Mathematical modelling of thin layer hot air drying of carrot pomace

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Abstract Thin layer carrot pomace drying characteristics were evaluated in a laboratory scale hot air forced convective dryer. The drying experiments were carried out at 60, 65, 70 & 75 °C and at an air velocity of 0.7 m/s. Mathematical models were tested to fit drying data of carrot pomace. The whole drying process of carrot pomace took place in a falling rate period except a very short accelerating period at the beginning. The average values of effective diffusivity ranged from 2.74×10^{-9} to 4.64×10^{-9} m²/s for drying carrot pomace. The activation energy value was 23.05 kJ/mol for the whole falling rate period.

Keywords Carrot pomace · Hot air drying · Modelling · Drying rate · Effective diffusivity · Activation energy

Introduction

Carrot is a rich source of β -carotene and contains other vitamins, like thiamine, riboflavin, vitamin B-complex and minerals (Walde et al. 1992). Carrot is also an excellent source of calcium pectate; an extraordinary pectin fibre that has the cholesterol lowering properties. It has a property to reduce the risk of high blood pressure, stroke, heart disease and some type of cancer (Bakhru 1993). The edible part of carrot, which is eaten as raw, converted to juice drink, used as salads, cooked as vegetable dish, used to make sweet dishes. Carrot juice has particularly high content of pro-

vitamin A (β carotene) and is also high in B complex vitamins and many minerals including calcium, copper, magnesium, potassium, phosphorus, iron and folic acid. Carrot pomace is a by-product obtained during carrot juice processing. The juice yield in carrots is only 60–70%, and even up to 80% of carotene may be lost with left over carrot pomace (Bohm et al. 1999). The carrot pomace has good residual amount of all the vitamins, minerals and dietary fibre. So far, the left over pomace after juice extraction from carrots does not find proper utilization. The pomace is perishable as it contains about $830 \pm 1\%$ (dry basis) moisture. Drying or dehydration is the useful means to increase the shelf life of perishable food for further use (Roberts et al. 2008). Dried pomace has β carotene and ascorbic acid in the range of 9.87 to 11.57 mg and 13.53 to 22.95 mg per 100 g respectively (Upadhyay et al. 2008). The dried carrot pomace can be used to develop extrudates, flavoured breads, cakes.

Drying of materials having high moisture content is a complicated process involving simultaneous heat and mass transfer (Yilbas et al. 2003). The materials are dried by thin layer drying due to faster drying with minimum loss of nutrients. Thin-layer drying describes the process of drying in a single layer of sample particles. Three types of thin-layer drying models are used to describe the drying phenomenon of farm product. The theoretical model considers only the internal resistance to moisture transfer between product and heating air whereas semi-theoretical and empirical models consider only the external resistance (Midilli et al. 2002, Panchariya et al. 2002). Theoretical model needs assumptions of geometry of a typical food, its mass diffusivity and conductivity (Demirtas et al. 1998, Ece and Cihan 1993); empirical model neglects the fundamentals of drying process and presents a direct relationship between average moisture and drying time by means of

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regression analysis (Ozdemir and Devres 1999, Wang and Singh 1978), and semi-theoretical model is a trade off between the theoretical and empirical ones, derived from simplification of Fick's second law of diffusion or modification of the simplified model, which are widely used, such as the Lewis, Page, Modified Page, Henderson and Pabis, Logarithmic, Two term, Approximation of diffusion, Verma and Midilli-Kucuk models.

Hot air oven drying of carrot pomace was reported by Upadhyay et al. (2008) in a hot air oven tray dryer without the consideration of air velocity. However, no published detailed information is available on hot air force convection drying of thin layer carrot pomace.

The present investigation was focused on the thin-layer drying characteristics of carrot pomace in a forced convective dryer and modelling the air drying process of carrot pomace over a temperature range of 60 to 75 °C with air velocity of 0.7 ± 0.1 m/s. In addition, the effective diffusivities and activation energy in the convective drying process of carrot pomace were also calculated.

Materials and methods

Experimental apparatus

An electric forced convection dryer (Raste Enterprises, Sangli, Maharashtra, India) was modified for drying carrot pomace, which could regulate to desired drying air temperature between 20 and 100 °C with ± 1 °C accuracy. The dryer consisted of a preheating and heating chamber with thermostat based control unit, an electrical centrifugal fan, measurement sensors, an air-duct and a plenum chamber. The pre-heating control unit included an electric heater (2 kW) placed inside a duct where as the main heating control unit included four heaters of 1 kilowatt each. The drying chamber was constructed from sheet iron with the cavity dimension of $0.42 \times 0.32 \times 0.40$ m. The perforated area and side wall height of the tray were 0.113 m^2 and 0.10 m to accommodate the sample. The product was spread in a thin layer on a steel perforated tray having opening size 0.001×0.001 m. The drying air temperature in the chamber was measured directly using thermocouple based temperature indicator (Digital Multi-thermometer, Taiwan, Precision 1 °C). The air passed from the heater at the desired temperature, entered into the chamber and mixed there and then passed through the layer of the sample. The air velocity was kept at a constant value of 0.7 m/s just above the tray surface and measured using a hot wire digital anemometer (Lutron Anemometer, Taiwan, Precision 0.1 m/s). A digital balance with measurement precision of ± 0.1 g was used for the measurement of weight loss of the sample.

Experimental material

Commercial variety of carrot (Variety: Pusa Kesar) was procured from local market, Longowal, District: Sangrur (Punjab). The samples were washed in running tap water to remove impurities. Trashes were removed with a plane stainless steel knife and then trimmed with the same knife. The juice was extracted using a Juice Mixer Grinder cum Food Processor (Make: Maharaja Whiteline, Asiatic Engineers Pvt. Ltd., 600 W) as per the process developed by Goyal (2004). The pomace was collected and initial moisture content was measured by drying fresh pomace in hot air oven at 100 °C (Ranganna 2003).

Experimental procedure

Drying experiments were performed at 60, 65, 70 and 75 °C in the forced convection dryer. The thickness of the sample was about 0.01 m with a load of $7.2 \pm 0.1 \text{ kg/m}^2$. The weight of the sample was 205 ± 1 g per trial. The weight of tray with the sample was measured with a digital balance and recorded at 5 min interval for all temperature range selected for the study. For measuring the weight of the sample during experimentation, the tray with sample was taken out of the drying chamber, weighed on the digital top pan balance and placed back into the chamber. The digital top pan balance was kept very close to the drying unit (within 1 m). Each process of weight measurement lasted about 8.25 ± 0.25 s. The drying procedure was continued till the moisture content of the sample was reduced to about 4–8% (dry basis), when the moisture content would not change any more.

The weight of the sample was converted to moisture content on dry basis using the standard formula: $M_c = (W - W_d)/W_d$, where W is the weight of sample and W_d is the weight of dry material in the sample.

Modelling of the thin-layer drying curves

Development of model is necessary to investigate the drying characteristics of carrot pomace. In this study, the experimental drying data of carrot pomace at different temperatures were fitted into 12 commonly used thin-layer drying models, listed in Table 1. In these models, MR represents the dimensionless moisture ratio, namely, $MR = (M - M_e)/(M_0 - M_e)$, where M is the moisture content of the product at each moment, M_0 is the initial moisture content of the product and M_e is the equilibrium moisture content. The equilibrium moisture content of carrot pomace was calculated at different temperatures (Henderson and Perry, 1976).

The goodness of fit of the selected mathematical models to the experimental data was evaluated with the correlation coefficient (R^2), the reduced chi-square (χ^2) and the root

Table 1 List of models with references

S. No.	Model name	Model	References
1	Lewis	$MR = \exp(-kt)$	Bruce (1985)
2	Page	$MR = \exp(-kt^n)$	Page (1949)
3	Henderson & Pabis	$MR = a \exp(-kt)$	Henderson and Pabis (1961)
4	Logarithmic	$MR = a \exp(-kt) + c$	Togrul and Pehlivan (2002)
5	Two Term	$MR = a \exp(-k_0t) + b \exp(-k_1t)$	Henderson (1974)
6	Wang & Singh	$MR = 1 + at + bt^2$	Wang and Singh (1978)
7	Simplified Fick's	$MR = a \exp(-c(t/L^2))$	Diamante and Munro (1991)
8	Approximation of diffusion	$MR = a \exp(-kt) + (1-a) \exp(-k_1t)$	Yaldiz et al. (2001)
9	Modified Page -II	$MR = \exp(-c(t/L^2)^n)$	Diamante and Munro (1991)
10	Verma	$MR = a \exp(-kt) + (1-a) \exp(-gt)$	Verma et al. (1985)
11	Midilli–Kucuk	$MR = a \exp(-kt^n) + bt$	Midilli et al. (2002)
12	Hii, Law & Cloke	$MR = a \exp(-kt^n) + c \exp(-gt^n)$	Hii et al. (2009)

mean square error (RMSE). The goodness of fit will be better, if R^2 values are higher and χ^2 and RMSE values are lower (Wang et al. 2006, Ertekin and Yaldiz 2004, Ozdemir and Devres 1999). The reduced chi-square (χ^2) and the root mean square error (RMSE) were calculated using following expressions:

$$\chi^2 = \frac{\sum_{i=1}^N (MR_{Exp,i} - MR_{Pre,i})^2}{(N - Z)} \quad (1)$$

$$RMSE = \sqrt{\frac{1}{N} \sum_{i=1}^N (MR_{Pre,i} - MR_{Exp,i})^2} \quad (2)$$

Where $MR_{Exp,i}$ is the i^{th} experimental moisture ratio, $MR_{Pre,i}$ is the i^{th} predicted moisture ratio, N is the number of observations and z is the number of constants. In this study, the nonlinear regression analysis was performed with statistical software, OriginPro 8.0 (Origin Lab, Massachusetts) and ANOVA was analysed with Microsoft Excel 2007.

Calculation of effective diffusivities

The falling rate period can be described by using Fick's diffusion equation for the characteristics of biological products (Wang et al. 2006). The solution to this equation developed by Crank (1975) can be used for various regularly shaped bodies such as rectangular, cylindrical and spherical products, and the form of Eq. 3 can be applicable for particles with slab geometry by assuming uniform initial moisture distribution:

$$MR_i = \frac{8}{\pi^2} \sum_{n=0}^{\infty} \frac{1}{(2n+1)^2} \exp\left(-\frac{(2n+1)^2 \pi^2 D_{eff} t}{4L_0^2}\right) \quad (3)$$

Where D_{eff} is the effective diffusivity (m^2/s); L_0 is the half thickness of slab (m). For longer drying period, Eq. 3 can be further simplified to only the first term of series (Tutuncu & Labuza, 1996) and can be written in a logarithmic form as follows:

$$\ln MR = \ln \frac{8}{\pi^2} - \frac{\pi^2 D_{eff} t}{4L_0^2} \quad (4)$$

Diffusivities were determined by plotting experimental drying data in terms of $\ln MR$ versus drying time t in Eq. 4. The slope and effective diffusivity from the above equation was calculated as:

$$Slope = \frac{\pi^2 D_{eff}}{4L_0^2} \quad (5)$$

$$D_{eff} = \left(\frac{4L_0^2}{\pi^2}\right) Slope \quad (6)$$

Where $Slope = (\ln MR_2 - \ln MR_1)/(t_2 - t_1)$

Calculation of activation energy

The temperature dependence of the effective diffusivity may be described by an Arrhenius-type relationship (Wang et al. 2006, Akgun and Doymaz 2005, Madamba et al. 1996, Ozdemir and Devres 1999, Sanjuan et al. 2003) as follows:

$$D_{eff} = D_0 \exp\left(-\frac{E_a}{RT}\right) \quad (7)$$

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 (kJ/mol K), and T is the absolute temperature (K).

$$Slope = \frac{E_a}{R} \quad (8)$$

From the slope of the straight line of $\ln D_{\text{eff}}$ versus reciprocal of T , described by the Arrhenius equation, the activation energy, E_a , could be calculated.

Results and discussion

Drying characteristics

The carrot pomace was dried at 60, 65, 70 and 75 °C in the forced convection dryer in thin layer with thickness of about 10 mm. The initial moisture content of carrot pomace was about $830 \pm 1\%$ (db), and the final moisture content was 7.68, 6.64, 5.68 and 4.07% (db) at 60, 65, 70 and 75 °C respectively.

The moisture content versus drying time for carrot pomace at the selected temperatures is shown in Fig. 1. The drying times to reach the equilibrium moisture content for the fresh carrot pomace sample were 250, 225, 210 and 200 min at 60, 65, 70 and 75 °C, respectively. Obviously, within a certain temperature range (60–75 °C), increasing drying temperature speeds up the drying process, thus shortens the drying time. Similar findings have been reported for fruit and vegetable products drying (Vergara et al. 1997, Fenton and Kennedy 1998, Ramaswamy and Nieuwenhuijzen 2002, Wang and Chao 2002, Wang et al. 2006).

In each equal increased temperature interval of 5 °C from 60 to 75 °C, the drying time decreased by 10%, 6.67%, and 4.76% correspondingly. The increased temperature interval of 5 °C from 60 to 65 °C has greater effect on the decreasing drying time.

The moisture ratio decreases continuously as the drying progress (Fig. 2). It took 55, 45, 42 and 40 min to remove the first half moisture at 60, 65, 70 and 75 °C respectively, which is about one fourth of the total drying time. Therefore, three fourth of total drying time was required to remove the residual moisture due to slower diffusion.

Fig. 1 Thin layer drying curves of carrot pomace at selected temperatures

Fig. 2 Moisture ratio versus drying duration of carrot pomace at different temperatures

The maximum drying rates for drying carrot pomace were 0.0941, 0.1125, 0.1157 and 0.1172 g water/g dry matter/min at temperatures of 60, 65, 70 and 75 °C respectively, whereas minimum drying rate was observed as low as 0.0009 g water/g dry matter/min. The average drying rates were 0.0305, 0.0343, 0.0366 and 0.0384 g water/g dry matter/min at temperatures of 60, 65, 70 and 75 °C respectively, indicating that the maximum drying time is about three times more than the average drying rate. It was also observed that the drying rates were higher at elevated drying temperatures. The average drying rate increased by 12.64%, 6.79% and 4.85% at each equal temperature interval of 5 °C from 60 to 75 °C. These observations are in agreement with previous results on thin-layer drying of biological products (Diamante and Munro 1991, Doymaz and Pala 2003, Wang et al. 2006).

It can be observed from Fig. 3 that constant rate period was not present during drying of carrot pomace samples. The

Fig. 3 Drying rate versus drying duration of carrot pomace at different temperatures

Table 2 Statistical results obtained from different thin layer drying models

S. No.	Model Name	Temperature °C	Constants					R ²	χ^2	RMSE
			1st	2nd	3rd	4th	5th			
1	Lewis Model	60	k = 0.01524					0.97019	0.00291	0.0533964
2		65	k = 0.01741					0.98706	1.15E-03	0.0335151
3		70	k = 0.0193					0.97875	0.00199	0.0440507
4		75	k = 0.02033					0.97916	0.00196	0.0437147
5	Page Model	60	k = 0.00228	n = 1.43464				0.99977	2.27E-05	0.0046653
6		65	k = 0.00614	n = 1.24498				0.9997	2.66E-05	0.0050433
7		70	k = 0.00464	n = 1.34319				0.99932	6.38E-05	0.0078058
8		75	k = 0.00492	n = 1.34659				0.99984	1.52E-05	0.0037997
9	Henderson Pabis	60	k = 0.01695	a = 1.12531				0.9823	0.00173	0.0407287
10		65	k = 0.01874	a = 1.08242				0.99275	6.43E-04	0.024808
11		70	k = 0.02107	a = 1.10187				0.98688	0.00123	0.0342019
12		75	k = 0.02225	a = 1.10455				0.98773	1.15E-03	0.0331258
13	Logarithmic	60	a = 1.15937	k = 0.01426	c = -0.06612			0.99008	9.679E-04	0.0301825
14		65	a = 1.10536	k = 0.01634	c = -0.04858			0.99741	2.302E-04	0.0146703
15		70	a = 1.12996	k = 0.01807	c = -0.05621			0.99355	6.036E-04	0.0236938
16		75	a = 1.13069	k = 0.01926	c = -0.05252			0.99365	5.965E-04	0.0235144
17	Two Term	60	a = -17.2447	b = 18.33097	k ₀ = 0.00929	k ₁ = -0.0096		0.99204	7.765E-04	0.0267523
18		65	a = -16.0184	b = 17.06799	k ₀ = 0.01103	k ₁ = -0.01136		0.99831	1.503E-04	0.0117121
19		70	a = -10.40858	b = 11.4747	k ₀ = 0.01175	k ₁ = -0.01235		0.99533	4.369E-04	0.0199068
20		75	a = -15.57962	b = 16.65025	k ₀ = 0.01274	k ₁ = -0.01316		0.99533	4.389E-04	0.0199022
21	Wang & Singh	60	a = -0.01053	b = 2.71E-05				0.9917	8.10E-04	0.0278969
22		65	a = -0.0118	b = 3.41E-05				0.98797	0.00107	0.0319613
23		70	a = -0.01298	b = 4.08E-05				0.99047	8.91E-04	0.0291548
24		75	a = -0.01365	b = 4.52E-05				0.98864	0.00107	0.0318648
25	Simple Fick's	60	a = 1.12531	c = 0.42366				0.9823	0.00173	0.0407287
26		65	a = 1.08243	c = 0.46852				0.99275	6.43E-04	0.024808
27		70	a = 1.10187	c = 0.52673				0.98688	0.00123	0.0342019
28		75	a = 1.10455	c = 0.55613				0.98773	1.15E-03	0.0331258
29	Approx Diffusion	60	k = 0.02305	a = 1.9741				0.99846	1.50E-04	0.0119967
30		65	k = 0.02419	a = 1.80235				0.99938	5.47E-05	0.0072382
31		70	k = 0.02801	a = 1.89359				0.99826	1.63E-04	0.0124546
32		75	k = 0.02976	a = 1.90731				0.99915	8.02E-05	0.0087374
33	Modified Page II	60	c = 0.23123	n = 1.43464				0.99977	2.27E-05	0.0046653
34		65	c = 0.33756	n = 1.24498				0.9997	2.66E-05	0.0050433
35		70	c = 0.35001	n = 1.34319				0.99932	6.38E-05	0.0078058
36		75	c = 0.37521	n = 1.34659				0.99984	1.52E-05	0.0037997

Table 2 (continued)

S. No.	Model Name	Temperature °C	Constants					R ²	χ^2	RMSE
			1st	2nd	3rd	4th	5th			
37	Verma	60	a=-141.71508	k=0.03018	g=0.02999			0.9992	7.81E-05	0.0085749
38		65	a=-78.58823	k=0.03037	g=0.0301			0.9998	3.71E-05	0.0058792
39		70	a=-119.17054	k=0.03598	g=0.03574			0.9984	1.09E-04	0.0100464
40		75	a=-165.14426	k=0.03826	g=0.03807			0.9956	4.17E-05	0.0062274
41	Midilli-Kucuk	60	k=0.002	n=1.46112	a=0.98748	b=-3.42E-06		0.9986	1.40E-05	0.0035938
42		65	k=0.00689	n=1.2142	a=1.00268	b=-5.23E-05		0.9993	6.49E-06	0.002434
43		70	k=0.00467	n=1.33635	a=0.99256	b=-4.31E-05		0.9953	4.40E-05	0.0063246
44		75	k=0.00507	n=1.33633	a=0.99798	b=-3.02E-05		0.9993	7.58E-06	0.0026158
45	Hii, Law & Cloke	60	a=9.37161	k=0.00887	n=1.22862	c=-8.37812	g=0.00948	0.9992	8.23E-06	0.0027245
46		65	a=0.94985	k=0.00608	n=1.24664	c=0.04805	g=0.00603	0.9968	2.82E-05	0.005
47		70	a=11.33287	k=0.00439	n=1.2825	c=-10.33576	g=0.00427	0.9973	2.55E-05	0.0047441
48		75	a=6.65144	k=0.00473	n=1.2976	c=-5.65029	g=0.00454	0.9997	2.55E-06	0.0014959

drying process took place in a falling rate period except a very short accelerating period at the beginning. It can be seen that at higher moisture content, the increase in temperature has more considerable effect on the drying rates than at lower moisture content, which was almost negligible at the end. It was further observed that moisture loss was faster at the start of drying than at the end. The reduction in the drying is mainly due to reduction in moisture content as drying advances. The rate of migration of moisture from inner surface to outer surface decreases at the final stage of drying and hence lower drying rates (Rajkumar et al. 2007).

In practice, when the heating temperature is higher, then the loss of quality will occur in carrot pomace (Upadhyay et al. 2008). Therefore, with a view of optimization of energy efficiency and the product quality, the heating temperature zone between 60 and 65 °C is a better option for drying carrot pomace. Similar results have been reported by Upadhyay et al. (2008).

Fitting of mathematical models to the drying curves

The moisture content data observed at the drying experiment were converted into the moisture ratio (MR) and fitted to the 12 models listed in Table 1. The statistical results of the different models, including the drying model coefficients and the comparison criteria used to evaluate goodness of fit, namely, R^2 , χ^2 and RSME, are listed in Table 2. In all cases, R^2 values were higher than 0.97, and χ^2 and RMSE values were lower than 0.0029 and 0.0533, respectively.

The Page model performed better than the Lewis model. Similar results have been reported by Upadhyay et al. (2008). However, Hii, Law & Choke model fitted better than other models on the basis of R^2 , χ^2 and RSME. The residual of actual and predicted moisture ratio for the Hii, Law & Choke model varied from 0.000013 to 0.00989 with an average value of 0.002970. A variation of the selected

Fig. 4 Experimental vs Predicted values using the Hii et al. (2009) model for different air temperatures

Table 3 Calculated effective diffusivity at different drying temperatures

S. No.	Temperature	Absolute temperature	Effective diffusivity, m ² /s		
			First period	Second period	Overall period
1	60	333	2.74E-09	3.12E-09	2.98E-09
2	65	338	3.01E-09	3.75E-09	3.47E-09
3	70	343	3.41E-09	4.06E-09	3.82E-09
4	75	348	3.62E-09	4.64E-09	4.27E-09

model was established by comparing the experimental data with predicted values for each drying curve. The plotted responses in Fig. 4 demonstrates that the data points follows a straight line at 45° angle signifying the suitability of the model in describing the thin layer drying of the carrot pomace. Similar approach for selecting the model for thin layer drying of fresh figs was reported by Babalis et al. (2006).

The values of the selected model coefficients (a, k, n, c and g of Eq. 12) are reported in Table 2. The regression analysis was used to set up the relations between these parameters and the temperatures. Thus, the regression equations of these parameters against drying temperature, T (°C) for accepted model using third order polynomial equation are as follows:

$$a, k, n, c, g = f \quad (9)$$

$$a = 13905.60529 - 619.95731 T + 9.18210 T^2 - 0.04516 T^3, \quad R^2 = 1.00 \quad (10)$$

$$k = -0.21037 + 0.01238 T - 0.00022 T^2, \quad R^2 = 1.00 \quad (11)$$

$$n = 16.45430 - 0.69205 T + 0.01039 T^2 - 0.00005 T^3, \quad R^2 = 1.00 \quad (12)$$

$$c = -13908.27 + 620.14037 T - 9.18481 T^2 + 0.4517 T^3, \quad R^2 = 1.00 \quad (13)$$

$$g = 0.05894 + 0.00082 T - 0.00005 T^2, \quad R^2 = 1.00 \quad (14)$$

All the coefficients were dependent on drying air temperature. The coefficient 'a', 'c' varied in nearly sinusoidal shape with temperature, whereas 'k', 'n' and 'g' varied in nearly liner shape. The R² values for above equations were 1.00, thus the coefficients of selected model could be calculated using these equations to estimate moisture ratio of carrot pomace.

Determination of effective diffusivities

The results indicated that internal mass transfer resistance controlled the drying time due to which falling rate drying period dominated the drying process. The average values of effective diffusivities of carrot pomace in the drying process at 60–75 °C varied in the range of $2.74\text{--}4.64 \times 10^{-9}$ m²/s (Table 3). Two way ANOVA was used to analyze the variation of effective diffusivity with the temperature and falling rate periods. The F and p values for temperature were 47.4 and 0.0001 against F critical value of 4.757, showing that the variation with respect to temperature is significant. It may also be observed from Table 3 that effective diffusivity increased with the increase in temperature. The results are in agreement with the findings of Wang et al. (2007). The evaluated effective diffusivities were within the range of published values ranging from 10^{-11} to 10^{-9} for food materials (Wang et al. 2006, Madamba et al. 1996).

The F and p values for falling rate periods were 28.751 and 0.0008 against F critical value of 5.143, indicating that effective diffusivities were different in first, second and overall falling rate periods (Table 4). The average effective diffusivity for first, second and overall falling rate periods were 3.19×10^{-9} , 3.89×10^{-9} and 3.64×10^{-9} respectively. The average effective diffusivity was higher in second falling rate period than first falling rate period. Similar results have been reported by Wang et al. (2007).

Table 4 Two way ANOVA on effective diffusivity without replication

Source of Variation	SS	df	MS	F	P-value	F crit
Temperatures	2.47E-18	3	8.22E-19	47.4077	0.000143	4.757063
Falling rate periods	9.97E-19	2	4.99E-19	28.75146	0.000843	5.143253
Error	1.04E-19	6	1.73E-20			
Total	3.57E-18	11

Fig. 5 The Arrhenius type relationship between effective diffusivity and drying temperature

Determination of activation energy

The natural logarithm of D_{eff} as a function of the reciprocal of absolute temperature was plotted (Fig. 5) and showed a linear relationship of Arrhenius-type. The activation energy was then obtained from the slope of line. The calculated values of activation energy were 17.96, 25.36 and 23.05 KJ/mol for first, second and overall falling rate periods. Similar activation energy for apple pomace 24.512 KJ/mol for overall falling rate period was reported by Wang et al. (2006).

The value of activation energy in second falling rate was higher than that of first falling rate period, which may be due to removal of free water on first falling rate and requirement of more heat to evaporate bound water in second period.

Conclusions

Thin layer drying of carrot pomace at 60, 65, 70 & 75 °C and at an air velocity of 0.7 m/s followed falling rate period except a very short accelerating period at the beginning. Out of the mathematical models tested, the Hii et al. (2009) model was the best fit model. The drying time of carrot pomace decreased with the increase of temperature where as the effective diffusivity increased as the drying temperature increased. The average values of effective diffusivity ranged from 2.74×10^{-9} to 4.64×10^{-9} m²/s. The activation energy value was 23.05 kJ/mol for the whole falling rate period.

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