(D_{em})_{ave} = 1.034 \times 10^{-9} \times L^{2.026} \exp\left(-\frac{404.5}{P}\right) \qquad R^2 = 0.9953 \tag{31}$$

Activation energy

The activation energy was calculated by plotting D_{em} versus the moisture content and m_0/P as depicted in Fig. 11. Eqs. (32, 33 and 34) show the effect of moisture content and m_0/P on D_{em} of the kiwi samples with following coefficients:

$$D_{em}(3\ \mathrm{mm}) = 2.33 \times 10^{-8} \exp\left(-\frac{17.96\ m_0}{P} - 0.564M\right) \qquad R^2 = 0.966 \tag{32}$$

$$D_{em}(6\ \mathrm{mm}) = 9.61 \times 10^{-8} \exp\left(-\frac{20.09\ m_0}{P} - 0.536M\right) \qquad R^2 = 0.958 \tag{33}$$

$$D_{em}(9\ \mathrm{mm}) = 2.17 \times 10^{-7} \exp\left(-\frac{21.38\ m_0}{P} - 0.434M\right) \qquad R^2 = 0.971 \tag{34}$$

The activation energy values were found to be 17.96 (±1.30), 20.09 (±1.97) and 21.38 (±1.57) W/g for the 3, 6 and 9 mm slice thickness of kiwi samples, respectively. As can be observed, increasing the slice thickness caused an important increase in the moisture diffusivity, thus the activation energy was decreased ($p \leq 0.05$). The activation energy is an indication of the required energy to remove moisture from a solid matrix (Aghbashlo et al. 2009). The lower activation energy translates to higher moisture diffusivity in the drying process (Sharma and Prasad 2004). These values are comparable to 13.6 W/g for

Table 8 Average value of moisture diffusivity ($\times 10^{-9}$ m^2/s) of kiwi slices

Thickness (mm)	Microwave power (W)			
	200	300	400	500
3	1.47	2.56	3.00	4.93
6	5.83	8.17	13.69	18.02
9	12.35	22.20	33.28	39.29

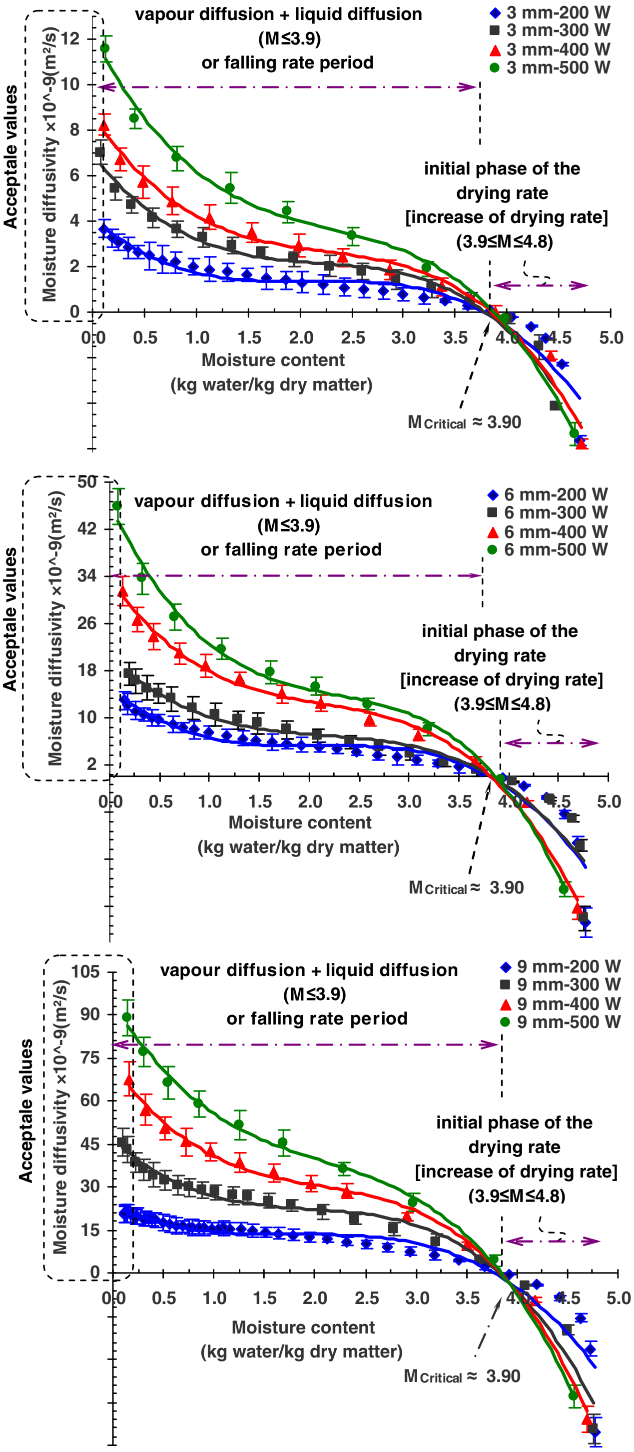


Fig. 10 Variation of the effective moisture diffusivity with moisture content

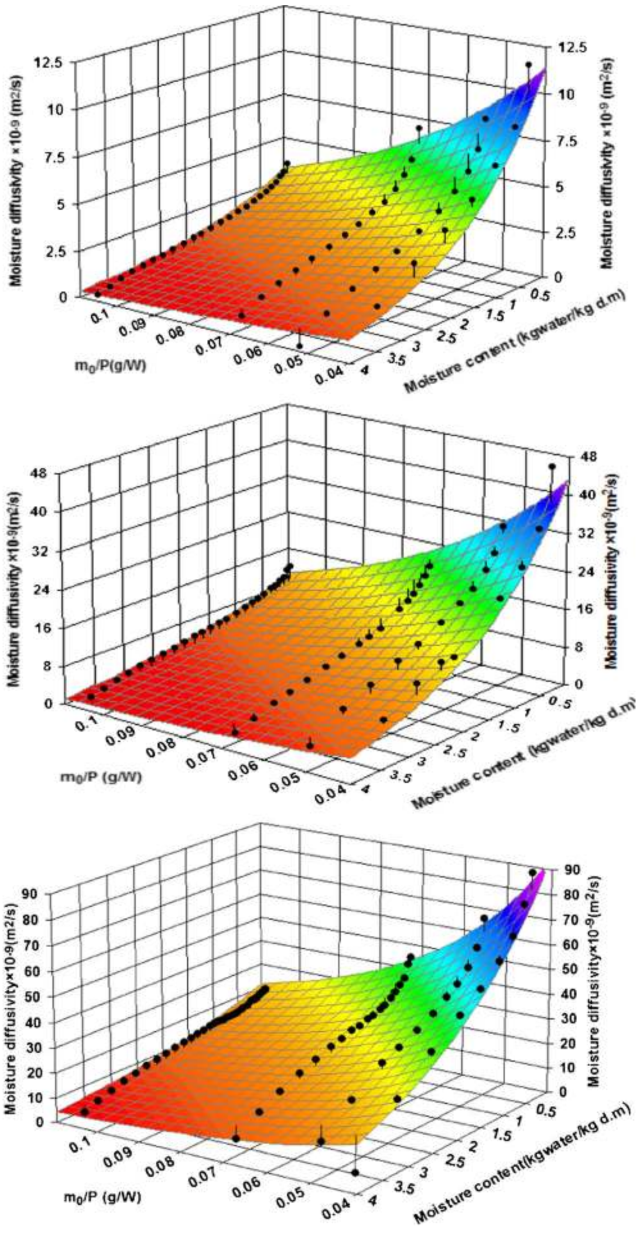


Fig. 11 Effect of moisture content and m_0/P on moisture diffusivity in for kiwi slice (3, 6and 10 mm, respectively)

pandanus leaves (Rayaguru and Routray 2011), 14.19 W/g for pepper (Darvishi et al. 2013), 5.54 W/g for okra (Dadali et al. 2007), 12.284 W/g for (Ozbek and Dadali 2007), and 3.986 W/g for white mulberry (Darvishi et al. 2014a).

Conclusion

This work is concerned with the energy and exergy analyses, drying kinetics, moisture diffusivity and modeling of the single layer drying process of kiwi slices via a microwave dryer. Drying periods ranged from 4 to 14.5, 5 to 15.5 and 5.5 to 23.5 min for 3, 6 and 9 mm thickness, respectively. Constant drying rate period was not observed, the kiwi slices drying occurring in the falling rate period. The results showed that the Page model was the best one to describe the drying process of the kiwi slices. The activation energy for moisture diffusion was found as 17.96, 20.09 and 21.38 W/g for the thickness of 3, 6 and 9 mm, respectively. The effective moisture diffusivity increased with a decrease in moisture content and increases in microwave power and slice thickness. The energy efficiency of microwave drying of kiwi slices varied between 15.15 and 32.27 % while exergy efficiency varied between 11.35 and 24.68 %. Specific energy consumption was found between 7.79 and 16.20 to MJ/kg water evaporated, and decreased with increasing microwave power and decreasing slice thickness. The best values of energy and exergy efficiency, drying time, energy consumption and drying rate were obtained at 2 mm slice thickness and 500 W microwave power levels.

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