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EXPERIMENTAL INVESTIGATION AND MATHEMATICAL MODELING OF CONVECTIVE DRYING KINETICS OF WHITE RADISH

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ABSTRACT

The influence of air temperature on drying kinetics of radish slices in a bench scale convective tray dryer was examined experimentally and suitable drying model was developed. The experiments of drying of radish slices were conducted at 40, 50 and 60 °C with an air velocity of 2 m/s. The moisture transport from the radish slices are defined by Fick's diffusion model and effective diffusivity changes between $3.3-5.55\times10^{-8}$ m^2/min. An Arrhenius relation with activation energy value of 18.49 kJ/mol expressed the effect of temperature on the diffusivity. Also, drying data were fitted to ten commonly used thin-layer drying models. The statistical parameters coefficient of determination (R^2) and root mean square error (*RMSE*) were examined for evaluating the models. Among the models, Hii et al. model was the best to explain the single layer drying of white radish slices.

Keywords: *Air temperature, Forced air convective drying, Thin-layer mathematical modeling, Transport properties, White Radish*.

1. INTRODUCTION

Root crops such as radish, carrot, beets, onion, garlic etc. are being consumed either raw or cooked with other vegetables. Radish (Raphanus sativus L.) is popular salad crop for fresh market and home gardening. In India, they are chiefly cultivated in warm-humid states like Uttar Pradesh, Punjab, Maharashtra and Gujarat. Radish roots are considered to be good for patients suffering from gallbladder ailments, hemorrhoids, jaundice enlarged spleen and liver trouble (Benjamin et al., 2003).

Drying is a common technique employed in processing of the white radish. Dried radish is conventionally produced by sun drying. But the main limitation to sun drying is it requires a longer drying time and it is difficult to monitor the moisture content of sample (Lee et al., 2006). In addition, quality of products degrades in sun drying, due to wind-borne dust and dirt, infestation by insects, rodents and other animals (El-Beltagy et al. 2007). Forced convective drying provides an alternative to traditional sun drying. It allows controlled removal of moisture under low pressure. Simultaneously with forced convective drying it is possible to have a higher drying rate and lower drying temperature.

Knowledge of the drying kinetics of the radish is essential to design, optimize and control the process of drying. It is also necessary to investigate the forced convective drying characteristics of the radish to evaluate the process parameters and feasibility of convective drying for improving the quality of the dried radish. Although several studies have been carried out to investigate forced convective drying characteristics of various food materials (Akpinar et al. 2003, Samira et al. 2016, Agarry et al. 2005, Doymaz 2007, Gokhale and Lele 2011, Darvishi et al. 2016, Aregbesola et al. 2015, Waheed and Komolafe 2019), no data on forced convective drying behavior of radish slices are available for the engineering design of drying.

The objective of this experimental work is to determine the effect of drying temperature on drying characteristics of radish slices. Also, an appropriate thin-layer drying model is selected for describing the drying process of radish in thin layers through non-linear regression analysis and computed effective moisture diffusivity and activation energy of radish samples.

2. MATERIALS AND METHODS

2.1 Sample preparation

Fresh radishes were procured from nearby market and kept at room temperature before use. Prior to dehydration, the radishes were thoroughly washed to remove the dirt before peeling manually. The radishes were cut into slices having dimensions $(50\pm0.2)\times(50\pm0.2)\times 2\ mm$. The thickness of the slices was measured using a Vernier calipers. The initial moisture content of the radish slices was found to be $15.5\pm0.5\ kg\ w/kg\ ds$ by drying the samples in an oven at 105 °C for 24 h (Ozbek and Dadali 2007).

2.2 Drying equipment

In direct drying process as that of in convective tray dryer, the sample will be in direct contact with drying medium and effective drying is carried out when compared to indirect drying. Moreover, convective tray dryer is simple and relatively low-cost technique (Anwar and Tiwari 2001, Akpinar and Toraman, 2016, Ratiya et al. 2011). Hence in the present work, drying was performed in a laboratory-scale induced draft convective tray dryer at Koneru Lakshmaiah Education Foundation, India. The dryer consists of a variable speed blower, heating control system, air duct, tray, temperature, humidity, weight and velocity measuring instruments. The dryer is equipped with controllers for monitoring the temperature and air flow velocity. Air was drawn into the duct by a motor driven axial flow induced blower. In the tunnel of the dryer there are carriers for trays with samples, which are connected to a balance. The balance is placed outside the dryer, which determines and

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displays sample weight continuously during the operation. A digital anemometer is used to measure the airflow velocity. the heating systems consists of three electric heaters each of $1\,kW$ placed inside the duct. A rheostat is used to adjust the drying chamber temperature. The drying chamber is constructed in concentric form with an annulus, insulated with glass wool. Temperatures are measured using T-type thermocouples which are manually controlled by a six-channel temperature indicator with an accuracy of $\pm 0.5\ °C$.

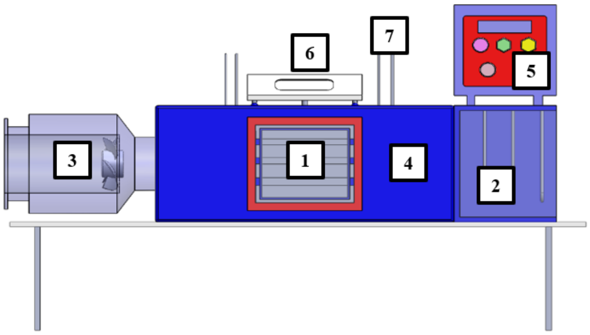

Fig. 1 Bench-scale convective tray dryer.

1- Drying space; 2- Heating coils; 3- Induced draft fan; 4- Air duct; 5- control switches; 6- Digital weighing balance; 7- Measuring instruments

2.3 Experimental test procedure

Drying equipment was operated at no load conditions till it reaches steady state. Later 500 g of radish slices is equally distributed over the trays and kept inside the drying chamber. After every 10 minutes, the weight loss of radish slices was recorded. This experimental study was continued till no change in the weight of the product is noticed for three successive readings.

2.4 Experimental uncertainty

Errors and uncertainties in the experiments can arise from instrument selection, condition, calibration, environment and human factors (Midilli 2001b). In drying experiments of white radish slices, the temperatures, velocity of drying air, weight losses were measured with appropriate instruments. During the measurements of the parameters, the uncertainties occurred were presented in Table 1.

Table 1 Uncertainties of the parameters during drying of radish slices

Parameter	*Uncertainty*
Temperature between trays	$\pm 0.4\ °C$
Velocity measurement	$\pm 0.2\ m/s$
Mass loss measurement	$\pm 0.01\ g$
Relative humidity	$\pm 3\%$

3. MATHEMATICAL MODELING

3.1 Drying kinetics

The moisture transfer from radish to surrounding hot air is mathematically analogous to the flow of heat from a hot body immersed in a cool fluid that is represented by Newton's law of cooling (Gokhale and Lele 2011). Therefore, the drying rate is proportional to the difference in moisture content between the material being dried and the equilibrium moisture content (M_e) which is dependent on the drying air conditions.

The moisture ratio M^* and drying rate DR of radish slices during the thin-layer drying experiments were calculated using Eq. (1) and Eq. (2) (Midilli 2001a, Akpinar 2002)

$$M^* = \frac{M_\tau - M_e}{M_o - M_e} \tag{1}$$

$$DR = \frac{M_{\tau+d\tau} - M_\tau}{d\tau} \tag{2}$$

Table 2 Selected thin-layer drying models for describing radish drying data.

Model Name	*Thin-layer drying model*	*References*
Lewis model	$M^* = e^{(-k\tau)}$	El-Beltagy et al. (2007)
Page model	$M^* = e^{(-k\tau^n)}$	Akoy et al. (2014)
Single term model	$M^* = a\,e^{(-k\tau)}$	Hashim et al. (2014)
Logarithmic model	$M^* = a\,e^{(-k\tau)} + c$	Kaur and Singh (2014)
Two-term model	$M^* = a\,e^{(-k_1\tau)} + b\,e^{(-k_2\tau)}$	Sacilik (2007)
Wang and Singh Model	$M^* = 1 + a\tau + b\tau^2$	Omolola et al. (2014)
Verma model	$M^* = ae^{(-k\tau)} + (1-a)e^{(-g\tau)}$	Akpinar (2006)
Midilli model	$M^* = ae^{(-k\tau)} + b\tau$	Ayadi et al. (2014)
Diffusion approach model	$M^* = ae^{(-k\tau)} + (1-a)e^{(-kb\tau)}$	Yaldyz and Ertekyn (2007)
Hii et al. model	$M^* = ae^{(-k_1\tau^n)} + be^{(-k_2\tau^n)}$	Kumar et al. (2012b)

Drying curves were fitted to ten well-known thin-layer drying models in Table 2. to select the best suited model for describing the drying characteristics of radish slices. Non-linear square regression analysis was performed using MATLAB 18.1 (MathWorks, Inc., 1984, Natick, USA) computer program. The goodness of the fit can be checked with different statistical methods such as Correlation coefficient (R), Coefficient of determination (R^2), Chi square (χ^2), Sum of Squares for Error (*SSE*), Root Mean Square Error (*RMSE*), Mean Absolute Percentage Error (*MAPE*) and Mean Bias Error (*MBE*) respectively. Of all these statistical indicators, the most widely used method in literature is R^2 and RMSE. Hence, in the present work, the goodness of the fit was determined by using coefficient of determination (R^2) and root mean square error *(RMSE)* (Wang et al. 2007a, Vedavathi et al. 2019, Kiran et al. 2019, Midilli et al. 2002).

These parameters can be calculated by Eq. (3-5). The higher values of R^2 and the lower values of $RMSE$ are chosen as the criteria for goodness of fit in the present study (Yaldiz et al. 2001, Wang et al. 2007b, Lahsasni et al. 2004, Abhishek et al. 2019).

$$R^2 = 1 - \frac{\sum_{i=1}^{N}\left(M^*_{pre,i} - M^*_{\exp,i}\right)^2}{\sum_{i=1}^{N}\left(M^*_{\exp,i} - M^*_{avg}\right)^2} \tag{3}$$

$$RMSE = \left[\frac{1}{N}\sum_{i=1}^{N}\left(M^*_{pre,i} - M^*_{\exp,i}\right)^2\right]^{1/2} \tag{4}$$

3.2 Effective moisture diffusivity

From the drying data analysis, it was recognized that the air-drying of radish didn't consist of constant rate drying period. Hence, Fick's II law of unsteady state diffusion in Eq. (5) can be used to interpret the experimental results.

For an infinite slab and uniform initial moisture concentration, Crank (1975) proposed analytical solution Eq. (6) for Eq. (5) with the following suitable boundary conditions.

$$\tau = 0 \;\&\; 0 < z < L \Rightarrow M = M_o$$

$$\tau > 0 \;\&\; z = 0 \Rightarrow \frac{dM}{d\tau} = 0$$

$$\tau > 0 \;\&\; z = L \Rightarrow M = M_e$$

$$\frac{\partial M}{\partial \tau} = D_{eff} \frac{\partial^2 M}{\partial z^2} \qquad (5)$$

$$M^* = \frac{8}{\pi^2} \sum_{n=0}^{\infty} \frac{1}{(2n+1)^2} e^{\left(-(2n+1)^2 \pi^2 \frac{D_{eff}}{4L^2} \tau\right)} \qquad (6)$$

D_{eff} mainly varies with internal conditions like product's temperature, the moisture content and the structure. By considering very low thickness to width ratio, the sample was assumed to be infinite slab. For longer drying periods, the Eq. (6) can be reduced to Eq. (7).

$$\ln\left(M^*\right) = \ln\left(\frac{8}{\pi^2}\right) - \pi^2 \frac{D_{eff}}{4L^2} \tau \qquad (7)$$

3.3 Activation energy

Many researchers studied the effect of temperature on D_{eff} and this effect can be generally described by an Arrhenius equation (Madamba et al. 1996).

$$D_{eff} = D_o \exp\left(-10^3 \frac{E_a}{R(T+273.15)}\right) \qquad (8)$$

The value of E_a shows the sensibility of the diffusivity against temperature. The greater value of E_a means more sensibility of D_{eff} to temperature (Kaymak-Ertekin 2002). Here, D_o is the pre-exponential factor of the Arrhenius equation (m^2/s) that is generally defined as the reference diffusion coefficient at infinitely high temperature.

4. RESULTS AND DISCUSSIONS

Single layer radish slices with thickness of 2 mm are dried in an induced draft convective tray dryer at the drying temperatures of 40, 50 and 60 $°C$. The radish slices of 15.67 $kgw/kgds$ were dried to a final moisture content of 0.03 $kgw/kgds$. The variations in the moisture content as a function of the drying time at various drying temperatures are presented in Figure 2. It can be seen that moisture content decreases continually with drying time. As expected, drying air temperature has a significant effect on the moisture content of radish slices. The drying times required to remove 15.64 $kgw/kgds$ quantity of moisture from radish slices were 450, 320 and 260 min at the drying air temperatures of 40, 50 and 60 °C, respectively.

Figure 3. shows the change in moisture ratio of radish slices with time at different temperatures. The results indicate that higher air-drying temperature resulted in greater slope of the curve and shorter drying time. The reason for this could be, increased air-drying temperature leads to an improved temperature gradient and surface evaporation rate, accelerating moisture diffusion from the center to the surface. These results are consistent with another study, where the decreased drying time was attributed to increase of the air-drying temperature (Akpinar et al. 2003).

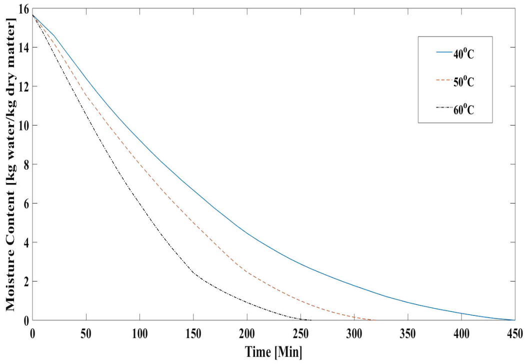

Fig. 2 Moisture content of radish slices as a function of time at different drying temperatures

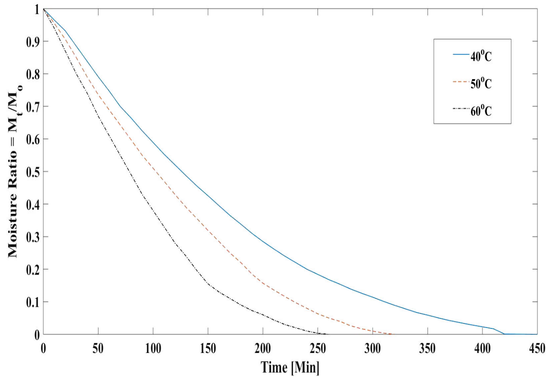

Fig. 3 Variation of M^* of white radish slices with τ for different temperatures

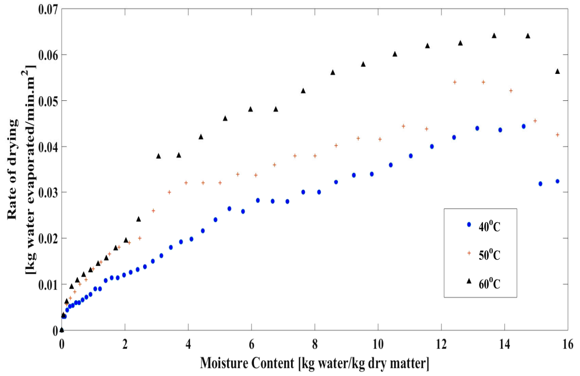

Fig. 4 Drying rate curves of white radish slices at different temperatures

The changes in the drying rates with moisture content for the radish slices are shown in Figure 4. It is apparent that the drying rate decreases continuously with decreasing moisture content or increasing drying time. It is also noted that the drying rate increased with the increase in drying air temperature. The drying rate was greater for radish slices dried at a higher temperature than for radish slices dried at a lower temperature for the same average moisture content of the radishes. Consequently, the drying time decreased at a higher drying air temperature condition. Similar characteristics for variation of drying rate with moisture content were reported by Xiao-Kang et al. (2012), Manuel Cuevas et al. (2019).

Sliced radishes did not exhibit a constant-rate drying period and all the drying operations are seen to occur in the falling rate period. This is due to the quick removal of moisture from the skin of radish slices and shows the diffusion dominant drying phenomena. At the beginning of the drying process, the drying rate was very high, but decreased as the moisture content approached an equilibrium. Similar results have been presented for many agricultural products (Kaya et al. 2007, Correia et al. 2015).

The moisture content data from the drying experiment were converted into the moisture ratio M^* and then fitted to the selected thin-layer drying models in Table 2. The statistical results of the different models, including the comparison criteria used to evaluate goodness of the fit, viz., the values of the coefficient of determination (R^2) and root mean square error ($RMSE$) are presented in Table 3. Based on the criteria of the highest R^2 and the lowest $RMSE$, the best model describing the thin-layer drying characteristics of radish slices was selected. For all the experiments, the R^2 and $RMSE$ values for the models changed between 0.965 and 0.9995, 0.007 and 0.06, respectively. From Table 3, the highest R^2 values and the lowest value of $RMSE$ values were obtained from the Hii et al. model. The R^2 and $RMSE$ values of Hii et al. model vary between 0.999 and 0.9995, 0.0071 and 0.01, respectively. According to these results, the Hii et al. model was selected as the appropriate model to represent the drying behavior of radish slices in thin layers.

Table 3 Selected thin-layer drying models for describing radish drying data.

Model	T ($°C$)	Coefficients					Statistics	
							R^2	$RMSE$
Lewis		k						
	40	0.006317					0.9773	0.04623
	50	0.008034					0.965	0.0593
	60	0.01061					0.9667	0.05892
Page		k	n					
	40	0.001303	1.302				0.998	0.01378
	50	0.001165	1.389				0.9955	0.02148
	60	0.001565	1.407				0.9977	0.01593
Single term		a	k					
	40	1.09	0.006865				0.9858	0.03698
	50	1.097	0.008786				0.9754	0.05047
	60	1.098	0.01159				0.9769	0.05001
Logarithmic		a	k	c				
	40	1.191	0.004916	-0.1517			0.9986	0.01162
	50	1.308	0.005271	-0.2748			0.9978	0.0154
	60	1.247	0.007692	-0.2031			0.9956	0.02236
Two term		a	k_1	b	k_2			
	40	19.89	0.01117	-18.88	0.011594		0.9975	0.01592
	50	1.137	0.0091	-0.1368	2.138		0.9795	0.04761
	60	-0.1542	2.186	1.154	0.01216		0.9825	0.04544
Wang and Singh		a	b					
	40	-0.004597	$5.36\ e^{-06}$				0.999	0.00961
	50	-0.005787	$8.225\ e^{-06}$				0.9994	0.00818
	60	-0.00769	$1.477\ e^{-05}$				0.9984	0.01298
Verma		a	k	g				
	40	1.118	0.007036	10.89			0.9883	0.03394
	50	1.137	0.0091	3.185			0.9795	0.04681
	60	1.154	0.01216	3.129			0.9825	0.04448
Midilli		a	k	b				
	40	1.044	0.005553	-0.0002461			0.9982	0.01344
	50	1.036	0.006348	-0.0005392			0.9972	0.01738
	60	1.048	0.008947	-0.0005391			0.9942	0.02458
Diffusion Approach		a	k	b				
	40	209.8	0.00276	0.9958			0.9978	0.01457
	50	225.5	0.00283	0.9947			0.9973	0.01709
	60	21.6	0.02004	1.041			0.9964	0.02022
Hii et al.		a	k_1	b	k_2	n		
	40	0.7894	0.00012	0.1997	0.0013	1.709	0.9995	0.00709
	50	0.7703	$4.102\ e^{-05}$	0.2133	0.0008	1.994	0.9995	0.0077
	60	0.9406	0.00072	0.059	11.37	1.556	0.999	0.01085

Figure 5 compare the experimental and the predicted moisture ratios with the Hii et al. model versus the drying time for dried radish slices at 40, 50 and 60 °C. It is observed that, the proposed model provided conformity between the experimental and predicted moisture ratios. Accordingly, this indicates the suitability of Hii et al. model in describing drying behavior of radish slices. The Hii et al. model has also been suggested by others to describe hot-air drying of Pumpkin (Onwude et al. 2016), Native Cassava Starch (Aviara and Igbeka 2016), Apple snails (Du Luo et al. 2015).

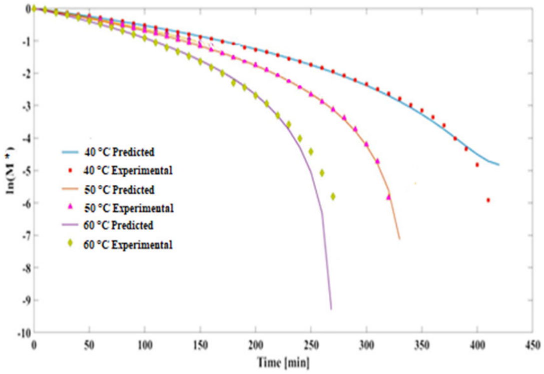

Fig. 5 Experimental and predicted moisture ratios (Hii et al. model) versus drying time

The values of effective diffusivity (D_{eff}) at different drying temperatures obtained by using Eq. (7) and the estimated values are presented in Table 4. The average value of effective diffusivities of radish slices in the drying process at 40, 50 and 60 °C varied in the range of $3.3 - 5.55 \times 10^{-8}\ m^2/min$. The values of D_{eff} increased progressively as the drying air temperature increased. It is due to fact that increase in the drying air temperature increases the activity of water particles in the sample slices. As a result, moisture gradient inside the product increases and thus D_{eff} increases. Similar findings were reported by Sacilik and Elicin (2006), Akpinar and Toraman (2013).

Also, the variation of moisture effective diffusivity (D_{eff}) with temperature is illustrated in Figure 6.

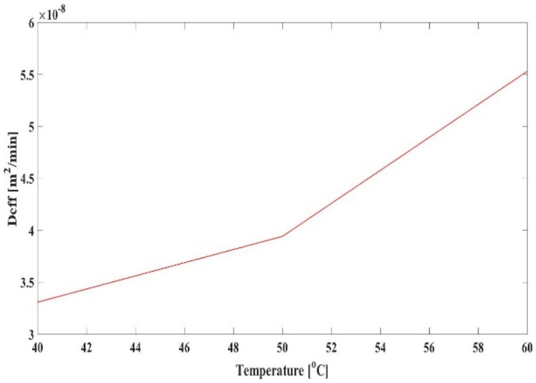

Fig. 6 Effect of air temperature on D_{eff}

The variation of the moisture effective diffusivity (D_{eff}) with moisture ratio is shown in Figure 7. It can be seen that D_{eff} increases with decrease in moisture ratio and further it can be seen that D_{eff} increases with increase in drying air temperature.

Table 4 Effective moisture diffusivity values attained at various air temperatures

T (°C)	$D_{eff}\ (m^2/min)$
40	3.3085×10^{-8}
50	3.9418×10^{-8}
60	5.5301×10^{-8}

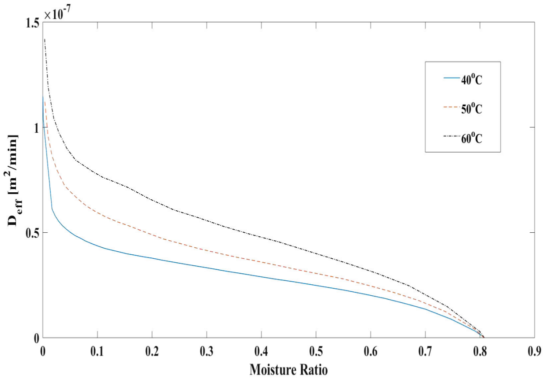

Fig. 7 Variation of effective moisture diffusivity versus moisture ratio at different drying temperatures

The temperature dependence of D_{eff} can be described by Arrhenius-type of relationship as given in Eq. (8). The activation energy E_a was calculated from the slope of the plot on $\ln(D_{eff})$ vs $1/T$ in Figure 8. It was found to be $18.49\ kJ/mol$. The value obtained in this study is in close range of $15 - 40\ kJ/mol$ with various foods reported by Rizvi (1995). The E_a of radish slices is close to that of lettuce and cauliflower leaves, mushrooms, red chillies, apple slices and Uryani plums (Lopez et al. 2000, Arora et al. 2003, Kaleemullah and Kailappan 2006, Kaya et al. 2007, Sacilik et al. 2006).

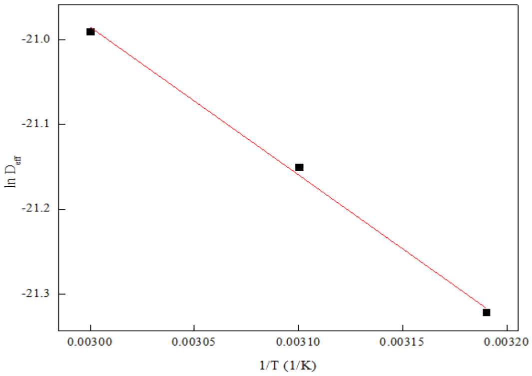

Fig. 8 Temperature dependence of D_{eff} by Arrhenius relation

5. CONCLUSIONS

The drying kinetics of the radish slices were investigated in an induced draft convective tray dryer at the drying air temperatures of 40, 50 and 60 °C. Constant drying rate period was not observed, the entire radish drying occurring in the falling rate period. The moisture content and drying rate were influenced significantly by the drying air temperature. Increase in the drying air temperature caused a decrease in the drying time and an increase in the drying rate. The effective diffusivity increased with the increase in the drying air temperature. Based on the non-linear regression analysis, the Hii et al. model was considered adequate to describe the thin-layer behavior of radish slices. The values of calculated effective moisture diffusivity varied from $3.3 – 5.55 \times 10^{-8}\ m^2/min$ over the temperature range. The effective diffusivity increases as temperature increases. Temperature dependence of the diffusivity values was described by an Arrhenius-type relationship. The activation energy for moisture diffusion was found to be $18.49\ kJ/mol$.

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NOMENCLATURE

D_{eff}	effective moisture diffusivity (m^2/min)
D_o	pre-exponential factor of Arrhenius equation (kJ/mol)
E_a	activation energy (kJ/mol)
exp,i	i^{th} experimental moisture ratio value
M_τ	moisture content at any time (kg w/kg ds)
M_e	equilibrium moisture content (kg w/kg ds)
M_o	initial moisture content (kg w/ kg ds)
M^*	fractional moisture ratio
N	number of observations
pre,i	i^{th} predicted moisture ratio value
R^2	coefficient of determination
$RMSE$	root mean square error
R	universal gas constant (8.314 J/mol K)
T	temperature (°C)

Greek Symbols

τ	drying time (min)

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