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Thin layer drying characteristics and modeling of melon slices (*Cucumismelo*)

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The thin-layer drying characteristics of melon slices were investigated under four air temperatures, 40, 50, 60 and 70 °C, two different thicknesses of 4 and 6 mm, and natural convective airflow of 0.01 m/s. Data were analyzed to obtain diffusivity values from the period of falling drying rate. Four mathematical models for describing the thin-layer drying behavior of melon were investigated. The results show that the Midilli et al. is the most appropriate model for drying behaviour of thin layer melon slices. An analysis of variance (ANOVA) revealed that temperature and slice thickness significantly affected the drying time, drying rate, effective diffusivity, and activation energy. The effective diffusivity varied from 1.21×10^{-8} m^2/s to 4.18×10^{-8} m^2/s for slice thickness of 4mm, and from 1.69×10^{-8} to 8.54×10^{-8} m^2/s for slice thickness of 6 mm. The activation energy for the moisture diffusion was determined to be 36.40 and 49.47 kJ/mol for the slice thicknesses of 4 and 6mm, respectively.

Key words: Melon slice; Effective diffusivity; Modeling; Drying

Introduction

Melon (*Cucumismelo* L), a seasonal fruit of summer,has high commercial value and is appreciated because of its sensorial characteristics but has a short post-harvesting life at room temperature. This short life makes commercialization and transportation of melons to distant places difficult,, thus contributing to increased fruit losses. However, melon can be dried to save part of the harvest that would otherwise not be readily consumed. Drying is a classical method of food preservation that extends shelf-life, reduces transportation costs due to decreased weight, and requires comparatively less storage space. Drying also avoids the need for expensive cooling systems. (Doymaz and Ismail, 2011; Doymaz, 2011; Arabhosseini *et al*., 2009).The

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demand for dried fruits as an alternative to fresh fruits is steadily increasing in the international market because of the desirable taste and flavor of dried fruits.

Convective air drying is a thermal process in which heat and moisture transfer occurs simultaneously. The heat from the air drying is transferredto the sample as the moisture content decreases. . The heat transfer process is completed when the sample temperature no longer changes significantly.. On the other hand, because the steam pressure in the sample is greater than the pressure in the air, the sample transfers moisture to its surroundings; this process also concludes when the moisture content does not change significantly.Several factors can influence convective drying of food; for example, velocity and temperature of air, water diffusion through material, load density, and the thickness and shape of the product to be dried.

The most important aspects of drying technology are the mathematical modeling of the process and the experimental setup (Akpinar *et al*., 2006). The modeling is based on the design of a set of equations that describe the system as accurately as possible. [not altogether sure what that sentence means. I think that my small corrections are sufficient here. Drying characteristics of the chosen products and simulation models are needed in the design, construction, and operation of drying systems (Celma *et al*., 2011).

No published work seems to have been done on the drying behavior of melon slices. Therefore, the aims of this study were (i) to determine the drying characteristics of melon slices and the effect of drying parameters such as drying temperature, and thickness of slices; and (ii) to obtain the most suitable mathematical model defining the oven-drying process.

Materials and methods

Sample preparation

Melon (*Cucumismelo* L) was procured from local vegetable markets in Gorgan, Iran (Fig. 1). The samples were stored at 5±0.5 °C before use in experiments. Melons were washed, peeled, and thinly sliced in two different thicknesses of 4 and 6 mm using a sharp stainless steel knife. The average initial moisture content of the samples was found to be 83.8% wet basis, as determined by using convective oven at 105 ºC for 24h.

Experimental apparatus and procedure

The melon slices (about 100 g) were dried using an air-ventilated oven at temperature of 40, 50, 60 and 70 °C with natural convective airflow of 0.01 m/s (Fig. 1). Heat was generated by the heater integrated into the walls of the oven, and the distributor fan was not switched on in order to simulate the natural convective environment of the commercial dryer. The exhaust air escaped through a ventilation hole (diameter = 4 cm) at the back of the oven. The product was spread in a thin layer on aluminum in the center of the chamber. The drying chamber is constructed from sheet iron with the cavity dimension of 71 × 55 × 64.5cm.

Experiments were performed at four temperatures of 40, 50, 60 and 70 °C. The moisture losses of samples were recorded at 1h 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 sample during experimentation, the tray with the samples was taken out of the drying chamber, weighed on the digital top pan balance and placed back into the chamber. Drying was carried out until the final moisture content reached a level less than 5% (w.b.).

Analysis of data

To find a suitable mathematical model, the moisture content data at different drying air temperatures and slice thickness of samples were converted to the moisture ratio (MR) expression by using following equation.

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

where M_t, M_0 and M_e are the moisture content at any time of drying: initial moisture content and equilibrium moisture content (kg water/kg dm), respectively.

Since the values of m_e are very small compared to m_t or m_0, Eq. (1) can be simplified to M_t/M_0 (Berruti et al. 2009; Sarimeseli, 2011).

The drying rate (DR) of melon slices was calculated using Eq. (2):

$$\mathrm{DR} = \frac{M_{t+dt} - M_t}{dt} \qquad (2)$$

where DR is the drying rate (kg waret/kg dm.hr), M_{t+dt} is the moisture content at t+dt (kg water/kg dm), and t is drying time (hr).

Four thin-layer drying models (Table 1) were fitted to experimental data to find the best suitable model for describing the drying behavior of melon slices in oven dryer. 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. Statistical values are defined as follows:

$$\chi^2 = \frac{\sum_{i=1}^{n}\left(MR_{exp,i}-MR_{pre,i}\right)^2}{N-z} \tag{3}$$

$$RMSE = \sqrt{\frac{\sum_{i=1}^{n}\left(MR_{exp,i}-MR_{pre,i}\right)^2}{N}} \tag{4}$$

In these equations, N is the number of observations, z is the number of constants, MR_{exp} and MR_{pre} are the experimental and predicted moisture ratios, respectively. The best model describing the thin-layer drying characteristics of melon slices was chosen based on the higher value of R^2 and lower values of χ^2 and RMSE.

Calculation of moisture diffusivity and activation energy

Fick's second equation of diffusion was used to calculate theeffective diffusivity, considering a constant moisturediffusivity,infinite slab geometry and uniform initial moisture distribution:

$$MR = \frac{8}{\pi^2}\sum_{n=o}^{\infty}\frac{1}{(2n+1)}\exp\left(-\frac{(2n+1)\pi^2}{4L^2}D_{eff}t\right) \tag{5}$$

whereD_{eff} is the effective diffusivity (m^2/s), and L is the half thickness of slab (m).

The Eq. (5) can be simplified by taking the first term of Eq. (6):

$$MR = \frac{8}{\pi^2}\exp\left(-\frac{\pi^2 D_{eff}\,t}{4L^2}\right) \tag{6}$$

The effective diffusivity was also typically calculated by using the slope of Eq. (7). A straight line with a slope of K was obtained when ln(MR) was plotted versus time:

$$\ln(MR) = \ln\left(\frac{8}{\pi^2}\right) - \frac{\pi^2 D_{eff}}{4L^2} \tag{7}$$

$$K = \frac{\pi^2 D_{eff}}{4L^2} \tag{8}$$

The effect of temperature on diffusivity values can be describe using the Arrhenius relationship,

$$D_{eff} = D_0 \exp\left(-\frac{E_a}{RT}\right) \tag{9}$$

where D_0 is the pre-exponential factor of the Arrhenius equation (m^2/s), E_a is the activation energy (kJ/mol), R is the universal gas constant (8.314 J/mol K), and T is the absolute temperature (K). From the slope of the straight line of $\ln D_{eff}$ versus reciprocal of T, described by the Arrhenius equation, the activation energy, E_a, could be calculated.

Statistical analysis

All measurements were carried out in triplicate. ANOVA test was performed in order to examine the effect of temperature and slice size on drying kinetics. The SPSS version 17.0 was used for statistical investigations. For all statistical analysis, the level of significance is fixed at 95%. Each factor having a P value ≤ 0.05 was considered significant.

Results and discussion

Effect of air temperature and slice thickness on drying behaviour

The changes in the ratio of moisture to drying time of melon slice in oven drying are presented in Figs. 2 and 3. It was found that the moisture content is affected by the temperature and slice thickness, and the drying time of the melon slice was significantly reduced from 13 to 6hours for slice thickness of 4mm, and from 21 to 7 hours for slice thickness of 6mm, as the temperature increased as can be seen in Figs. 2 and 3. It is also clear from the same Figure that increasing the temperature resulted in shortened drying times up to 54%and 67% for slice thicknesses of 4 and 6 mm, respectively.

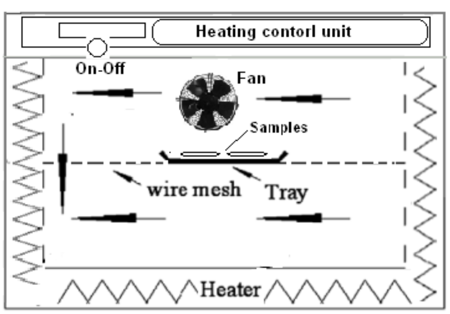

Fig. 1. Schematic diagram of oven drying system and Melon (Cucumismelo)

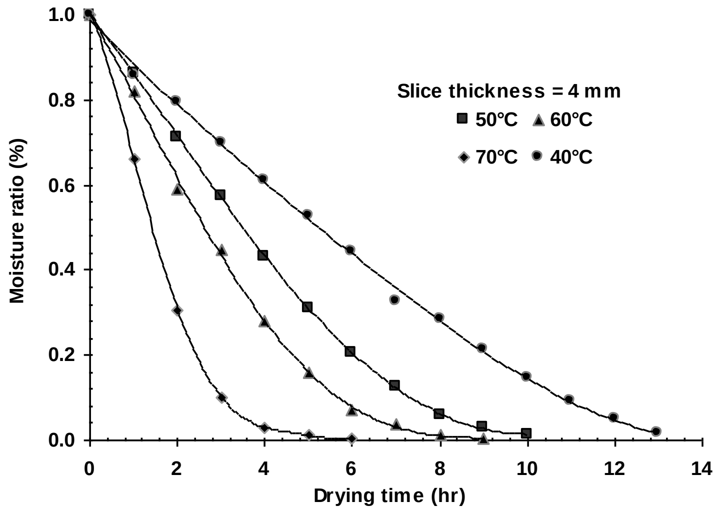

Fig. 2. Variation of moisture ratio with drying time for the melon slice thickness of 4 mm

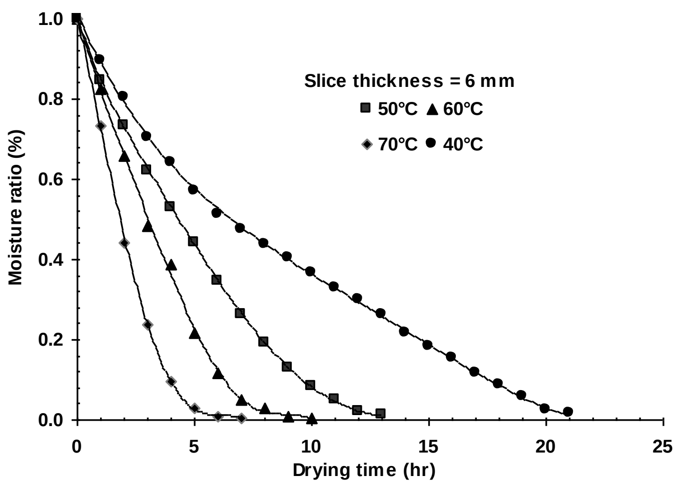

Fig. 3. Variation of moisture ratio with drying time for the melon slice thickness of 6 mm

To evaluate the individual effect of independent variables on the drying rate, analysis of variance (ANOVA) table was constructed as shown in Table 1. Comparing F-values of the slice thickness and temperature showed that the effect of temperature on the drying rate was higher (high F-value) than the effect of slice thickness (low F-value).Higher drying rates were obtained at higher temperature (70°C) and low slice thickness (4mm). Thus, the temperature and slice thickness had a crucial effect on the drying rate. As seen in Figs. 4 and 5, all curves have two stages. The drying rate increases rapidly and then slowly decreases as drying progresses. This increase is due to the increased heat transfer potential between the air and kiwifruit slices, thus enhancing the evaporation of water from melon slices.Similar findings were reported in previous studies (Wang *et al*., 2007; Soysal *et al*., 2006; Therdthai and Zhou, 2009). In general, it has been observed that the drying rate decreases with time or with the reduction of moisture content. As mentioned earlier, the product's moisture content reduces over time. The drying process takes place in the falling rate period.

Table 1. Mathematical models given by various authors for drying curves

Model name	Model	References
Page	$MR=\exp(-kt^n)$	Sarimeseli (2011)
Wang and Singh	$MR = 1 + bt + at^2$	Arslan and Özcan (2010)
Logarithmic	$MR=a\exp(-kt) + b$	Akpinar (2008)
Midilli *et al.*	$MR=a\exp(-kt^n)+ bt$	Midilli *et al.* (2002)

where, k is the drying constant and a, b, n are equation constants

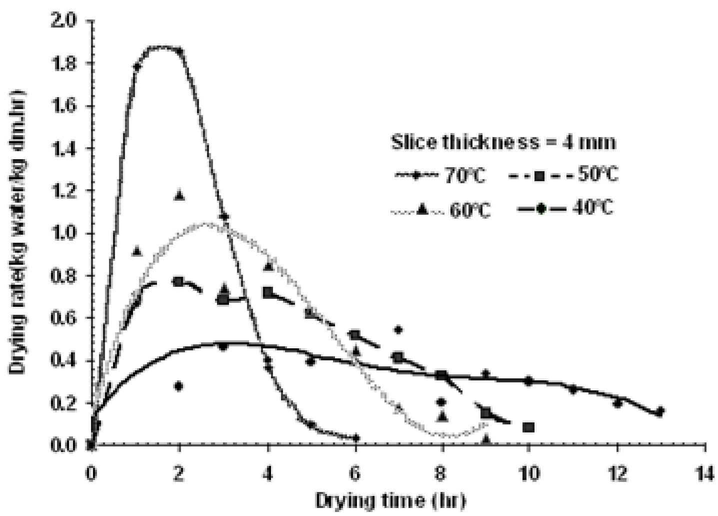

Fig. 4. Variation of drying rate with time for the melon slice thickness of 4 mm

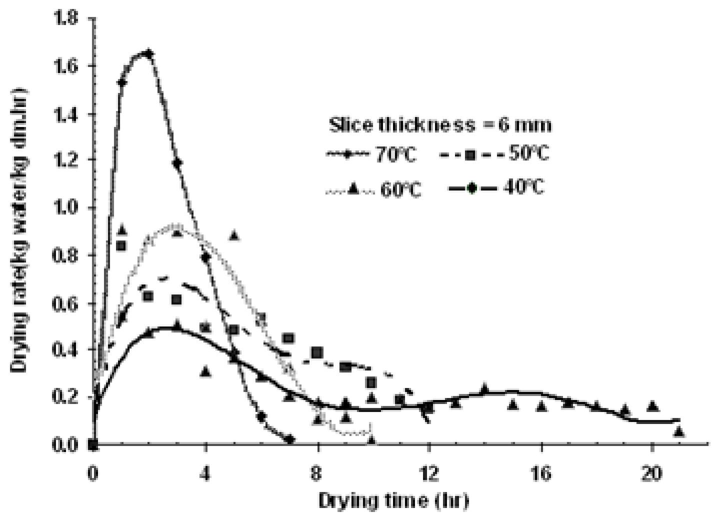

Fig. 5. Variation of drying rate with time for the melon slice thickness of 6 mm

Modeling of drying kinetics

The statistical results from models are summarised in Tables 2 and 3. The best model describing the thin-layer drying characteristics of melon slice was chosen as the one with the highest R^2 values and the lowest χ^2 and RMSE values. The statistical parameter estimations showed that R^2, χ^2 and RMSE values ranged from 0.9784 to 0.9999, 0.00002 to 0.01232, and 0.00354 to 0.10040, for slice thickness of 4mm, and from 0.9858 to 0.9999, 0.00009 to 0.00797, and 0.00667 to .07060, for slice thickness of 6mm.. Of all the models tested, the Midilli et al. model gives the highest value of R^2 and the lowest values of χ^2 and RMSE.

Table 2. Analysis of variance (ANOVA) for effect of slice thickness and temperature on drying rate of melon slices

Source of variation	**Sum of Squares**	**df**	**Mean Square**	**F**	**Sig.**
Corrected Model	1.204	7	0.172	31.791	0.000
Intercept	6.564	1	6.564	1213.253	0.000
Thickness	0.064	1	0.064	11.785	0.003
temperature	1.128	3	0.376	69.531	0.000
thickness× temperature	0.012	3	0.004	0.719	0.555
Error	0.087	16	0.005		
Total	7.854	24			
Corrected Total	1.290	23			

Table 3. Results of statistical analysis on the modeling of moisture content and drying time for the oven dried melon slice (4mm)

Model	T (°C)	Model constants	R^2	$\chi 2$	RMSE
Page	70	k=0.413, n=1.538	0.9999	0.00002	0.00354
	60	k=0.179,n=1.447	0.9984	0.00036	0.01706
	50	k=0.038, n=1.934	0.9996	0.01232	0.10040
	40	k=0.071, n=1.421	0.9895	0.00125	0.03269
Wang and Singh	70	a=0.0425, b= - 0.4172	0.9944	0.00101	0.02687
	60	a= 0.0134, b= - 0.2318	0.9975	0.00037	0.01719
	50	a= 0.0071, b= - 0.1721	0.9969	0.00042	0.01853
	40	a= 0.0026, b= - 0.1107	0.9978	0.00025	0.01473
Logarithmic	70	k= 0.506, a=1.115, b= -0.087	0.9784	0.00304	0.04167
	60	k= 0.235, a=1.220, b= -0.185	0.9926	0.00129	0.03006
	50	k= 0.142, a= 1.393, b= -0.362	0.9953	0.00080	0.02406
	40	k= 0.064, a= 1.770, b= -0.774	0.9971	0.00032	0.01590
Midilli *et al.*	70	k= 0.412, a= 0.999, b= 0.001, n=1.549	0.9999	0.00003	0.00366
	60	k= 0.183, a= 0.995, b= -0.003, n=1.388	0.9982	0.00031	0.01367
	50	k= 0.116, a= 0.991, b= -0.006, n=1.391	0.9998	0.00016	0.01015
	40	k= 0.078, a=0.982, b= -0.016, n=1.164	0.9984	0.00033	0.01534

It was determined that the value of the drying rate constant (k) increased with the increase in temperature. This implies that the increase in temperature drying curve becomes steeper, indicating increase in drying rate.Fig. 6 and 7compares experimental data with those predicted with the Midilli et al. model for melon slice samples at the temperatures of 40, 50, 60 and 70 ºC; and the slice thicknesses of 4 and 6 mm. The prediction using the model showed MR values banded along the straight line, demonstrating the suitability of these models in describing drying characteristics of melon slice.

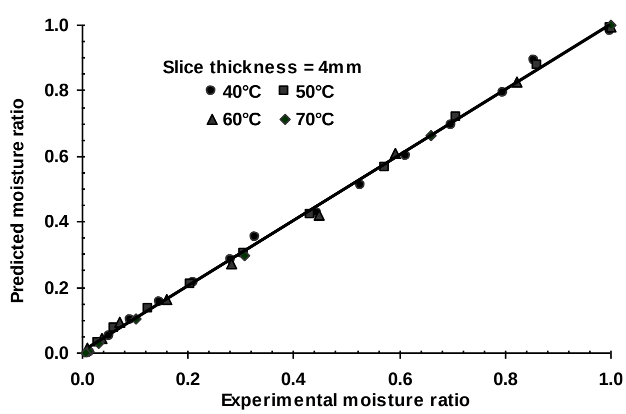

Fig. 6. Comparison of moisture ratios determined by experimentation and prediction using the Midilli et al. model for the melon slice thickness of 4 mm

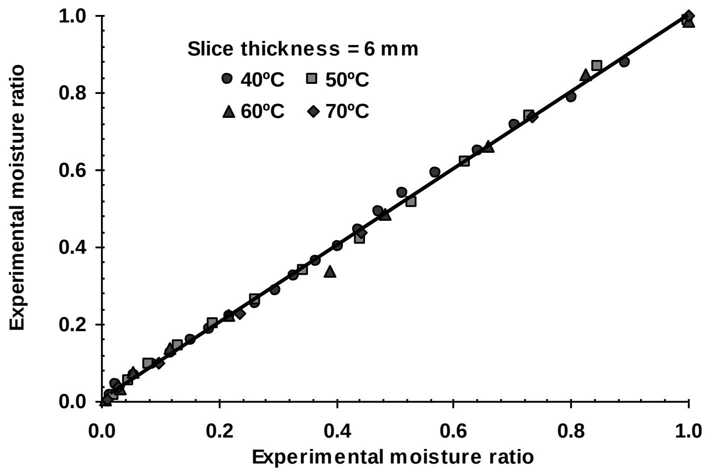

Fig. 7. Comparison of moisture ratios determined by experimentation and prediction using the Midilli et al. model for the melon slice thickness of 6 mm

Effective moisture diffusivity and activation energy

Analysis of variance (ANOVA) showed that the effect of temperature on the effective moisture diffusivity was higher than the effect of slice thickness. The effective moisture diffusivities of melon slices for different temperatures and slice thicknesses are presented in Table 4. The values ranged from 1.21×10^{-8} m^2/s at 40 °C to 4.18×10^{-8} m^2/s at 70 °C for slice thickness of 4mm and from 1.69×10^{-8} to 8.54×10^{-8} m^2/s for slice thickness of 6 mm. Table 4 shows that D_{eff} increased progressively with the increase of drying air temperature and slice thickness. 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 temperature (Xiao *et al.*, 2010). This finding agrees well with those of Hayaloglu *et al*. (2007) for drying strained yogurt using a convective tray-dryer, Celma *et al*. (2008) for thin layer infrared drying of wet olive husk, Celma *et al*. (2009) for infrared drying of industrial grape by-products, Lee and Kim (2009) for vacuum drying of Asian white radish, and Lee and Zuo (2011) for drying Zizyphus jujube miller slices using hot air drying.

Table 4. Results of statistical analysis on the modeling of moisture content and drying time for the oven dried melon slice (6mm)

Model	T (°C)	Model constants	R^2	χ2	RMSE
Page	70	k=0.299, n=1.466	0.9999	0.00009	0.00810
	60	k=0.146,n=1.463	0.9954	0.00078	0.02519
	50	k=0.107, n=1.324	0.9927	0.00092	0.02807
	40	k=0.091, n=1.087	0.9869	0.00122	0.03330
Wang and Singh	70	a=0.0271, b= - 0.3309	0.9978	0.00036	0.01633
	60	a= 0.0104, b= - 0.2047	0.9962	0.00053	0.02084
	50	a= 0.0047, b= - 0.1384	0.9993	0.00008	0.00825
	40	a= 0.0018, b= - 0.0835	0.9858	0.00125	0.03365
Logarithmic	70	k= 0.370, a=1.155, b= -0.124	0.9916	0.00797	0.07060
	60	k= 0.199, a=1.246, b= - 0.214	0.9910	0.00148	0.03283
	50	k= 0.116, a= 1.314, b= - 0.312	0.9986	0.00021	0.01279
	40	k= 0.072, a= 1.201, b= -0.236	0.9958	0.00046	0.01986
Midilli et al.	70	k= 0.299, a=0.998, b= -0.002, n=1.442	0.9999	0.00009	0.00667
	60	k= 0.146, a= 0.986, b= -0.004, n=1.406	0.9963	0.00067	0.02069
	50	k= 0.121, a= 0.988, b= -0.010, n=1.127	0.9999	0.00021	0.01228
	40	k= 0.130, a=1.010, b= -0.013, n=0.744	0.9987	0.00017	0.01192

Table 5. Values of effective diffusivity obtained for melon slice at different temperatures and at two slice thicknesses

T(°C)	Effective diffusivity (D_{eff} , m^2/s)	
	4mm	6mm
70	4.18×10^{-8}	8.54×10^{-8}
60	2.72×10^{-8}	5.78×10^{-8}
50	1.89×10^{-8}	2.97×10^{-8}
40	1.21×10^{-8}	1.69×10^{-9}

The values for D_{eff} obtained from this study lie within the general range 10^{-11}–10^{-8} m^2/s for drying of food materials (Sacilik *et al*., 2006; Lee and Zuo, 2011). The values of D_{eff} are comparable with the reported values of 6.20×10^{-11}–3.50×10^{-10} m^2/s mentioned for onion slices infrared drying (Sharma *et al*., 2005), 3.72×10^{-9} –12.27×10^{-9} m^2/s for tomatoes hot air drying at 45–75 °C (Akanbi *et al*., 2006), 6.36×10^{-11} to 9.75×10^{-9} m^2/s for sweet potato hot air drying at 50–80 °C (Falade and Solademi, 2010), 2.24×10^{-10} to 16.4×10^{-10} m^2/s for blueberry infrared drying at 60–90 °C (Shi *et al*., 2008), 6.92×10^{-10} to 14.59×10^{-10} m^2/s for Asian white radish hot air drying at 40–60 °C(Lee and Kim, 2009); 6.2×10^{-11} –3.50×10^{-10} m^2/s for orange slices hot air drying at 40–80 °C (Rafiee *et al*., 2010).

The activation energy was calculated by plotting ln (D_{eff}) versus the reciprocal of the temperature (1/T), and presented in Fig. 8. The activation energy values were found to be 36.40 and 49.47 kJ/mol for the slicethicknesses of 4 and 6mm, respectively.These valuesarelower than the activation energies of okra drying (51.26 kJ/mol) (Doymaz, 2005), pumpkin slice drying (78.93 kJ/mol) (Doymaz, 2007), green pepper drying (51.4 kJ/mol) (Ertekin, 2002), mint drying (82.93 kJ/mol) (Park *et al*., 2002) and higher than the activation energy of red chillies (24.47 kJ/mol) (Kaleemullah and Kailappan, 2005), berberis(130.6 kJ/mol) (Aghbashlo *et al*., 2009), apple slices (19.96–22.62 kJ/mol) (Kaya *et al.*, 2007), and Asian white radish (16.49–20.26 kJ/mol) (Lee and Kim, 2009).

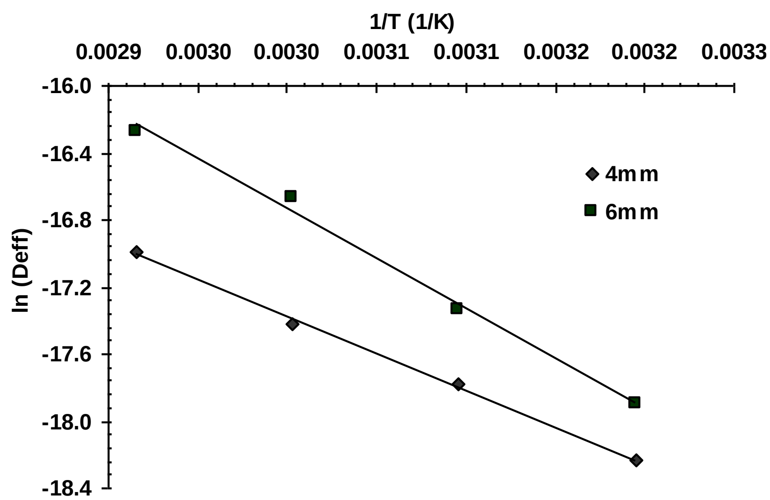

Fig. 8. Plot of $\ln D_{eff}$ versus 1/T for calculating the activation energy

Conclusion

Thin layer drying experiments were conducted to determine the thin layer drying characteristics of melon slice. Four thin layer drying models were evaluated for their suitability. The Midilli et al. model was found to be the most suitable model for describing the thin layer drying of melon slice. Slice thicknesses and drying temperatures affected all the drying characteristics significantly ($P<0.05$). The effective moisture diffusivity was obtained based on Fick’s second law. The activation energy required to detach and move the water out from melon slices during the drying process was found to be 36.40 and 49.47 kJ/mol for the slice thickness of 4 and 6mm, respectively.

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