

Modelling the Carrot Thin-Layer Drying in a Semi-Industrial Continuous Band Dryer

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Abstract

AGHBASHLO M., KIANMEHR M.H., ARABHOSSEINI A., NAZGHELICHI T. (2011): **Modelling the carrot thin-layer drying in a semi-industrial continuous band dryer**. Czech J. Food Sci., **29**: 528–538.

This paper presents a mathematical modelling of the drying process in a semi-industrial continuous band dryer. Carrot slices with the thickness of 5 mm were used for the drying experiments. The experiments were conducted at three air temperatures, 50, 60, and 70°C, three air velocities, 0.5, 1.0, and 1.5 m/s, and three chain linear velocities, 2.38×10^{-4} , 2.78×10^{-4} , and 3.33×10^{-4} m/s with three replications for each treatment. The Lewis, Henderson & Pabis, and Page models were fitted to the experimental data of the moisture ratio against the sample position using non-linear regression analysis by MATLAB computer program. The models were compared based on their coefficients of determination (R^2), root mean square errors (RMSE), and reduced chi-squares (χ^2) between the experimental and predicted moisture ratios. Consequently, the Page model was selected as the best mathematical model for describing the drying kinetics of the carrot slices. The correlations of the Page model constants k and m with the variables T , U_a and U_c were determined. The effective moisture diffusivity varied from 3.21×10^{-7} to 8.98×10^{-7} m²/s. The energy of activation varied from 23.02 kJ/mol to 28.1 kJ/mol using Arrhenius type equation.

Keywords: carrot; thin-layer drying; mathematical modelling; semi-industrial-continuous band dryer; effective moisture diffusivity

Carrot is one of the most common vegetables used for human nutrition due to high vitamin and fiber contents (DOYMAZ 2004). Carrot is an excellent source of beta carotenes reported to prevent cancer, vitamin A, and potassium, and it contains cholesterol-lowering pectin, vitamin C, vitamin B₆, thiamine, folic acid, and magnesium. Dried carrots are used in dehydrated soups and in the form of powder in pastries and sauces (ERENTURK & ERENTURK 2007). The main objective of drying agricultural products is the reduction of the moisture content to a level which allows safe storage over an extended the period. It also brings about substantial reduction in weight and volume,

minimises packaging, storage and transportation costs (DOYMAZ 2007). Conventional air-drying is the most frequently used dehydration operation in food industry (GORNICKI & KALETA 2007). A critically important aspect of the drying technology is mathematical modelling of the drying processes (DEMIR *et al.* 2007). Thus, the definition of accurate mathematical models is necessary to simulate the drying kinetics of biological materials. Simulation models of the drying process are used for designing new drying systems, improving the existing systems, predicting the air flow over the product, and even for controlling the process (XIA & SUN 2002; BABALIS *et al.* 2006). Recently,

Supported by the University of Tehran, Iran.

many literature data have been published by several researches covering mathematical modelling of food products drying using laboratory dryers (OZDEMIR & DEVRES 1999; DOYMAZ 2004; ERTEKIN & YALDIZ 2004; SACILIK & UNAL 2005; MENGES & ERTEKIN 2006; CELMA *et al.* 2007; KASHANINEJAD *et al.* 2007; JOKIĆ *et al.* 2009; GAZOR & MOHSENI-MANESH 2010), but little information is available on mathematical modelling food products of drying in industrial or semi-industrial dryers. Biological materials are heterogeneous and indicate different exclusive characteristics under the processing activities even under the same operation conditions. Thus, the behaviour of biological material in laboratory conditions will be different from that in the industrial equipment, and designing new industrial equipment based on laboratory data will impose many deviations. Due to this, mathematical modelling of industrial equipment is very useful for engineers.

Recently, AGHBASHLO *et al.* (2009) presented mathematical modelling of thin-layer drying of potato slices in a continuous band dryer, but investigation into other food products is required. Despite many advantages of the tray drying method for removing moisture from foods (e.g. fruits and vegetables), continuous dryers ensure hygienic and homogeneous drying conditions due to the uniformity of the drying air flow and provide a better and more consistent product quality than trays (AGHBASHLO *et al.* 2009).

The main goals of present study were: the evaluation of the effects of the drying variables on the drying kinetics during drying of carrot slices over the length of the continuous dryer; the evaluation of the Lewis, Henderson & Pabis, Simplified Fick's diffusion, and Page drying models, for describing the drying kinetics of carrot slices over the length of continuous band dryer; the development of single mathematical model of carrot drying as a function of the sample position, air temperature, air velocity, and chain linear velocity; the calculation of the effective moisture diffusivity and energy of activation; and finally the evaluation of the effects of the drying variables on effective diffusivity.

MATERIAL AND METHODS

Sample. Carrots (*Daucus carota* L.) were purchased from the local market (Tehran, Iran) and stored for the experiments in a refrigerator at

about 5°C. The initial moisture contents of the carrot samples were determined by the oven drying method. About 50 g of the sample was dried in an oven at $105 \pm 2^\circ\text{C}$ for about 24 hours. The experiments were replicated three times.

Equilibrium moisture content. The equilibrium moisture content of the carrot slices was determined using a dynamic method at different temperatures and air velocities used in the drying experiments (KASHANINEJAD *et al.* 2007). 200 g of sliced carrots were placed into the dryer in a thin layer and exposed to the air temperatures of 50, 60, and 70°C and air velocities of 0.5, 1, and 1.5 m/s until the mass loss of the sample ceased.

Drying equipment. A semi-industrial continuous band dryer was used in this study. It was developed at the Department of Agrotechnology Laboratory of Abouraihan Campus, University of Tehran, Iran (Figure 1). The dryer consisted of an adjustable centrifugal blower, hot air suction tube, heater, gas flow rate controller, gas contour, control panel, air channel for uniform distribution of hot air, drying chamber, perforated bands (20 cm × 50 cm), sprockets, chain, two inverters (Lenze 8300, Aerzen, Postfach, Germany), temperature and humidity sensors, electrical motor, removable upper part, base, shafts, and chain guide. The dryer was of 2 m in useful length. The hot-air orientation on the samples was vertical and the outlet air was exhausted from the top part of the dryer. The dryer included an automatic temperature controller with accuracy of $\pm 1^\circ\text{C}$. The air velocity was measured using a PROVA AVM-07 (TES, Taipei, Taiwan) anemometer with accuracy of ± 0.05 m/s. The air velocity was fixed using an inverter cooperating directly with the blower motor. The chain linear velocity was fixed by an inverter, a gearbox, and a large scale gear. The inverter directly adjusted the rotations of the electric motor, the gearbox decreased the outlet rotational speed of the electric motor to an optional speed, and the large scale gear decreased the rotational speed of the sprocket in the ratio of 4 to 1.

The temperature sensors (PT100 type) were located at different positions of the dryer (dryer frame, air channel and beneath of the band). The air temperature was controlled by a sensor which was located beneath of the upper bands. During the experiments, the temperature and relative humidity of the ambient, inlet, and outlet air were recorded.

Experimental procedure and sampling method. Prior to the drying experiments, the carrots were

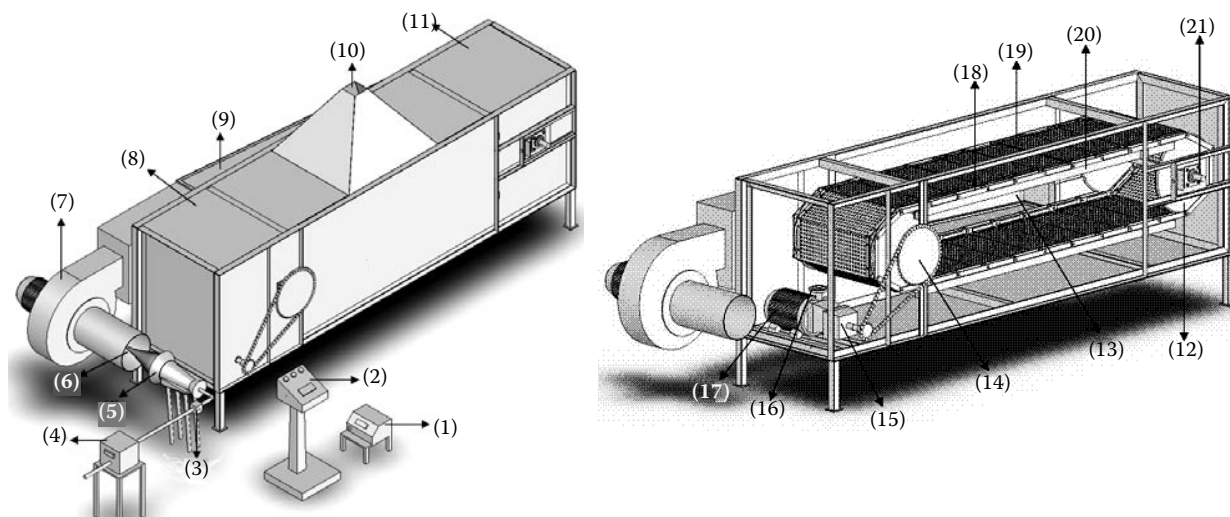


Figure 1. Schematic of dryer: (1) inverter; (2) control panel; (3) gas flow rate controller; (4) gas controller (for large range) and contour; (5) heater; (6) hot air suction tube and intake of hot air by fan; (7) fan; (8) removable inlet part; (9) air channel; (10) outlet air and location of temperature and humidity sensors, (11) removable outlet part, (12) sprocket; (13) location of major temperature sensor (beneath of upper bands); (14) large scale gear; (15) gearbox; (16) manual rotation speed controller (for large range); (17) electrical motor; (18) chain; (19) perforated bands; (20) chain guide, (21) shaft and bearing

washed and cut into slices with the thickness of 5 mm. The dryer was put in operation about 1 h before each experiment in order to achieve desirable steady state conditions. Then, each band of the dryer was manually filled in the same manner with 250 g of sliced carrot in a thin layer at the inlet part of the dryer. The interval time for the bands filling depended on the chain linear velocity. Fresh samples were weighed using a balance with accuracy of 0.01 g (KERN & Sohn, Balingen, Germany). Consequently, the length of the dryer was filled with sliced carrot at the calculated time. When the first band reached the end of the dryer, the removable outlet part of the dryer was removed and 40 g of the sample were taken from each band and put in an oven at a temperature of $105 \pm 2^\circ\text{C}$ for 24 h to determine the moisture content of the samples. The experiments were performed at air temperatures of 50, 60, and 70°C , air velocities of 0.5, 1, and 1.5 m/s, and chain linear velocities of 2.38×10^{-4} , 2.78×10^{-4} , and 3.33×10^{-4} m/s.

Statistical analysis. Statistical evaluation of the results was performed using a $3 \times 3 \times 3$ split (on time) factorial design (three temperatures, three velocities, and three chain linear velocities) with three replications for each treatment. Analysis of variance was carried out to find the effects ($P < 0.05$) of air temperature, air velocity, and chain linear velocity on the moisture ratio, effective moisture diffusivity, and selected model constants.

Multiple comparison tests were performed using LSD test at 95% confidence level. All the analysis were carried out using MATLAB (Math Works, Natick, USA) computer program.

Theoretical consideration

Drying curve. The moisture content of the samples was found during the drying process at different lengths of the dryer chain using Eq. 1:

$$M_x = \frac{W_x - W_d}{W_d} \quad (1)$$

The moisture ratio of the carrot slices was determined using Eq. 2:

$$MR = \frac{M_x - M_e}{M_0 - M_e} \quad (2)$$

The calculated moisture ratio (Eq. 3–6) was fitted to four commonly used thin-layer drying models shown in Table 1 by using non-linear least squares regression solved by the Levenberg-Marguardt numerical method.

Three criteria were used to select the best model for describing the drying kinetics of carrot over the length of the continuous dryer, coefficient of determination (R^2), reduced chi-square (χ^2), and root mean square error (RMSE).

Table 1. Thin-layer drying models

Model	Equation	Reference
Lewis	$MR = \exp(-kx)$ (3)	AKPINAR <i>et al.</i> (2003); KASHANINEJAD <i>et al.</i> (2007)
Henderson & Pabis	$MR = a \exp(-kx)$ (4)	DOYMAZ (2004)
Simplified fick's diffusion	$MR = a \exp(-kx/L^2)$ (5)	DIAMANTE & MUNRO (1993)
Page	$MR = \exp(-kx^m)$ (6)	BABALIS <i>et al.</i> (2006); KASHANINEJAD <i>et al.</i> (2007)

$$R^2 = 1 - \frac{\sum_{i=1}^N (MR_{pre,i} - MR_{exp,i})^2}{\sum_{i=1}^N (\overline{MR}_{pre} - MR_{exp,i})^2} \quad (7) \quad K_1 = \frac{\pi^2 D_{eff}}{4L^2} \quad (12)$$

$$\chi^2 = \frac{\sum_{i=1}^N (MR_{exp,i} - MR_{pre,i})^2}{N - z} \quad (8)$$

$$RMSE = \left[\frac{1}{N} \sum_{i=1}^N (MR_{pre,i} - MR_{exp,i})^2 \right]^{\frac{1}{2}} \quad (9) \quad D_{eff} = f(U_a, U_c, T_{abs}) = \alpha_0 U_a^{\alpha_1} U_c^{\alpha_2} \exp\left(-\frac{\alpha_3}{T_{abs}}\right) \quad (13)$$

The obtained constants of the selected model were regressed against the air temperature (T), air velocity (U_a), and chain linear velocity (U_c), using multiple regression analysis to find out the effects of the drying variables on the selected model constants.

Calculation of effective moisture diffusivity.

Fick's second equation of diffusion was used to calculate the effective moisture diffusivity (D_{eff}), considering a constant moisture diffusivity, infinite slab geometry, and a uniform initial moisture distribution (CRANK 1975):

$$MR = \frac{M_x - M_e}{M_0 - M_e} = \frac{8}{\pi^2} \sum_{n=0}^{\infty} \frac{1}{(2n+1)} \exp\left(-\frac{(2n+1)^2 \pi^2 D_{eff} \left(\frac{x}{U_c}\right)}{4L^2}\right) \quad (10)$$

Eq. 10 can be simplified by taking the first term of series solution:

$$MR = \frac{8}{\pi^2} \exp\left(-\frac{\pi^2 D_{eff} \left(\frac{x}{U_c}\right)}{4L^2}\right) \quad (11)$$

The effective moisture diffusivity was also typically calculated by using the slope of Eq. 11. A straight line with a slope of K_1 was obtained when $\ln(MR)$ was plotted versus x/U_c :

The effects of air temperature, air velocity, and chain linear velocity on the effective diffusivity were described by an Arrhenius type equation. The relationship between the diffusion coefficient and air temperature, air velocity, and chain linear velocity for carrot drying is:

The energy of activation was calculated by using an Arrhenius type equation (BABALIS & BELES-SIOTIS 2004; SACILIK & UNAL 2005; MENGES & ERTEKIN 2006; KASHANINEJAD *et al.* 2007; AGH-BASHLO *et al.* 2008).

$$D_{eff} = D_0 \exp\left(-\frac{E_a}{RT_{abs}}\right) \quad (14)$$

A plot of $\ln(D_{eff})$ versus $1/T_{abs}$ from Eq. 14 gives a straight slope of K_2 :

$$K_2 = \frac{E_a}{R} \quad (15)$$

Consequently, the energy of activation (E_a) was obtained using Eq. 15.

RESULTS AND DISCUSSION

The initial moisture content of carrot slices was found to be 8.3 ± 0.36 (kg water/kg dry matter). The equilibrium moisture content of the carrot slices varied from 0.133 ± 0.019 to 0.284 ± 0.031 (kg water/kg dry matter). The moisture content under different drying conditions was converted into the moisture ratio expression (MR).

The drying curves are shown in Figure 3 for thin layer drying of carrots over the length of continu-

ous band dryer at constant air velocity and chain linear velocity influenced by the temperature from 50°C to 70°C. Similar results were found for other air velocities and chain linear velocities.

Drying of carrot occurred in the falling rate period over the length of the dryer. Higher drying air temperatures results in an increase of the drying rate because a higher air temperature causes a higher reduction of the moisture content. In other words, at high temperatures the transfer of heat and mass was higher and the water loss was more excessive.

Figure 3 shows that at high temperatures, the samples lost most of their moisture during the first 100 cm chain movement. In general, the required distance to reduce the moisture ratio to each given level depended on the drying temperature, the ratio being the highest at 50°C and the lowest at 70°C. Analysis of variance showed that the moisture content decreased ($P < 0.05$) with increasing drying temperature at all air velocities and chain linear velocities.

The drying curves are shown in Figure 4 for thin layer drying of carrots over the length of the continuous band dryer at constant air temperature and chain linear velocity influenced by air velocity ranging from 0.5 m/s to 1.5 m/s. Similar results were found for other air temperatures and chain linear velocities.

Higher air velocity showed an increase of the drying rate and it consequently decreased MR over the length of the dryer. The results of analysis of variance showed that the moisture ratio decreased ($P < 0.05$) with increasing air velocity at all air temperatures and chain linear velocities. However, the effect of air velocity on the moisture ratio was smaller than that of temperature. The effect of air velocity on the moisture ratio is evident in a shorter distance from the inlet part. It could be related to the surface moisture evaporation at the initial drying time. After this stage, evaporation recedes to

the interior of the solid. Thus, the major effect of air velocity was observed in the middle and final sample positions, being the most important factor in these positions. In general, the distance required to reduce the moisture ratio to each given level depended on the air velocity, the ratio being the highest at 0.5 m/s and the lowest at 1.5 m/s.

The drying curves are shown in Figure 4 for thin layer drying of carrots over the length of the continuous band dryer influenced by the chain linear velocity from 2.38×10^{-4} m/s to 3.33×10^{-4} m/s. Similar results were found at other air temperatures and air velocities.

Lower chain linear velocities caused a great decrease of MR , because the products remained in the dryer for a longer time. The results of analysis of variance showed that the moisture ratio decreased ($P < 0.05$) with decreasing chain linear velocity at all air temperatures and velocities. However, the effect of the chain linear velocity on the moisture ratio was smaller than the effects of air temperature and air velocity.

The drying models were fitted to the drying data and sorted in descending order of R^2 and ascending order of χ^2 and $RMSE$. The average values of R^2 , χ^2 , and $RMSE$ of the drying models for all treatments are shown in Figure 5. The Page model showed the best fitting for modelling the drying kinetics of carrot slices over the length of the continuous dryer due to the high value of R^2 and the low values of χ^2 and $RMSE$.

Table 2 shows the fitting results of R^2 , χ^2 , $RMSE$, k , and m for the Page model. Generally, the R^2 , χ^2 , $RMSE$, k , and m obtained for the Page model were found in the ranges of 0.9935 to 0.9998, 1.08×10^{-8} to 3.58×10^{-5} , 0.027114–0.003575 m^{-1} , 0.4174–0.9916, and 0.9845–1.31, respectively.

Analysis of variance indicated that the constant k was affected by air temperature, air velocity, and

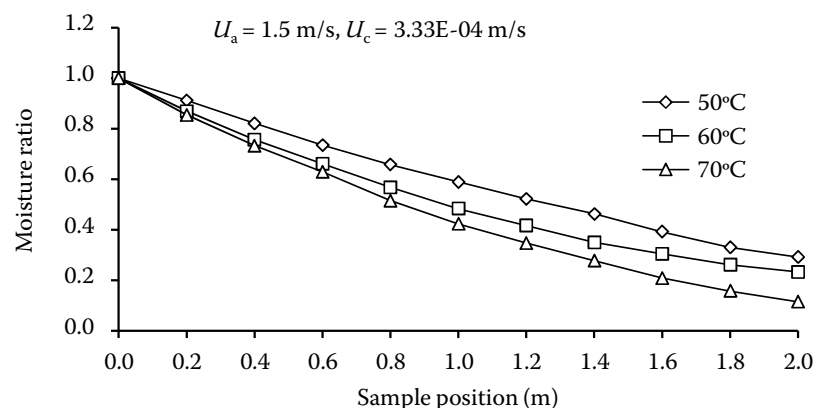


Figure 2. Effect of temperature on moisture ratio at different level of air velocity and chain linear velocity during drying of carrot slice in continuous dryer

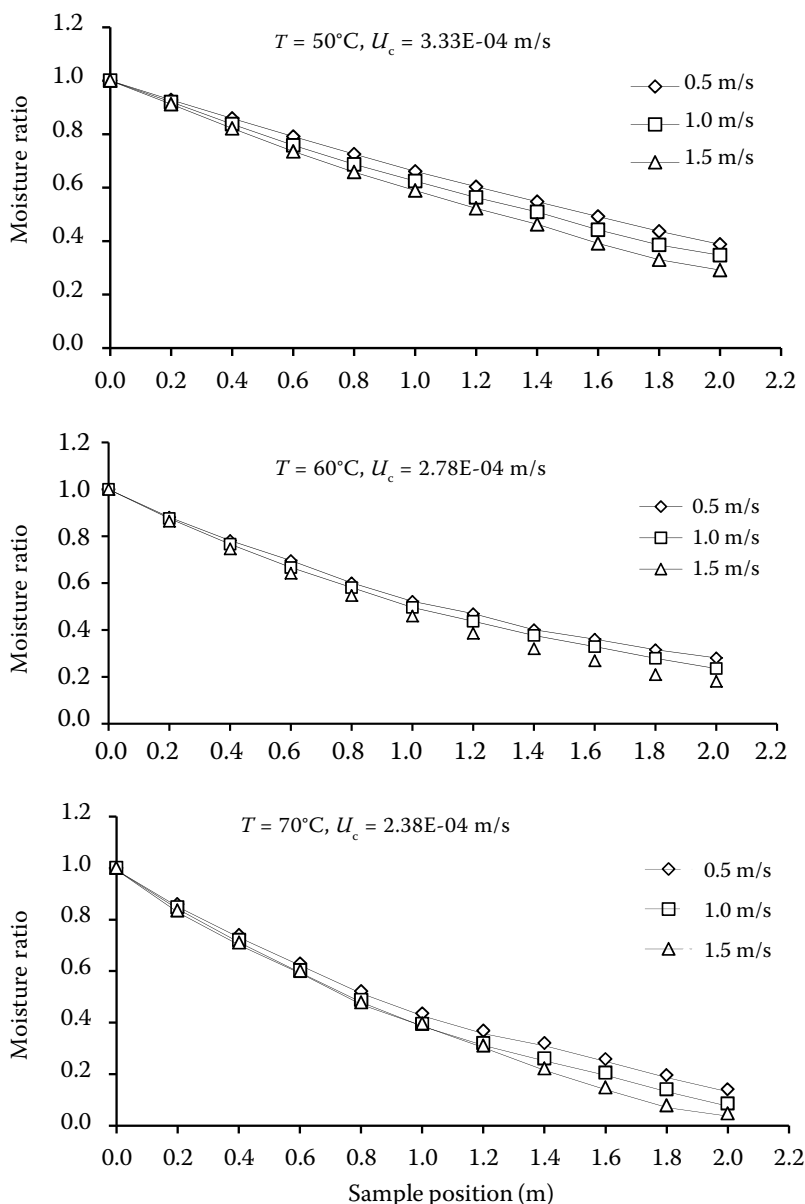


Figure 3. Effect of air velocity on moisture ratio at different level of air temperature and chain linear velocity during drying of carrot slice in continuous dryer

chain linear velocity. Generally, k increased ($P < 0.05$) with increasing air temperature and velocity but decreased ($P < 0.05$) with increasing chain linear velocity.

The Page model constants k and m were regressed against the drying variables using multiple regressions analysis, and the following equations resulted:

$$k = 0.0172T + 0.149U_a - 872.31U_c - 0.2428 \quad R^2 = 0.9869 \quad (16)$$

$$m = 0.001092T^2 + 0.04388U_a^2 + 3322701U_c^2 - 0.13075T - 0.01306U_a - 2475.62U_c + 5.36 \quad R^2 = 0.8547 \quad (17)$$

In Eq. 16, the coefficients for air temperature and air velocity are positive which indicates that

k increases with the increase in air temperature and air velocity.

The moisture ratio of carrot during the drying process can be estimated using the Page model. Figure 6 shows the plot of the experimental data of the moisture ratio versus the predicted values of the moisture ratio calculated using the Page model (Eqs 16 and 17). The data points are banded around a 45° straight line, demonstrating the suitability of the Page model in describing the thin-layer drying behaviour of carrot over the length of the continuous band dryer.

Table 3 shows the effective moisture diffusivity (D_{eff}) derived from Eq. 8 for each test. The minimum value of moisture diffusivity was 3.21×10^{-7}

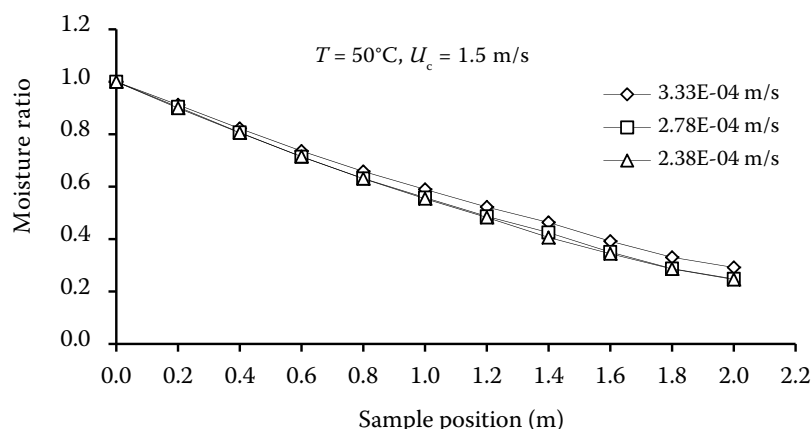


Figure 4. Effect of chain linear velocity on moisture ratio at different level of air temperature and velocity during drying of carrot slice in continuous dryer

at air temperature of 50°C, air velocity of 0.5 m/s, and chain linear velocity of 2.38×10^{-4} m/s. The maximum value of the moisture diffusivity was 8.98×10^{-7} at air temperature of 70°C, air velocity of

1.5 m/s, and chain linear velocity of 3.33×10^{-4} m/s. Higher drying air temperature and air velocity caused an increase of the effective moisture diffusivity because of a higher mass transfer. The

Table 2. The fitting results of the Page model for different drying conditions

Air velocity (m/s)	Temperature (°C)	Chain linear velocity $\times 10^{-4}$ (m/s)	k (m ⁻¹)	m	R^2	RMSE	χ^2
0.5	50	3.33	0.4174 ± 0.009	1.148 ± 0.091	0.9993	0.005599	6.51E-08
		2.78	0.4367 ± 0.011	1.169 ± 0.024	0.9991	0.006581	1.24E-07
		2.38	0.4601 ± 0.008	1.176 ± 0.095	0.9984	0.009195	4.74E-07
	60	3.33	0.6087 ± 0.014	0.984 ± 0.052	0.9994	0.005805	7.53E-08
		2.78	0.6339 ± 0.007	1.020 ± 0.056	0.9994	0.005695	6.97E-08
		2.38	0.6695 ± 0.005	1.044 ± 0.085	0.9997	0.003970	1.65E-08
	70	3.33	0.7293 ± 0.007	1.096 ± 0.059	0.9994	0.006734	1.36E-07
		2.78	0.7526 ± 0.012	1.108 ± 0.018	0.9989	0.009063	4.47E-07
		2.38	0.8260 ± 0.020	1.113 ± 0.014	0.9981	0.012686	1.72E-06
1.0	50	3.33	0.4791 ± 0.016	1.123 ± 0.097	0.9990	0.006992	1.60E-08
		2.78	0.5224 ± 0.006	1.157 ± 0.022	0.9991	0.007259	1.84E-07
		2.38	0.5582 ± 0.009	1.174 ± 0.084	0.9990	0.007889	2.57E-07
	60	3.33	0.6709 ± 0.021	1.024 ± 0.029	0.9996	0.004606	2.98E-08
		2.78	0.6906 ± 0.007	1.040 ± 0.096	0.9998	0.003575	1.08E-08
		2.38	0.7478 ± 0.009	1.086 ± 0.045	0.9996	0.005429	5.76E-08
	70	3.33	0.8063 ± 0.010	1.150 ± 0.095	0.9988	0.009948	6.49E-07
		2.78	0.8445 ± 0.016	1.163 ± 0.075	0.9986	0.011109	1.01E-06
		2.38	0.9387 ± 0.012	1.179 ± 0.068	0.9975	0.015506	3.83E-06
1.5	50	3.33	0.5414 ± 0.017	1.158 ± 0.087	0.9987	0.008784	3.95E-07
		2.78	0.6002 ± 0.007	1.176 ± 0.068	0.9985	0.010201	7.18E-07
		2.38	0.6086 ± 0.008	1.180 ± 0.013	0.9989	0.008530	3.51E-07
	60	3.33	0.7223 ± 0.013	1.047 ± 0.049	0.9996	0.004863	3.71E-08
		2.78	0.7865 ± 0.004	1.105 ± 0.073	0.9994	0.006640	1.29E-07
		2.38	0.8083 ± 0.003	1.156 ± 0.061	0.9989	0.009785	6.08E-07
	70	3.33	0.8793 ± 0.006	1.193 ± 0.057	0.9981	0.013444	2.16E-06
		2.78	0.9445 ± 0.016	1.206 ± 0.069	0.9985	0.012141	1.44E-06
		2.38	0.9916 ± 0.017	1.310 ± 0.081	0.9935	0.027114	3.58E-05

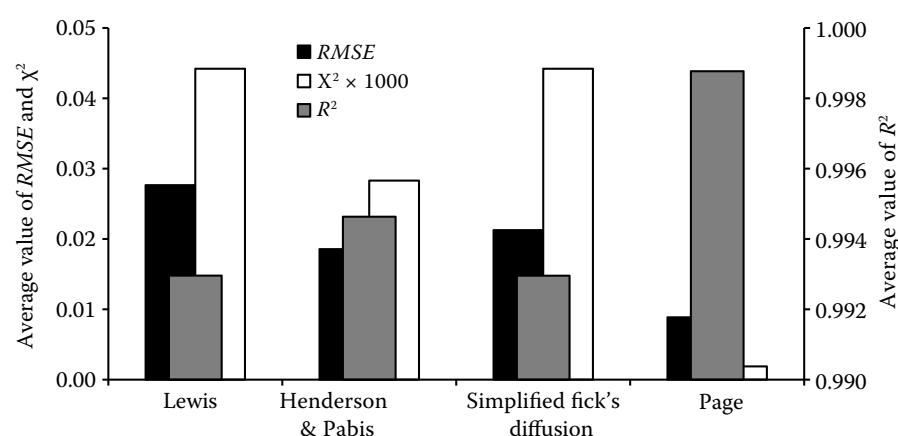


Figure 5. Average value of R^2 , χ^2 and RMSE for used model

values obtained are in a suitable range for various products reported in the literature (AKPINAR *et al.* 2003; DOYMAZ 2004; ERTEKIN & YALDIZ 2004; SACILIK & UNAL 2005; MENGES & ERTEKIN 2006; KASHANINEJAD *et al.* 2007).

The effective moisture diffusivity increased ($P < 0.05$) with increasing air temperature, air velocity, and chain linear velocity. Similar findings concerning the effects of air temperature and velocity on the effective moisture diffusivity have been reported by several researches (SACILIK *et al.* 2006; GOYAL *et al.* 2007).

RIZVI (1986) stated that the effective diffusivity depends on the drying air conditions besides the variety and composition of the material. The effects of air temperature, air velocity, and chain linear velocity on the effective moisture diffusivity are generally described using Arrhenius type equation.

Eq. 18 shows the effects of the drying variables on the effective moisture diffusivity of carrot drying at the statistically significant level of 1%:

$$D_{\text{eff}} = f(U_a, U_c, T_{\text{abs}}) = 0.2593 U_a^{0.2632} U_c^{0.5047} \exp(-2975.83/T_{\text{abs}}) \quad R^2 = 0.9831 \quad (18)$$

Similar relationship has been reported for the effects of the drying variables on the moisture effective diffusivity during potato slice drying (AKPINAR *et al.* 2003).

Figure 7 shows the experimental moisture diffusivity plotted against the predicted values calculated using Eq. 18. The data points are banded around a 45° straight line, demonstrating the suitability of the obtained model for predicting the effective moisture diffusivity of the carrot drying over the length of the continuous band dryer.

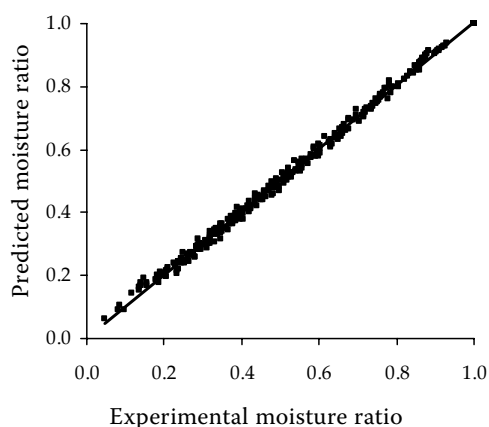


Figure 6. The experimental moisture ratio versus the predicted moisture ratio values by the Page model for different air temperature, air velocity and chain linear velocity for thin-layer drying of carrot in length of continuous band dryer

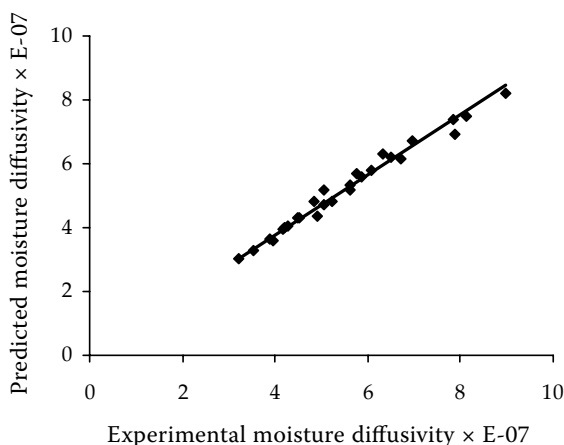


Figure 7. Experimental moisture diffusivity values versus predicted moisture diffusivity values using Eq. 18 for different air temperature, velocity and chain linear velocity values for thin-layer drying of carrot in length of continuous band dryer

Table 3. Effective moisture diffusivity for each experiment

Air velocity (m/s)	Temperature (°C)	Chain linear velocity $\times 10^{-4}$ (m/s)	$D_{\text{eff}} \times 10^{-7}$ (m ² /s)	R^2
0.5	50	3.33	3.97 ± 0.09	0.9942
		2.78	3.52 ± 0.11	0.9926
		2.38	3.21 ± 0.07	0.9898
	60	3.33	5.04 ± 0.16	0.9985
		2.78	4.51 ± 0.14	0.9994
		2.38	4.18 ± 0.05	0.9993
	70	3.33	6.69 ± 0.08	0.9972
		2.78	5.85 ± 0.07	0.9947
		2.38	5.63 ± 0.16	0.9868
1.0	50	3.33	4.48 ± 0.21	0.9950
		2.78	4.16 ± 0.06	0.9946
		2.38	3.86 ± 0.21	0.9934
	60	3.33	5.74 ± 0.09	0.9994
		2.78	5.04 ± 0.14	0.9991
		2.38	4.85 ± 0.08	0.9978
	70	3.33	7.83 ± 0.07	0.9918
		2.78	6.96 ± 0.13	0.9890
		2.38	6.49 ± 0.14	0.9718
1.5	50	3.33	5.22 ± 0.04	0.9922
		2.78	4.91 ± 0.19	0.9899
		2.38	4.26 ± 0.08	0.9918
	60	3.33	6.30 ± 0.08	0.9991
		2.78	6.08 ± 0.16	0.9961
		2.38	5.62 ± 0.15	0.9919
	70	3.33	8.98 ± 0.20	0.9845
		2.78	8.12 ± 0.14	0.9849
		2.38	7.86 ± 0.09	0.9801

$\ln(D_{\text{eff}})$ was plotted versus $1/T_{\text{abs}}$ and the activation energy was calculated using Eq. 11. The activation energy was calculated for each value of air velocity and chain linear velocity (Table 4). The activation energy is an indication of energy required to remove moisture from a solid matrix. The values of the activation energy lie in the range of 12.7 kJ/mol to 110 kJ/mol for most food materials (ZOGZAS *et al.* 1996). The activation energy (E_a) for carrot slices varied from 23.02 kJ/mol to 28.10 kJ/mol for air velocities of 0.5 m/s to 1.5 m/s and chain linear velocity of 2.38×10^{-4} m/s to 3.33×10^{-4} m/s. The obtained values of the activation energy were in a suitable range and in agreement with the previous works (BABALIS & BELESSIOTIS 2004; SACILIK & UNAL 2005; SACILIK *et al.* 2006; MENGES & ERTEKIN 2006; KASHANINEJAD *et al.* 2007). It is evident that the diffusion coefficients are very temperature sensitive at the chain linear

velocity of 2.38×10^{-4} m/s for all air velocities (Table 4).

CONCLUSION

The drying behaviour of carrot slices was studied in a continuous band dryer. The carrot moisture content decreased continuously over the length of the dryer. The results showed a significant effect of the drying variables on the drying kinetics. The Page model adequately predicted the moisture content of carrot during the drying process at temperatures 50°C to 70°C, air velocities 0.5 m/s to 1.5 m/s, and chain linear velocities 2.38×10^{-4} m/s to 3.33×10^{-4} m/s. The Page model constants k and m could be predicted as a function of the air temperature, air velocity, and chain linear velocity. Consequently, a general equation was obtained for

Table 4. Energy of activation for different level of air and chain linear velocities

Air velocity (m/s)	Chain linear velocity $\times 10^{-4}$ (m/s)	Energy activation (kJ/mol)	$\ln(D_0)$	R^2
0.5	3.33	24.02 ± 0.45	5.80 ± 0.14	0.9953
	2.78	23.36 ± 0.53	6.14 ± 0.17	0.9991
	2.38	25.85 ± 0.44	5.32 ± 0.17	0.9977
1.0	3.33	25.60 ± 0.57	5.08 ± 0.34	0.9935
	2.78	23.61 ± 0.33	5.91 ± 0.13	0.9743
	2.38	26.85 ± 0.84	4.78 ± 0.28	0.9792
1.5	3.33	24.77 ± 0.79	5.23 ± 0.30	0.9638
	2.78	23.02 ± 0.58	5.93 ± 0.18	0.9887
	2.38	28.10 ± 0.70	4.20 ± 0.27	0.9946

the moisture ratio of carrot slices as a function of the air temperature, air velocity, chain linear velocity, and sample position. The effects of variables on the effective diffusivity were represented by an Arrhenius-type relationship. The drying variables showed significant effects on the effective moisture diffusivity.

List of abbreviation

a, b, k, m	models constant
z	number of constants
n	number of term in Fick's equation
MR	moisture ratio (dimensionless)
D_{eff}	effective moisture diffusivity (m^2/s)
D_0	constant (m^2/s)
E_a	energy of activation (kJ/mol)
N	number of observation
L	half thickness of the halve in samples (m)
U_a	air velocity (m/s)
U_c	chain linear velocity (m/s)
x	position (m)
R^2	coefficient of determination
$RMSE$	root mean square error
χ^2	reduced chi-square
R	universal gas constant (8.3143 kJ/mol·K)
K_1, K_2	slop of line
T	temperature ($^{\circ}\text{C}$)
T_{abs}	absolute temperature (K)
MR_{exp}	experimental moisture ratio
MR_{pre}	predicted moisture ratio
W_x	dry matter at any position (kg)
W_d	dry matter (kg)
M_x	moisture content at any sample position (kg water/kg dry matter)
M_e	equilibrium moisture content (kg water/kg dry matter)
M_0	initial moisture content (kg water/kg dry matter)

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Received for publication May 5, 2010

Accepted after corrections September 3, 2010

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