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Effective moisture diffusivity during hot air solar drying of tomato slices

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Abstract

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Mathematical modelling and effective moisture diffusivity of tomato (*Lycopersicon esculentum*) was studied during hot air solar drying. An experimental solar dryer with a swivel collector was used for experiments. The collector followed the solar radiation using a precious sensor. Drying experiments were performed in a thin layer hot air drying at slice thicknesses of 3, 5 and 7 mm and air velocities of 0.5, 1 and 2 m/s. The experimental data were fitted to different mathematical moisture ratio models and the *Page* model was selected as the best model according to correlation coefficient R^2, chi-square χ^2 and root mean square error (RMSE) parameters. The maximum values of moisture diffusivity was 6.98×10^{-9} m^2/s at air velocity of 2 m/s and slice thickness of 7 mm while the minimum value of the moisture diffusivity was 1.58×10^{-9} m^2/s at air velocity of 0.5 m/s and slice thickness of 3 mm.

Keywords: falling rate period; Fick's second law; mathematical models; solar dryer; swivel collector

Tomato (*Lycopersicon esculentum*) is one of the vegetables, which is a good source of macro minerals such as Na, K, Ca, Mg, P, S and micro minerals as Mn, Fe, Cu, Zn and Se (Oyeta et al. 2012). Tomato is generally produced in moderate-warm climate zones (Davies, Hobson 1981). Iran is the seventh highest tomato-producing country in the world. In 2012, the total cultivation in Iran was about 160,000 ha and the total production was about 6 million tons (FAOSTAT 2014), which is mostly produced in the East Azerbaijan province, especially in Azarshahr city. Tomato is one of the main sources for fresh using and processing industries and its production creates job opportunities and supplies some parts of the market in dry form. The dry form refers to the removal of relatively small amount of moisture from a solid or nearly solid material by evaporation (Aghbashloo et al. 2008).

Solar drying could be a possible solution for the dehydration of food and agricultural products (Taheri et al. 2011). Solar drying is a process where moisture content, drying air temperature and product temperature change simultaneously along with the two basic inputs to the system i.e. the solar radiation and the ambient temperature. The drying rate is affected by ambient climatic conditions which include temperature, relative humidity, sunshine hours, available solar radiation, wind velocity, frequency and duration of rain showers during the drying period (Chandra Shahi et al. 2011). The most important feature of solar dryers is that the product does not include any kind of preservatives or other added chemical stuffs, which allows its use for people suffering from various allergic reactions from these (Akpinar et al. 2003).

Azarshahr city is situated in the Azerbaijan province at 45.8°E longitude and 37.4°N latitude having altitude of 1,450 m above mean sea level. The sunshine period of East Azerbaijan is about 2,852 h/year with a max. of 415 h/month in July and a min. of

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123 h/month in January. Max. solar radiation is about 4.9 kWh/m^2 per day. Because of the proper solar radiations in this area, solar energy is the main source for drying of fruits and vegetables. Properly designed solar drying systems must be taken into account for drying requirements of specific crops, energy efficiency requirements, and cost-effectiveness (Steinfeld, Segal 1986). Simulation models are needed in the design and operation of solar dryers. Several researchers have already developed simulation models for solar drying systems such as design theory for simple solar rice dryer (Exell 1980), solar drying of rough rice (Zaman, Bala 1989), testing of a new solar dryer and mathematical modelling of thin layer drying of sultana grapes (Yaldiz et al. 2001). Moreover thermodynamic analysis, particularly moisture diffusivity and exergy analysis, has appeared to be essential tools for the design, analysis and optimisation of thermal system (Dincer, Sahin 2004). Exergy is defined as the maxi. amount of work which can be produced by a stream of matter, heat or work as it comes to equilibrium with a reference environment (Dincer 2002). Exergy analysis, as is known, evaluates the available energy at different points in a system. In the design of a system, the exergy method provides the useful information to choose the appropriate component design and operation procedure. Exergy is the measure of the potential of a stream to cause change, as a consequence of not being completely stable relative to the reference environment (Sami et al. 2011). To calculate the energy and exergy of the drying process, finding the moisture diffusivity of drying of crops is essential. Several studies have been reported about exergetic and moisture diffusivity analysis on the thin layer vegetable and fruit solar dryers, such as barberries (Aghbashloo et al. 2008), seedless grapes (Doymaz, Pala 2002), pumpkin slices (Doymaz 2006), apple pomace (Wang et al. 2002), candle nuts (Tarigan et al. 2006), red pepper (Akpinar et al. 2003), green olive (Colak, Hepbasli 2007), coroba slices (Corzo et al. 2008) and mulberry (Akbulut, Durmus 2010). The objectives of this study are mathematical modelling of drying kinetics and the effective moisture diffusivity for thin-layer drying of tomato slices in a solar indirect cabinet dryer with swivel absorber plate and to evaluate the influence of air condition on moisture diffusivity for thin-layer drying of tomato slices.

MATERIAL AND METHODS

Sample preparation. Fresh harvested tomatoes were purchased from a local farm at Azarshahr city, East Azerbaijan province. The tomatoes were packed and stored in the refrigerator at +5°C to prevent undesired changes. Before each experiment, certain amount of tomatoes was cut in slices with thicknesses of 3, 5 and 7 mm. The average diameter of the samples was about 71 ± 2 mm. About 100 g of tomato slices with three replicates were dried in a hot oven at 105 ± 2°C for six hours until the mass did not change between two weighing intervals (AOAC 1984). The samples were weighed by using a digital balance with an accuracy of 0.05 g and a capacity of 1,500 g. The initial moisture content was about 93.6% (w.b.). For each drying experiment, about 180 g of samples were placed in the sample trays and put in the cabinet of the dryer.

Drying conditions. A laboratory scale solar dryer of the static-tray type, was developed at the Agriculture Machinery Laboratory of the Azarshahr Research Centre and was used for experiments (Fig. 1). Basically, the main divisions of the developed dryer are top collector and bottom drying chamber. The separated sections of energy collec-

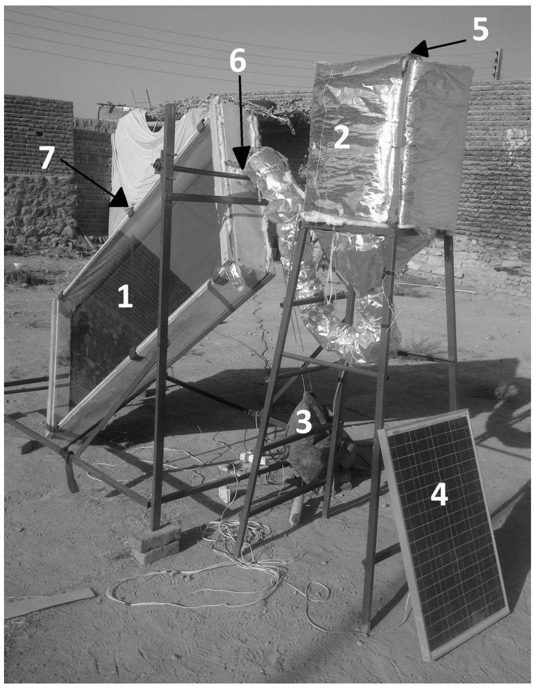

Fig. 1. The laboratory scale of the solar swivel dryer
1 – collector; 2 – isolated drying cabinet; 3 – DC motor; 4 – solar panel; 5 – location of fan; 6 – location of swivel; 7 – location of sensor

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Table 1. Thin layer drying models for describing drying of tomato slices

No.	Model	Mathematical equation	Reference
1	$MR = \exp(-kt)$	Lewis	Lewis (1921)
2	$MR = \exp(-kt^n)$	Page	Page (1949)
3	$MR = a \exp(-kt)$	Henderson and Pabis	Henderson and Pabis (1961)
4	$MR = a \exp(-kt) + c$	Logarithmic	Togrul and Pehlivan (2004)
5	$MR = a \exp(-k_1t) + b \exp(-k_2t)$	Two term	Verma et al. (1985)
6	$MR = a \exp(-kt) + (1 - a) \exp(-kat)$	Approximation of diffusion	Sharaf-Elden et al. (1980)
7	$MR = 1 + at + bt^2$	Wang and Singh	Yaldiz et al. (2001)

MR – moisture ratio; a, b, c, k, n – constants of the equation; t – drying time

tion and drying area help to avoid direct exposure of the product to the sun, thereby retaining the original colour for the dried products even at the end of the drying process. The absorber plate is made of steel sheet with dimensions of 1,800 × 900 mm and thickness of 2 mm. The plate was painted black to increase the solar absorption capacity. All the walls were isolated using glass wool and covered by aluminium foil to suppress heat losses. The glazing was a single layer of 4 mm thick transparent glass sheet with a surface area of 1,800 mm by 980 mm.

The distance between absorber plate and glazing was 180 mm. By assembling a controlling system, a direct current (DC) motor (020350; Daiichi-Kasei, Ymashina-ku, Japan), a precious photocell and a proper mechanism, the absorber would rotate by changing the solar radiation angle, therefore more energy will be absorbed by the solar panel. By a fan the air passes through the panel and moves to the cabinet via the orifice which is connected to the inlet of the cabinet dryer. The dryer cabinet was made of 10 mm thick wooden plates (MDF) 300 × 400 × 500 mm^3. All sides of the cabinet were insulated by 40 mm glass wool which is covered with aluminium foil. The cabinet consists of five perforated polyethylene trays to load the material to be dried. The size of a single tray was 250 × 350 mm. The trays were divided into two compartments each having two trays. A double layered door packed with rock wool insulation was provided in front of the dryer. The location of the axial fan was on the top of the cabinet, the opposite side from where the hot air entered. The dryer was installed in an environment with the relative air humidity of about 18–24% and the ambient air temperature of about 29–32°C. An automatic temperature controller with an accuracy of ± 0.1°C was used to fix the drying air temperature. The air velocity was controlled by controlling the speed of the fan and the required air velocity was regulated by using an anemometer Yk-2005AM model (Lutron, Taipei, Taiwan). The experiments were carried out at three levels of air velocity, 0.5, 1 and 2 m/s. The solar radiation intensity was measured by using a solarimeter (SL, 200; Meratex, Košice, Slovakia) with an accuracy of ± 1 W/m^2. During the experiments, the temperature of ambient air, drying chamber, absorber plate, dryer outlet, cover glass and inlet air were measured using T type thermocouples. The output data were recorded by a digital thermometer (DL-9601A; Lutron, Taipei, Taiwan) that was connected to a computer using RS232 cable and recorded the temperature at required point every 30 minutes. The ambient relative humidity was measured every hour by a digital hygrometer (HT.3600; Lutron, Taipei, Taiwan), with an accuracy of 0.1%. The samples in the dryer were weighed at 30 min intervals using an electronic digital weighing balance (± 0.05 g).

Theoretical principles. The moisture ratio of tomato slices during the drying experiments was found using Eq. (1):

$$MR = M/M_0 \qquad (1)$$

where:

MR – moisture ratio

M – moisture content at any time (kg water/kg dry mater)

M_0 – initial moisture content (kg water/kg dry mater)

The experimental data were fitted to seven different moisture ratio equations in order to select the most appropriate model for describing drying of tomato slices (Table 1).

The correlation coefficient (R^2) was one of the primary criteria to select the best equation to account for variation in the solar drying curves of the

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dried samples. In addition, reduced chi-square (χ^2) and root mean square error (RMSE) were other criteria to select the best mathematical model. Chi-square and RMSE were calculated using the following equations:

$$\chi^2 = \frac{\sum_{i=1}^{p}((MR_{\text{pre}})_i - (MR_{\text{exp}})_i)^2}{P - z} \quad (2)$$

$$\text{RMSE} = \sqrt{\frac{1}{P}\sum_{i=1}^{p}((MR_{\text{pre}})_i - (MR_{\text{exp}})_i)^2} \quad (3)$$

where:

$MR_{\exp,i}$ – i^{th} experimental moisture ratio

$MR_{\text{pre},i}$ – i^{th} predicted moisture ratio

P – number of observations

z – number of constants (Aghbashloo et al. 2009; Yaldiz et al. 2001)

The relationship between the constants and the drying variables like slice thickness and drying air velocity was also determined for the best suitable model. The effects of temperature and air velocity on equation constants were investigated by the simple linear, polynomial, logarithmic, exponential and power regression models (Guarte 1996).

The drying rate of tomato slices was calculated using Eq. (4) (Kavak Akpinar 2002):

$$DR = (M_{t+dt} - M_t)/dt \quad (4)$$

where:

M_{t+dt} – moisture content at the time $t + dt$ (kg water/kg dry mater)

M_t – moisture content at the time t (kg water/kg dry mater)

t – drying time (min)

Crank using the Fick's second law proposed Eq. (5) for the effective moisture diffusivity for an infinite slab (Crank 1975):

$$MR = \frac{M}{M_o} = \frac{8}{\pi^2}\sum_{n=1}^{\infty}\frac{1}{(2n-1)^2}\exp\left(-\frac{(2n-1)^2\pi^2 Dt}{4L^2}\right) \quad (5)$$

where:

n – number of terms taken into consideration

t – time of drying (s)

D – effective moisture diffusivity (m^2/s)

L – half thickness of the slice (m)

In this study the thickness of the tomato slices was 7 ± 0.1 mm. For longer times, the terms other than the first approach are equal to zero. Neglecting higher terms of the Eq. (5), we have:

$$MR = \frac{8}{\pi^2}\exp\left(-\frac{\pi^2 Dt}{4L^2}\right) \quad (6)$$

The Eq. (6) can be simplified to a straight-line equation as Eq. (7):

$$\text{Ln}(MR) = \text{Ln}\left(\frac{8}{\pi^2}\right) - \left(\frac{\pi^2 Dt}{4L^2}\right) \quad (7)$$

The diffusion coefficient is obtained by plotting experimental drying data in terms of Ln(MR) versus time (s) (Mirzaee et al. 2009; Rasouli et al. 2011). The slope (k_0) was calculated by plotting Ln(MR) versus time according to Eq. (8):

$$k_0 = \pi^2 D/4L^2 \quad (8)$$

RESULTS AND DISCUSSION

Variation of solar radiation during the day is shown in Fig. 2 for the days when experiments are done. The solar radiation increased by time and reached the max. level at around 13 pm. The solar radiation was fluctuating during the days and varied from 150–950 W/m^2. The Fig. 2 also shows the

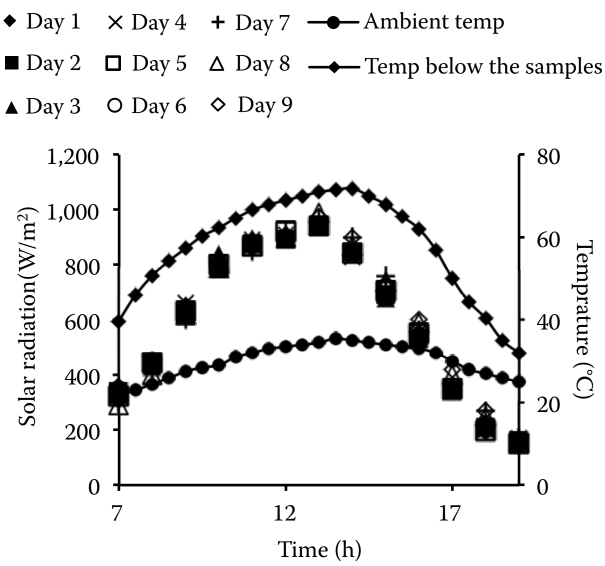

Fig. 2. Variation of solar radiation in 1–9 days, mean ambient temperature and temperature below the samples during the day

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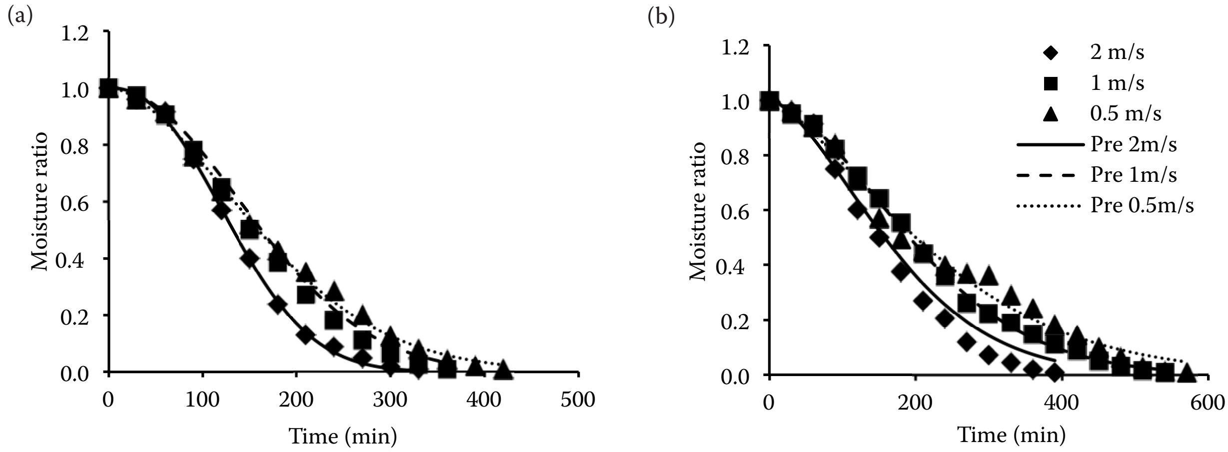

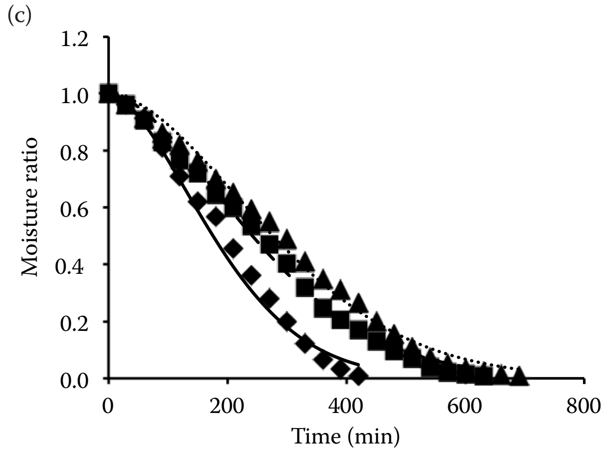

Fig. 3. Drying of tomato slices (3, 5, 7 mm) and fitted curves of the Page model at air velocity of (a) 2 m/s, (b) 1 m/s and (c) 0.5 m/s

variation of ambient temperature and temperature below the samples in the cabinet. Average temperatures were considered for charting (Fig. 2). The max. air temperature at the dryer inlet was 69.1°C at ambient air temperature of 36°C and solar radiance level of 952 W/m^2. The temperature of the collector consequently increased the temperature in the cabinet because of rotation of the collector and more energy absorbed (Fig. 2).

The moisture ratio versus drying time for different levels of tomato slice thickness is shown in Fig. 3 for air velocities of 2, 1 and 0.5 m/s respectively. The total drying time at 0.5 m/s was almost 1.21–1.26 times longer than 2 m/s for the samples with the same slice thickness. The drying time at constant air velocity increased about 1.31–2.1 times when the slice thickness changed from 3 to 7 mm and the effect of slice thickness on drying time was significant. The Page

Table 2. Constants for the Page model and values of correlation coefficient (R^2), RMSE and χ^2

Slices thickness	Air velocity (m/s)	$k \times 10^{-5}$	n	R^2	RMSE	χ^2
	0.5	10.80	1.729	0.9968	0.0202	0.000409
3 mm	1.0	2.84	2.011	0.9997	0.0067	0.000045
	2.0	1.06	2.270	0.9988	0.0133	0.000178
	0.5	39.20	1.412	0.9869	0.0376	0.001068
5 mm	1.0	10.10	1.682	0.9986	0.0129	0.000148
	2.0	22.00	1.593	0.9965	0.0208	0.000422
	0.5	3.57	1.756	0.9927	0.0291	0.000561
7 mm	1.0	6.45	1.691	0.9944	0.0255	0.000465
	2.0	10.80	1.696	0.9951	0.0241	0.000449

RMSE – root mean square error; k, n – constants of the Page model; χ^2 – chi-square

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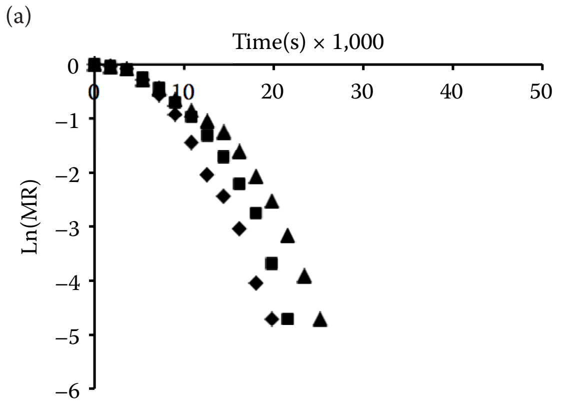

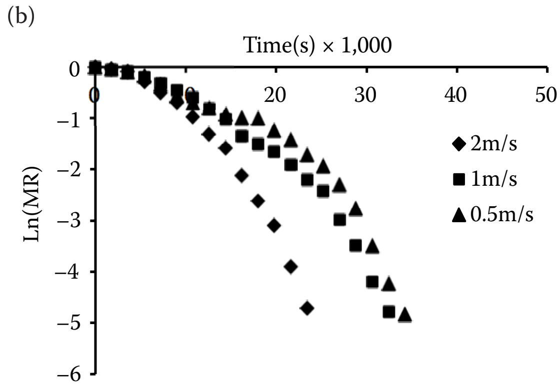

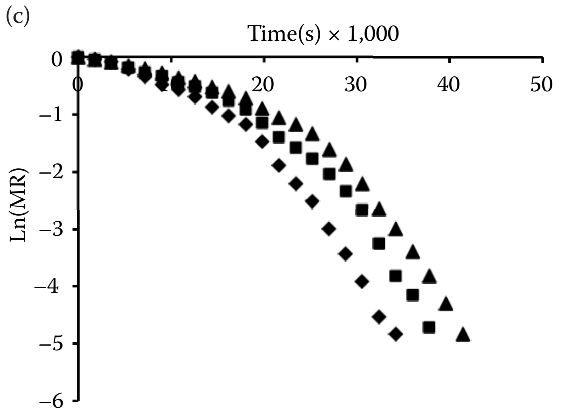

Fig. 4. Ln(*MR*) versus time for thin-layer solar drying of tomato slices with thickness of (a) 3 mm, (b) 5 mm and (c) 7 mm

model was the best mathematical model for describing the drying kinetics of tomato slices. The drying process took place in the falling rate period. Drying rate decreased continuously with moisture content or drying time. These results are in agreement with the observations of earlier researchers (Diamante, Munro 1993; Yaldiz et al. 2001, Aghbashloo et al. 2009). During the drying process, internal mass transfer occurs with liquid diffusion, vapour diffusion and capillary forces in the interior region of the product and water evaporates as it reaches the surface (Aghbashloo et al. 2009). Moisture removal has capillarity movement when the water content of tomato slices is high. Then, water removal occurs through capillary forces to the surface of the fruit. Free moisture evaporates from the fruit surface as the drying process progresses and so shrinkage occurs. Pores and free spaces lose and thus the rates

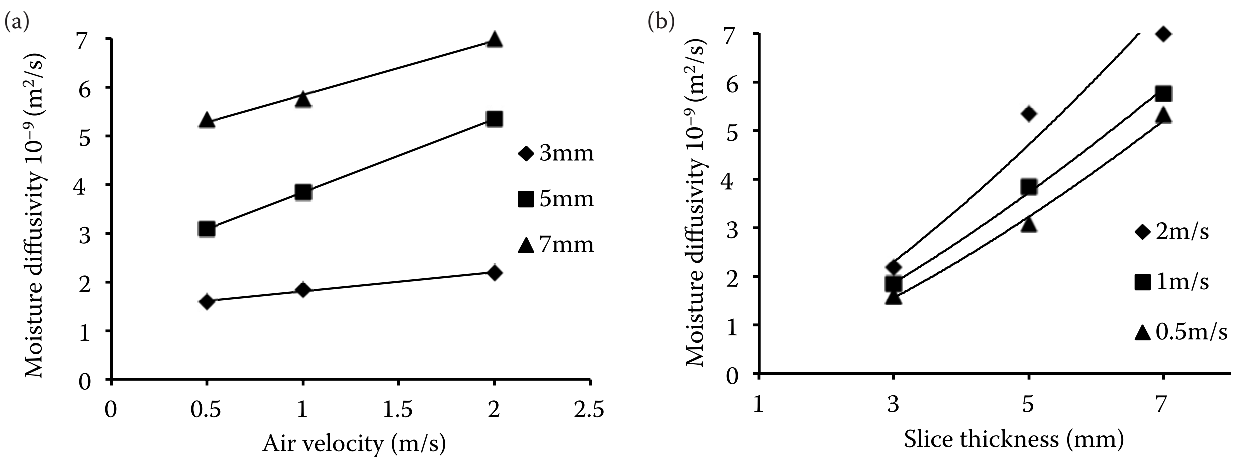

Fig 5. Moisture diffusivity (D) of tomato slices at (a) different air velocity for different levels of slice thickness and (b) different thicknesses at three levels of air velocity

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Table 3. Fitted equations for moisture diffusivity (D) for each slice thickness

Slice thickness (mm) ($l = 2L$)	Equation × 10^{-9}	R^2
3	$D = 4.85e^{0.181v}$	0.9966
5	$D = 2.62e^{0.360v}$	0.9847
7	$D = 1.38e^{0.279v}$	0.9994

l – slice thickness (m); L – half slice thickness; R^2 – correlation coefficient; e – neperian number; ν – air velocity (m/s)

of water removal and heat transfer decrease significantly.

Multiple regression analysis was performed in the MATLAB computer programme (Version 2013) environment. The best model describing the thin-layer drying kinetics was selected based on the highest R^2 average values and the lowest χ^2 and *RMSE* average values. The Page model showed the best fit to the experimental data and the best agreement for thin-layer drying curves. Table 2 shows the fitting results of statistical parameters (R, χ^2 and *RMSE*) and constant values k and n for the Page model using the experimental data values.

The constant values of Page model for different conditions were regressed against air condition using multiple regressions. Regression analysis for these parameters yielded the following relationships at the significance level of 1%:

$$k = (-3.90v^2 + 41.36v - 0.17(2L)^v + 82.12L^2 - 81.56L - 71.36) \times 10^{-5}; \quad R^2 = 0.9254 \tag{9}$$

$$n = 0.07v^2 - 0.91v + 0.21vL - 1.34L + 4.3; \quad R^2 = 0.9543 \tag{10}$$

where:

k, n – constant of Page model
ν – velocity of drying (m/s)
L – half thickness of the slice (m)

The Ln(MR) versus time (s) for different level of air velocity is shown in Fig. 4 for slice thicknesses of 3, 5 and 7 mm, respectively. All the figures show that the drying of tomato occurred in falling rate period, in other words the liquid diffusion is by the dry wing force controlling the drying process, and therefore the curves are straight lines. Plotted curves show that the increase in velocity increases the slop of straight line, in other words the effective moisture diffusivity increases, whereas the effect of thickness on the slope is adverse.

Table 4. Fitted equations for moisture diffusivity (D) for each air velocity

Air velocity (m/s)	Equation × 10^{-9}	R^2
0.5	$D = 1.14(2L) - 0.791$	0.9744
1	$D = 0.97(2L) - 1.077$	0.9998
2	$D = 0.93(2L) - 1.350$	0.9871

for abbreviations see Table 3

The effective moisture diffusivity was calculated using Eq. (8). The results are plotted in Fig. 5. The Fig. 5a shows that the moisture diffusivity of tomato slices increased by increasing air velocity for each slice thickness. Similar results are reported by the other researchers (Aghbashloo et al. 2008; Mirzaee et al. 2009; Rasouli et al. 2011). The linear equations were fitted to estimate the values of moisture diffusivity. The fitted equations and related correlation coefficients (R^2) are reported in Table 3.

Fig. 5b shows that the max. value of the moisture diffusivity was 6.98 × 10^{-9} m^2/s at 2 m/s air velocity and 7 mm slice thickness while the min. value of the moisture diffusivity was 1.58 ×10^{-9} m^2/s at 0.5 m/s air velocity and 3 mm slice thickness. Generally, the value of moisture diffusion (D) changes in the range of 10^{-11}–10^{-9} m^2/s for food materials (Babalis, Belessiotis 2004; Aghbashlo et al. 2008; Rasouli

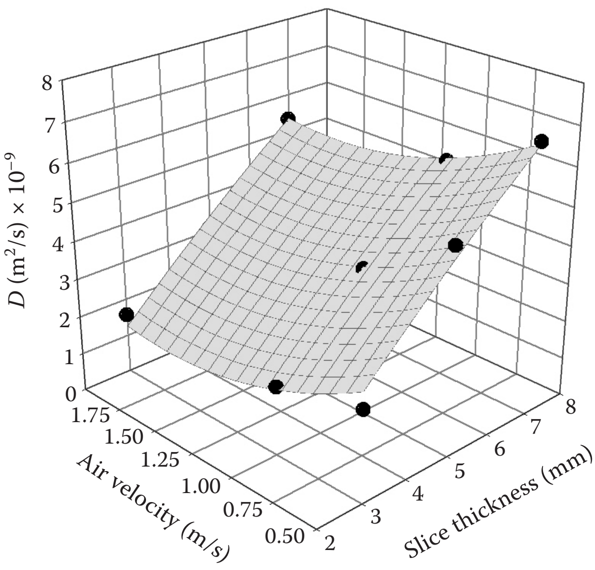

Fig 6. Effect of slice thickness and air velocity on moisture diffusivity (D) of tomato slices

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et al. 2011). Table 4 contains linear equation and related correlation coefficient (R^2), for different air velocity. In all levels of air velocity, the value of D increased linearly by increasing the slice thickness.

In Fig. 6 the value of the moisture diffusivity is plotted versus slice thickness of tomato and air velocity by using multiple regression analyses. The fitted parabolic equation and corresponding R^2 are also reported (Eq. 11).

$$D = (0.833 + 2.632L - 3.97v - 0.1172L^2 + 1.71v^2) \times 10^{-9};\ R^2 = 0.9826 \quad (11)$$

k,n – constants of Page model
v – velocity of drying (m/s)
L – half thickness of the slice (m)

CONCLUSION

The Page model showed the best fit to the experimental data with the highest average values of R^2 and the lowest average values of χ^2 and *RMSE*. The effective moisture diffusivity for tomato slices varied from 1.58×10^{-9} to 6.98×10^{-9} m^2/s. The effective moisture diffusivity increased with increasing air velocity and sample thickness. More moisture absorbed at higher air velocity (2 m/s), consequently the moisture gradient of the sample with ambient temperature increases and causes an increase in moisture diffusivity. In thicker slices (7 mm), the hot air hardly passes through the samples and decreases the moisture gradient and moisture diffusivity. The best method to reduce the drying time is to decrease the vapour pressure around the sample in the dryer and take the expelled moisture away from the product surface; this is accomplished with selection of proper thickness and hot-air velocity around the surface of tomato slices.

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