# 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 ($\chi^2$) 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 × $10^{-7}$ $m^2/s$. 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 $B_6$, 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,

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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 & Mohsenimanesh 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 ± 2°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 ± 1°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

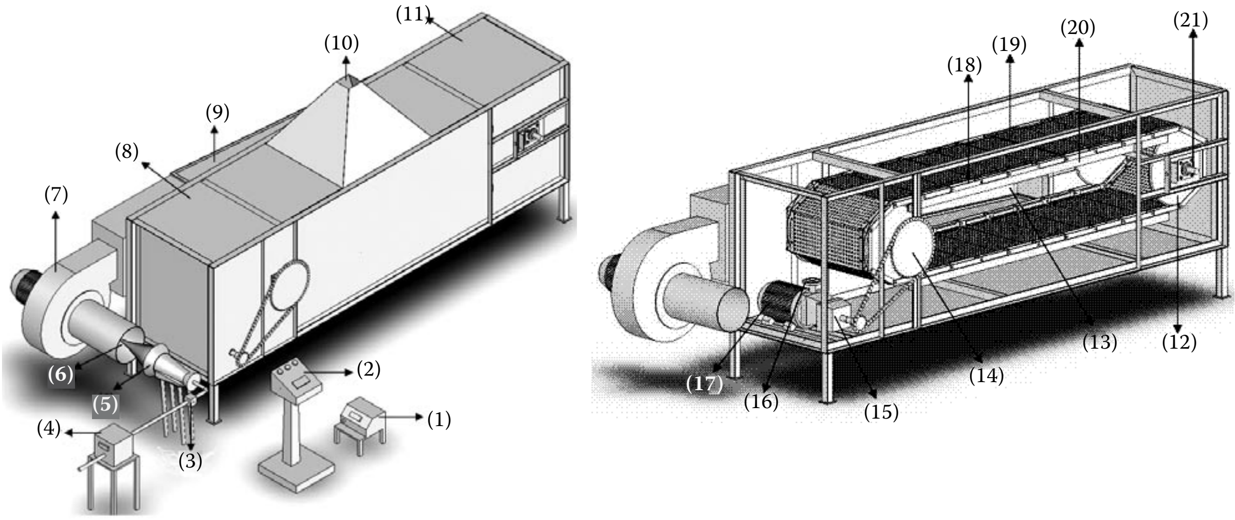


Figure 1. Schematic of dryer: (1) inverter; (2) control panel; (3) gas flow rate controller; (4) gas controller (for large range) and contour; (5) heater; (6) hot air suction tube and intake of hot air by fan; (7) fan; (8) removable inlet part; (9) air channel; (10) outlet air and location of temperature 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 ± 2°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 $2.38 \times 10^{-4}$, $2.78 \times 10^{-4}$, and $3.33 \times 10^{-4}$ m/s.

***Statistical analysis***. Statistical evaluation of the results was performed using a 3 × 3 × 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:

$$M_x = \frac{W_x - W_d}{W_d} \tag{1}$$

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

$$MR = \frac{M_x - M_e}{M_0 - M_e} \tag{2}$$

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 ($\chi^2$), and root mean square error (*RMSE*).

Table 1. Thin-layer drying models

| Model | Equation | | Reference |
|---|---|---|---|
| Lewis | $MR = \exp(-kx)$ | (3) | Akpinar *et al.* (2003); Kashaninejad *et al.* (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 *et al.* (2006); Kashaninejad *et al.* (2007) |

$$R^2 = 1 - \left[ \frac{\sum_{i=1}^{N} (MR_{\mathrm{pre},i} - MR_{\exp,i})^2}{\sum_{i=1}^{N} (\overline{MR}_{\mathrm{pre}} - MR_{\exp,i})^2} \right] \quad (7)$$

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

$$RMSE = \left[ \frac{1}{N} \sum_{i=1}^{N} (MR_{\mathrm{pre},i} - MR_{\exp,i})^2 \right]^{\frac{1}{2}} \quad (9)$$

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 ($D_{\mathrm{eff}}$), considering a constant moisture diffusivity, infinite slab geometry, and a uniform initial moisture distribution (Crank 1975):

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

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

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

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 $x/U_c$:

$$K_1 = \frac{\pi^2 D_{\mathrm{eff}}}{4L^2} \quad (12)$$

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:

$$D_{\mathrm{eff}} = f(U_a, U_c, T_{\mathrm{abs}}) = \alpha_0 U_a^{\alpha_1} U_c^{\alpha_2} \exp\left(-\frac{\alpha_3}{T_{\mathrm{abs}}}\right) \quad (13)$$

The energy of activation was calculated by using an Arrhenius type equation (Babalis & Belessiotis 2004; Sacilik & Unal 2005; Menges & Ertekin 2006; Kashaninejad *et al.* 2007; Aghbashlo *et al.* 2008).

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

A plot of ln($D_{\mathrm{eff}}$) versus $1/T_{\mathrm{abs}}$ 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 continuous 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 $2.38 \times 10^{-4}$ m/s to $3.33 \times 10^{-4}$ 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 $\chi^2$ and *RMSE*. The average values of $R^2$, $\chi^2$, 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 $\chi^2$ and *RMSE*.

Table 2 shows the fitting results of $R^2$, $\chi^2$, *RMSE*, *k*, and *m* for the Page model. Generally, the $R^2$, $\chi^2$, *RMSE*, *k*, and *m* obtained for the Page model were found in the ranges of 0.9935 to 0.9998, $1.08 \times 10^{-8}$ to $3.58 \times 10^{-5}$, 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

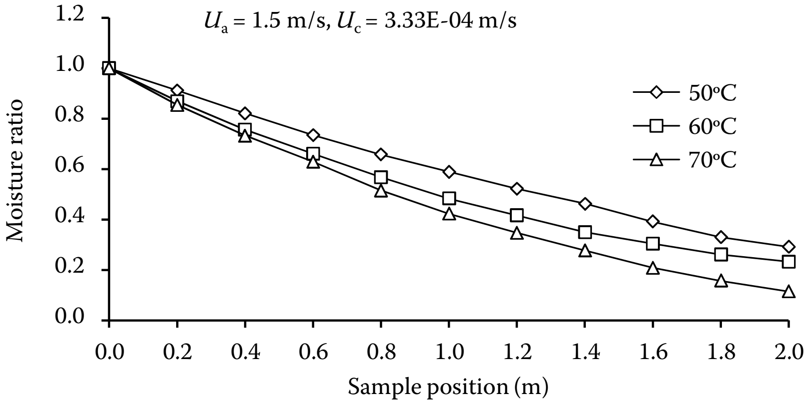


Figure 2. Effect of temperature on moisture ratio at different level of air velocity and chain linear velocity during drying of carrot slice in continuous dryer

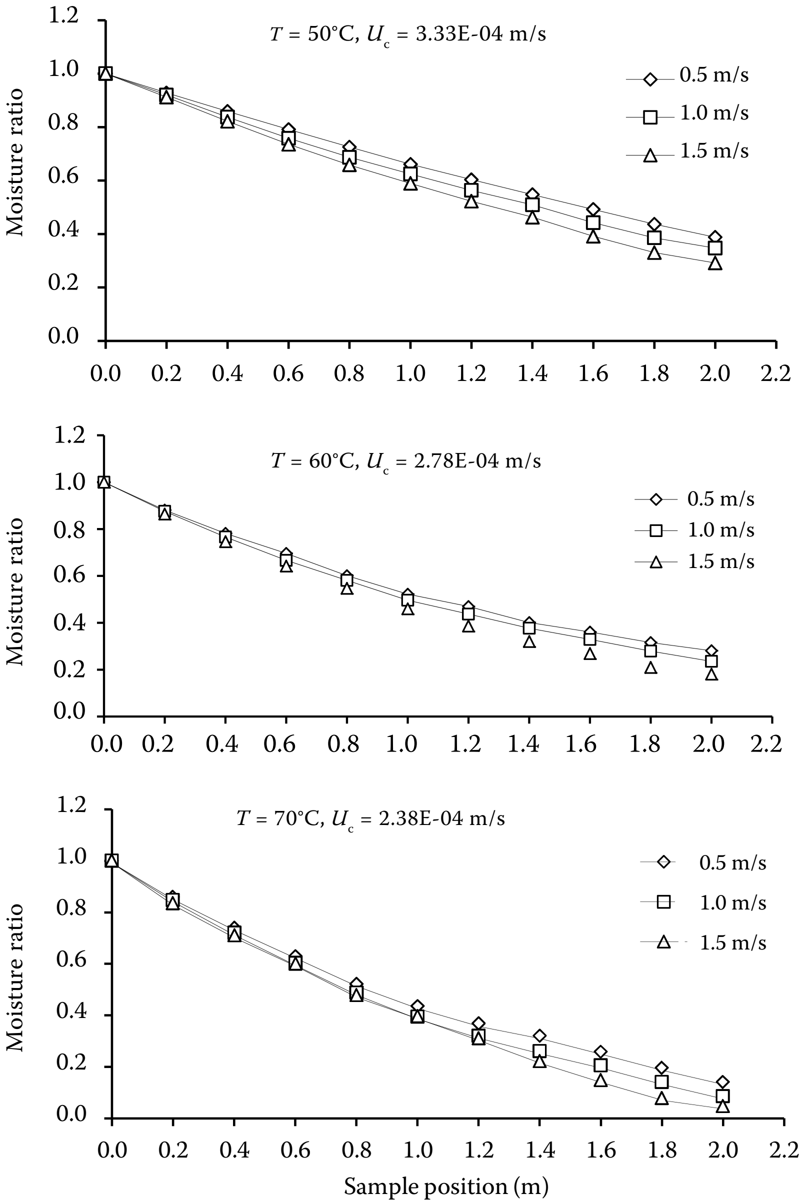


Figure 3. Effect of air velocity on moisture ratio at different level of air temperature and chain linear velocity during drying of carrot slice in continuous dryer

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 $3.21 \times 10^{-7}$

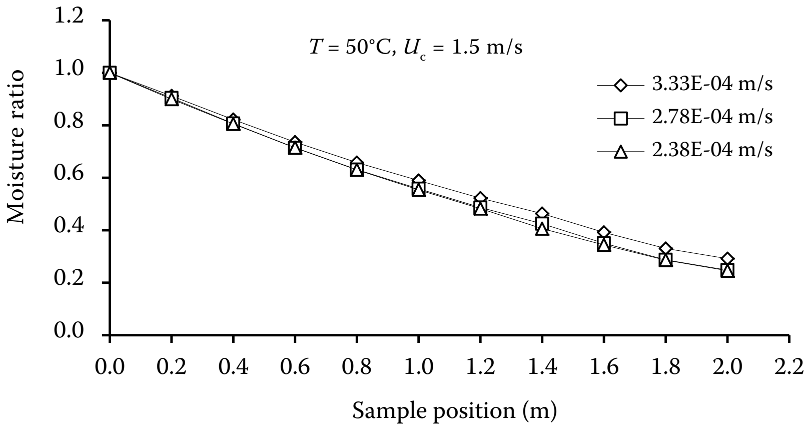


Figure 4. Effect of chain linear velocity on moisture ratio at different level of air temperature and velocity during drying of carrot slice in continuous dryer

at air temperature of 50°C, air velocity of 0.5 m/s, and chain linear velocity of $2.38 \times 10^{-4}$ m/s. The maximum value of the moisture diffusivity was $8.98 \times 10^{-7}$ at air temperature of 70°C, air velocity of 1.5 m/s, and chain linear velocity of $3.33 \times 10^{-4}$ 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) | $k$ ($m^{-1}$) | $m$ | $R^2$ | $RMSE$ | $\chi^2$ |
|---|---|---|---|---|---|---|---|
| 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 |

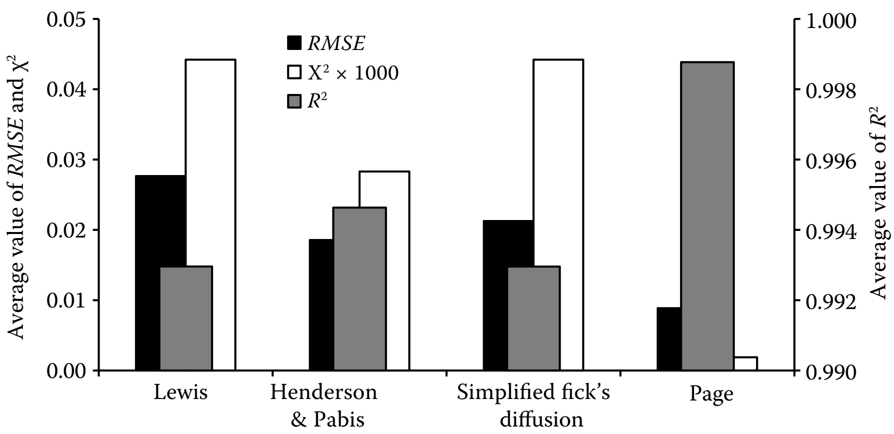


Figure 5. Average value of $R^2$, $\chi^2$ and RMSE for used model

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%:

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

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.

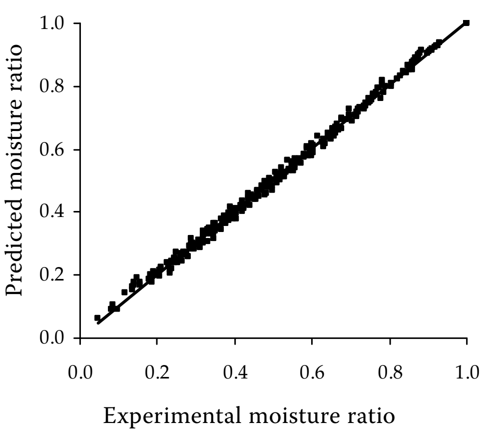


Figure 6. The experimental moisture ratio versus the predicted moisture ratio values by the Page model for different air temperature, air velocity and chain linear velocity for thin-layer drying of carrot in length of continuous band dryer

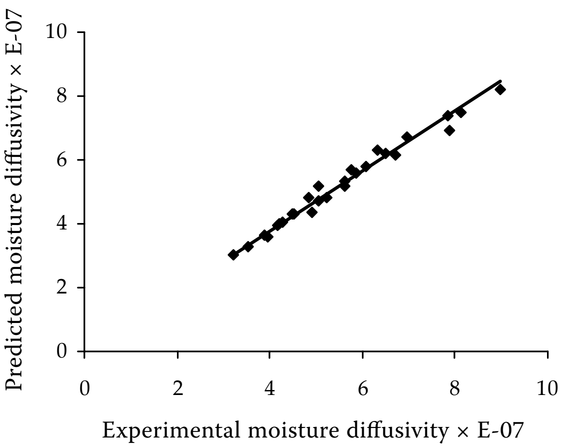


Figure 7. Experimental moisture diffusivity values versus predicted moisture diffusivity values using Eq. 18 for different air temperature, velocity and chain linear velocity values for thin-layer drying of carrot in length of continues band dryer

Table 3. Effective moisture diffusivity for each experiment

| Air velocity (m/s) | Temperature (°C) | Chain linear velocity × $10^{-4}$ (m/s) | $D_{eff}$ × $10^{-7}$ ($m^2$/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($D_{eff}$) was plotted versus $1/T_{abs}$ 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 0.5m/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 × $10^{-4}$ (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 abberation

| | |
|---|---|
| *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 |
| $\chi^2$ | reduced chi-square |
| *R* | universal gas constant (8.3143 kJ/mol·K) |
| $K_1$, $K_2$ | slop of line |
| *T* | temperature (°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) |

## References


Aghbashlo M., Kianmehr M.H., Samimi-Akhijahani H. (2008): Influence of drying conditions on the effective moisture diffusivity, energy of activation and energy consumption during the thin-layer drying of berberis fruit (*Berberis vulgaris*). Energy Conversion and Management, **49**: 2865–2871.

Aghbashlo M., Kianmehr M.H., Arabhosseini A. (2009): Modelling of thin-layer drying of potato slices in length of continuous band dryer. Energy Conversion and Management, **50**: 1348–1355.

Akpinar E., Midilli A., Bicer Y. (2003): Single layer drying behaviour of potato slices in a convective cyclone dryer and mathematical modelling. Energy Conversion and Management, **44**: 1689–1705.

Babalis S.J., Belessiotis V.G. (2004): Influence of drying conditions on the drying constants and moisture diffusivity during the thin-layer drying of figs. Journal of Food Engineering, **65**: 449–458.

Babalis S.J., Papanicolaou E., Kyriakis N., Belessiotis V.G. (2006): Evaluation of thin-layer drying models for describing drying kinetics of figs (*Ficus carica*). Journal of Food Engineering, **75**: 205–214.

Celma A.R., Rojas S., Lopez F., Montero I., Miranda T. (2007): Thin-layer drying behaviour of sludge of olive oil extraction. Journal of Food Engineering, **80**: 1261–1271.

Crank J. (1975): The Mathematics of Diffusion. 2nd Ed. Clarendon Press, Oxford.

Demir V., Gunhan T., Yagcioglu A.K. (2007): Mathematical modelling of convection drying of green table olives. Biosystems Engineering, **98**: 47–53.

Diamante L.M., Munro P.A. (1993): Mathematical modelling of the thin layer solar drying of sweet potato slices. Solar Energy, **51**: 271–276.

Doymaz I. (2004): Convective air drying characteristics of thin layer carrots. Journal of Food Engineering, **61**: 359–364.

Doymaz I. (2007): Air-drying characteristics of tomatoes. Journal of Food Engineering, **78**: 1291–1297.

Erenturk S., Erenturk K. (2007): Comparison of genetic algorithm and neural network approaches for the drying process of carrot. Journal of Food Engineering, **78**: 905–912.

Ertekin C., Yaldiz O. (2004): Drying of eggplant and selection of a suitable thin layer drying model. Journal of Food Engineering, **63**: 349–359.

Gazor H.R., Mohsenimanesh A. (2010): Modelling drying kinetics of canola in fluidized bed dryer. Czech Journal of Food Sciences, **28**: 531–537.

Gornicki K., Kaleta A. (2007): Drying curve modelling of blanched carrot cubes under natural convection condition. Journal of Food Engineering, **82**: 160–170.

Goyal R.K., Kingsly A.R.P., Manikatan M.R., Ilyas S.M. (2007): Mathematical modelling of thin layer drying kinetics of plum in a tunnel dryer. Journal of Food Engineering, **79**: 176–180.

Jokić S., Velić D., Bilić M., Lukinac J., Planinić M., Bucić-Kojić A. (2009): Influence of process parameters and pre-treatments on quality and drying kinetics of apple samples. Czech Journal Food Sciences, **27**: 88–94.

Kashaninejad M., Mortazavi A., Safekordi A., Tabil L.G. (2007): Thin-layer drying characteristics and modelling of pistachio nuts. Journal of Food Engineering, **78**: 98–108.

Menges H.O., Ertekin C. (2006): Mathematical modelling of thin layer drying of Golden apples. Journal of Food Engineering, **77**: 119–125.

Ozdemir M., Devres Y.O. (1999): The thin layer drying characteristics of hazelnuts during roasting. Journal of Food Engineering, **42**: 225–233.

Sacilik K., Unal G. (2005): Dehydration characteristics of Kastamonu garlic slices. Biosystems Engineering, **92**: 207–215.

Sacilik K., Keskin R., Elicin A.K. (2006): Mathematical modelling of solar tunnel drying of thin layer organic tomato. Journal of Food Engineering, **73**: 231–238.

Rizvi S.S.H. (1986): Thermodynamic properties of foods in dehydration. In: Rao M.A., Rizvi S.S.H. (eds): Engineering Properties of Foods. Marcel Dekker Inc., New York.

Xia B., Sun D.W. (2002): Application of computational fluid dynamics (CFD) in the food industry: a review. Computer and Electronics in Agriculture, **34**: 5–24.

Zogzas N.P., Maroulis Z.B., Marinos-Kouris D. (1996): Moisture diffusivity data compilation in foodstuffs. Drying Technology, **14**: 2225–2253.

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