Mathematical modeling of thin layer solar drying of tomato slices

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Abstract: Thin layer drying of tomato slices was evaluated using a laboratory solar dryer. The experimental moisture ratios of the samples were fitted to nine drying models. The drying experiments were carried out on tomato slices with thicknesses of 3, 5 and 7 mm at the air velocities of 0.5 and 1 m s^{-1}. The effect of drying thickness and air velocity on the drying time was evaluated. The mathematical models were tested with the drying behavior of tomato slices in the laboratory solar dryer. The coefficients of the models were determined by multiple regression method in three spaces (solar dryer, shadow, open sun drying) to find out the most suitable moisture ratio model. The Page model was found as the best model based on statistical parameters of R^2, *RMSE* and χ^2. The Page model is applicable to predict moisture content of tomato slices during solar drying of tomato slices.

Keywords: mathematical modeling; moisture ratio, tomato, thin layer drying, solar drying

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1 Introduction

Tomato (*Lycopersicon esculentum* Mill) is the world's most commercially produced vegetable (Gaware et al., 2010). USA, Turkey, Italy, Spain and Iran are the leading tomato growing countries (Jumah et al., 2004). The global tomato production reached to 153 million metric tons in 2009 (FAO, 2011). It is a rich source of minerals, vitamins, organic acid, and dietary fiber (Doymaz, 2007). Tomato is normally used in the fresh state and in some processes as juice, puree, sauces and canned varieties (Akanbi et al., 2006). Many experiments were done to process tomatoes by the foam-mat technique or by spray drying. Tomatoes cut into pieces were sun dried and dried by convection. Trials to dry whole tomatoes were also undertaken (Lewicki et al., 2002). Many researches have been conducted on the mathematical modeling and experimental studies on thin layer solar drying processes of various vegetables and fruits, such as green bean (Doymaz, 2005), pistachio (Midilli and Kucuk, 2003), red pepper (Akpinar et al., 2003), mint leaves (Akpinar, 2010), tarragon (Arabhosseini et al. 2008), potato (Aghbashlo et al. 2009), chilli pepper (Tunde-Akintunde, 2011), carrot (Berruti et al., 2009) and citrus aurantium leaves (Mohamed et al., 2005). Drying of agricultural products has always been of great importance for the preservation of food by human beings. Open sun drying is a well-known food preservation technique that reduces the moisture content of agricultural products, and thereby prevents deterioration within a period of time regarded as the safe storage period.

However, the quality of food can be seriously degraded if life is unprotected from rain, storm, windborne dirt, dust, and infestation by insects, rodents and other animals, so sometimes production becomes inedible. The drying process can be conducted by using

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several solar drying methods (Sacilik et al., 2006). Solar dryers can cost effectively because relatively unskilled village artisans can construct, operate and maintain the dryers at minimum cost and locally available materials can be used for the construction (Mumba, 1995). Ekechukwu and Norton (1999), in reviewing the various designs of solar-energy drying systems, classified them with respect to their operating temperature ranges, heat supply modes and sources, operational modes and structural modes as well. Natural circulation and forced-convection solar dryers are the two main groups that were identified (Vlachos et al., 2002). The drying characteristics of tomato and their mathematical drying model are still being developed. Thin layer drying equations are used to estimate drying time of several products and also to generalize drying curves. The main objectives of this study are: *a*) determination of the effect of different drying thicknesses, air flow rates and space on the drying kinetics of tomato; *b*) evaluation of the fitting of the drying experimental data to nine mathematical models; and *c*) finding the effective diffusivities in the convective drying process of tomato.

2 Materials and methods

2.1 Sample preparation and drying conditions

In this study, tomato produced in suberb of Tehran (51°19′E, 35°19′N), were used for experiments. Tomato samples were obtained from a local supplier and stored at. The initial moisture content of the samples was determined by oven drying method. About 100 g of sample were dried in an oven at 105℃ for 4 h (Doymaz 2007). At least three replicates of experiments were performed. The initial moisture content of tomato samples was 93% (w.b.).

After two hours stabilization at the ambient air temperature the samples were weighed and cut into cylindrical slices with different thickness (Sacilik et al., 2006). An amount of 300 g of ripped tomato were dried in each experiment. Samples were placed on the dryer tray in a single layer. The experiments were carried out at air velocities of 0.5 and 1 (m s^{-1}), thicknesses of 3, 5 and 7 mm and three drying methods (solar dryer, shadow, and open sun drying). During the drying process, experiments continued until the mass change between two weightings was less than 0.05 g. All the experiments were conducted in triplicate. The temperature and relative humidity of the drying air were recorded every five minutes during the drying process.

2.2 Drying procedures

Drying curves were drawn for the samples taken from the three sample trays in the dryer. The sample from open sun drying and shadow were also included, for comparison. Drying experiments were carried out using a laboratory solar dryer. Briefly, a schematic diagram of the experimental system is shown in Figure 1. The dryer consists of a fan, drying chamber (500 × 400 × 300 mm^3), collector, air channel and tray sample. The drying chambers and air channel were isolated with rock wool and wood, to decrease the undesirable effects of temperature and humidity of air on drying experiment. The drying tray isolated using the glassy cylinder and hot air exhaust from upper part of glassy cylinder. Drying air temperature in three spaces (solar dryer, shadow and open sun drying) was controlled every five minutes using an automatic temperature controller with an accuracy of ±0.1℃ and the air speed fixed using anemometer PROVA AVM-07 (TES, Co, Taipei, Taiwan) with an accuracy of ±0.1 (m s^{-1}). Hot air orientation on samples was vertical. The dried samples in three spaces (solar dryer, shadow and open sun drying) were weighed every 5 min by using a digital balance with an accuracy of 0.01 g. The temperature of the air chamber was recorded by a temperature controller with ±1℃. The relative humidity of the ambient air in three spaces (solar dryer, shadow and open sun drying) every five minutes was tested using a digital probe Bioblock thermohygrometer (precision: ±3% for RH≤80% and ±4% for RH>80%). Before each experiment, the dryer was started for one hour in order to achieve desirable steady state condition.

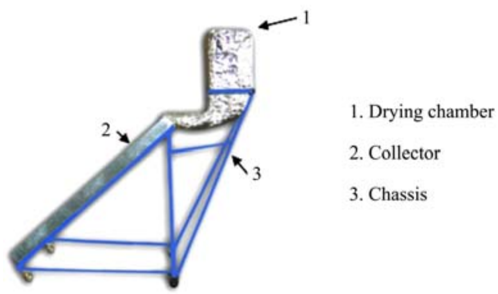

Figure 1 Schematic diagram of laboratory solar dryer

2.3 Mathematical modeling of drying curves

The moisture content was expressed in percentage wet basis (%, w.b) and then converted to kilogram water per kilogram dry matter. The drying curves were fitted to nine different moisture ratio models to select a suitable model for describing the drying process of tomato slices (Table 1).

Table 1 Mathematical models applied to the drying curves

Model name	Equation[1]	References
Newton	$MR=\exp(-kt)$	(Ayensu, 1997)
Page	$MR=\exp(-kt^n)$	(Page, 1949; Doymaz, 2004)
Henderson and Pabis	$MR=a\exp(-kt)$	(Rahman et al., 1998)
Logarithmic	$MR=a\exp(-kt)+c$	(Lahsasni et al., 2004)
Two-term	$MR=a\exp(-kt)+c\exp(-gt)$	(Dandamrongrak et al., 2002)
Modified Page	$MR=\exp[(-kt)^n]$	(Hayaloglu et al., 2007)
Two-term exponential	$MR = a\exp(-kt) + (1-a) c\exp(-kat)$	(Hayaloglu et al., 2007)
Wang and Singh	$MR=1+at+ct^2$	(Hayaloglu et al., 2007)
Midilli et al.	$MR=a\exp(-kt)+ct$	(Hayaloglu et al., 2007)

Note: [1]a, c, g, k and n are drying constants.

Moisture ratio of the samples during drying was expressed by the Equation (1):

$$MR = \frac{(M_t - M_e)}{(M_0 - M_e)} \tag{1}$$

However, the moisture ratio (MR) was simplified by modifying the Equation (1) to ($\frac{M_t}{M_0}$) instead of the $\frac{(M_t - M_e)}{(M_0 - M_e)}$), (Shanmugam and Natarajan, 2006). The reduced chi-square (χ^2) and root mean square error ($RMSE$) were used as the primary criterion to select the best equation to account for variation in the drying curves of the dried samples (Hossain and Bala, 2002). The lower the value of the χ^2 , the better the goodness of the fit. The $RMSE$ gives the deviation between the predicted and experimental values and it is required to reach zero. The statistical values were calculated by Equations (2) and (3):

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

$$RMSE = \left[\frac{1}{N}\sum_{i=1}^{n}(MR_{\exp,i} - MR_{pre,i})\right]^{\frac{1}{2}} \tag{3}$$

2.4 Calculation of effective diffusivities

It has been accepted that the drying characteristics of biological products in falling rate period can be described by using Fick's diffusion equation. The solution of Fick's law for a slab was according to Equation (4) (Okos et al., 1992).

$$\frac{M_t - M_e}{M_0 - M_e} = \frac{8}{\pi^2}\sum_{n=1}^{\infty}\frac{1}{(2n+1)^2}\exp\left(-(2n+1)^2\pi^2\frac{D_{eff}t}{4H^2}\right) \tag{4}$$

For long drying period, Equation (4) can be further simplified to only the first term of series (Tutuncu and Labuza, 1996). Thus, Equation (4) is written in a logarithmic form according to Equation (5):

$$\ln\left(\frac{M_t - M_e}{M_0 - M_e}\right) = \ln\left(\frac{8}{\pi^2}\right) - \left(\frac{\pi^2 D_{eff}t}{4H^2}\right) \tag{5}$$

Diffusivities are typically determined by plotting experimental drying data in terms of ln(MR) versus drying time t in Equation (5), because the plot gives a straight line with a slope according to Equation (6) (Babalis and Belessiotis, 2004; Doymaz, 2007).

$$Slope = \frac{\pi^2 D_{eff}}{4H^2} \tag{6}$$

3 Results and discussion

During the days of experiments, the variations of the ambient air temperature and solar radiation are shown in Figure 2 for a typical day of September 2010 in Tehran. The experiments run in sunny days from 09:00 to 19:00.

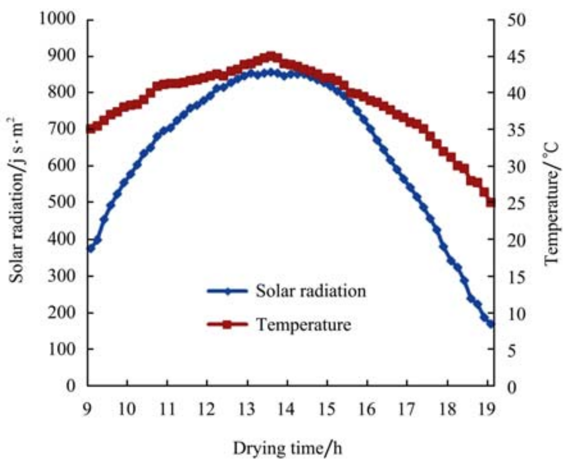

Figure 2 Variations of the ambient air temperature and solar radiation during drying

During the drying experiments, the daily mean values of ambient air temperature and solar radiation ranged from 25℃ to 45℃, 168.3-855 W m^{-2}, respectively. The ambient air temperature and solar radiation reached the highest figures between 12:20 h and 14:20 h. Results from the solar dryer, open sun drying and shadow are presented in Figure 3.

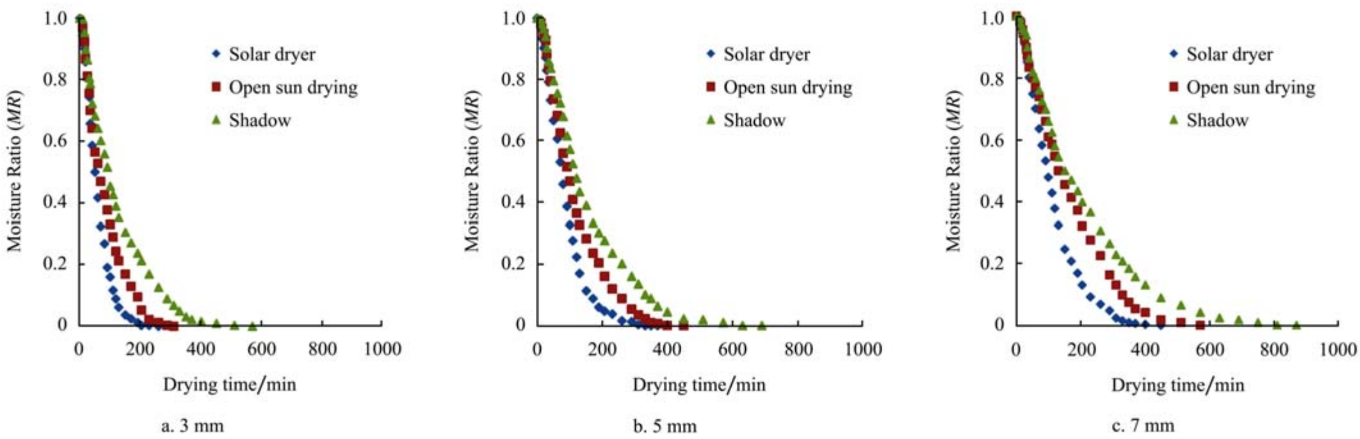

Figure 3 Experimental data of moisture ratio of tomato slices at different thicknesses in open sun drying, shadow and solar drying with air velocity

The experimental moisture content data were determined on the dry basis and used for modeling. The moisture content data at each time of drying process, obtained at different drying thicknesses, air velocity conditions and spaces, were converted to the moisture ratio values and fitted versus the drying time. Then the selected thin layer drying models were compared according to the statistical results of R^2, *RMSE* and χ^2 (Tables 2 to 4).

Table 2 Statistical results of the nine selected thin layer drying models at different drying conditions with 3 mm thickness

Models	R^2	*RMSE*	χ^2	*a*	*c*	*g*	*k*	*n*
Air velocity, 1 m s^{-1}								
Newton	0.9870	0.0449	0.0181	-	-	-	0.0167	-
Henderson and Pabis	0.9900	0.0401	0.0129	1.054	-	-	0.0179	-
Page	0.9995	0.0089	0.0006	-	-	-	0.0048	1.314
Logarithmic	0.9910	0.0370	0.0096	1.088	0.042	-	0.0166	-
Two-term	0.9991	0.0103	0.0006	-4.172	5.195	0.0302	0.3571	-
Modified Page	0.9904	0.0091	0.0007	-	-	-	0.0049	1.402
Two-term exponential	0.9900	0.0391	0.0019	4.547	-	-	0.3809	-
Wang and Singh	0.9836	0.0143	0.0179	2.410	0.152	-	-	-
Midilli et al.	0.9899	0.0426	0.0007	2.025	0.054	-	0.0075	1.759
Air velocity, 0.5 m s^{-1}								
Newton	0.9770	0.0592	0.0315	-	-	-	0.0127	-
Henderson and Pabis	0.9840	0.0520	0.0216	1.068	-	-	0.0139	-
Page	0.9990	0.0123	0.0012	-	-	-	0.0023	1.410
Logarithmic	0.9910	0.0419	0.0123	1.145	0.094	-	0.0115	-
Two-term	0.9980	0.0176	0.0019	-11.60	12.54	0.0264	0.0279	-
Modified Page	0.9914	0.0017	0.0007	-	-	-	0.0033	1.512
Two-term exponential	0.9930	0.0280	0.0019	11.20	-	-	0.0314	-
Wang and Singh	0.9801	0.0152	0.0179	3.001	0.171	-	-	-
Midilli et al.	0.9829	0.0305	0.0027	2.173	0.051	-	0.0073	1.801

Table 3 Statistical results of the nine selected thin layer drying models at different drying conditions with 5 mm thickness

Models	R^2	*RMSE*	χ^2	*a*	*c*	*g*	*k*	*n*
Air velocity, 1 m s^{-1}								
Newton	0.9872	0.0445	0.0243	-	-	-	0.0100	-
Henderson and Pabis	0.9910	0.0394	0.0171	1.054	-	-	0.0108	-
Page	0.9999	0.0135	0.0020	-	-	-	0.0026	1.304
Logarithmic	0.9994	0.0031	0.0010	1.093	-0.051	-	0.0096	-
Two-term	0.9991	0.0018	0.0140	-5.500	6.494	0.0186	0.0212	-
Modified Page	0.9991	0.0191	0.0032	-	-	-	0.0032	1.112
Two-term exponential	0.9911	0.0039	0.0119	4.219	-	-	0.0311	-
Wang and Singh	0.9899	0.0241	0.0151	2.201	0.242	-	-	-
Midilli et al.	0.9889	0.0435	0.0137	2.321	0.049	-	0.0174	1.852
Air velocity, 0.5 m s^{-1}								
Newton	0.9788	0.0594	0.0424	-	-	-	0.0084	-
Henderson and Pabis	0.9870	0.0486	0.0260	1.077	-	-	0.0092	-
Page	0.9995	0.0099	0.0011	-	-	-	0.0013	1.399
Logarithmic	0.9936	0.0357	0.0127	1.151	-0.094	-	0.0075	-
Two-term	0.9992	0.0135	0.0017	-6.430	7.430	0.0165	0.0187	-
Modified Page	0.9991	0.0028	0.0019	-	-	-	0.0039	1.714
Two-term exponential	0.9970	0.0181	0.0019	10.98	-	-	0.0131	-
Wang and Singh	0.9882	0.0162	0.0218	3.201	0.169	-	-	-
Midilli et al.	0.9899	0.0426	0.0317	2.071	0.062	-	0.0472	1.512

Table 4 Statistical results of the nine selected thin layer drying models at different drying conditions with 7 mm thickness

Models	R^2	*RMSE*	χ^2	*a*	*c*	*g*	*k*	*n*
Air velocity, 1 m s^{-1}								
Newton	0.9857	0.0481	0.0300	-	-	-	0.0076	-
Henderson and Pabis	0.9900	0.0401	0.0193	1.060	-	-	0.0082	-
Page	0.9991	0.0126	0.0019	-	-	-	0.0019	1.289
Logarithmic	0.9972	0.0231	0.0059	1.134	-0.096	-	0.0063	-
Two-term	0.9989	0.0150	0.0023	-6.890	7.899	0.0137	0.0151	-
Modified Page	0.9991	0.0190	0.0031	-	-	-	0.0040	1.214
Two-term exponential	0.9981	0.0139	0.0031	4.249	-	-	0.0400	-
Wang and Singh	0.9889	0.0250	0.0250	3.001	0.342	-	-	-
Midilli et al.	0.9901	0.0426	0.0233	2.331	0.054	-	0.0272	1.383
Air velocity, 0.5 m s^{-1}								
Newton	0.9782	0.0464	0.0597	-	-	-	0.0068	-
Henderson and Pabis	0.9849	0.0517	0.0321	1.067	-	-	0.0074	-
Page	0.9974	0.0215	0.0055	-	-	-	0.0012	1.349
Logarithmic	0.9963	0.0269	0.0080	1.199	-0.163	-	0.0052	-
Two-term	0.9992	0.0135	0.0017	-6.430	7.433	0.0165	0.0187	-
Modified Page	0.9969	0.0228	0.0019	-	-	-	0.0044	1.624
Two-term exponential	0.9911	0.0201	0.0060	11.01	-	-	0.0171	-
Wang and Singh	0.9892	0.0182	0.0223	3.302	0.157	-	-	-
Midilli et al.	0.9888	0.0445	0.0400	2.172	0.052	-	0.0461	1.313

The results indicated that, the lowest values of *RMSE* and χ^2 were obtained from Page model according to Equation (7):

$$MR = \exp(-kt^n) \tag{7}$$

The Page model represented the experimental values of moisture ratio satisfactorily. When the Page model was analyzed, individual constants were obtained according to the different drying thicknesses, air velocities and space (Table 5).

Table 5 Statistical results of Page model at different drying conditions

Thickness/mm	Air v	k	n	R^2	$RMSE$	χ^2
3	1.0	0.0048	1.314	0.9995	0.0089	0.0006
	0.5	0.0023	1.410	0.9990	0.0123	0.0012
5	1.0	0.0026	1.304	0.9999	0.0135	0.0020
	0.5	0.0013	1.399	0.9995	0.0099	0.0011
7	1.0	0.0019	1.289	0.9991	0.0126	0.0019
	0.5	0.0012	1.349	0.9974	0.0215	0.0055

To take into account the effect of the drying variables on the Page model constants of k (min^{-1}) and n, the values of these parameters were regressed against those of the drying thicknesses, air velocities and spaces using multiple regression analysis. The multiple combinations of different parameters, that resulted in the highest R^2, were finally included in the Page model according to Equation (8).

$$MR(k,n)=\frac{M_t}{M_0}\exp(-kt^n) \tag{8}$$

The moisture content of tomato slices during drying process could be estimated using these expressions with more accuracy. The model was in good agreement with the experimental results at all drying conditions (Figures 4 to 5). This means that, the generalized model is valid at drying thicknesses of 3, 5 and 7 mm and air velocities of 0.5 and 1 m s^{-1}.

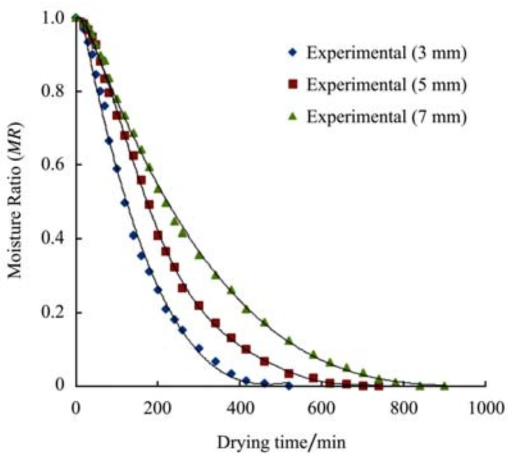

Figure 4 Experimental data of moisture ratio of tomato slices at different thicknesses with air velocity of 1 and the fitted curves to Page model

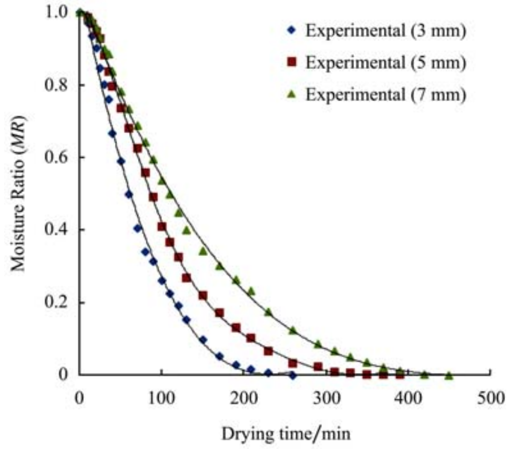

Figure 5 Experimental and of moisture ratio of tomato slices at different thicknesses with air velocity of 0.5 and the fitted curves to Page model

By comparing the experimental and predicted moisture ratio values at any particular drying condition for validation of the established model, these values laid around the straight line (Figure 6).

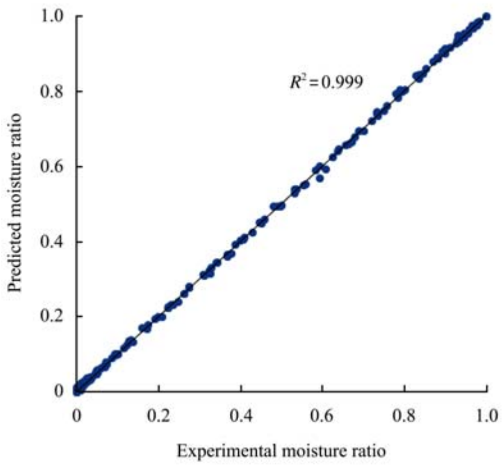

Figure 6 Experimental and predicted moisture ratio at different drying conditions

The values of effective diffusivity for laboratory solar dryer, open sun drying and shadow process were found to be 5.248-13.66×10^{-9}, 3.42-8.69×10^{-9} and 2.05-6.21×10^{-9} m^2 s^{-1} respectively (Figures 7 to 9). The value of D_{eff} for the laboratory solar dryer was slightly higher than that for the open sun drying and shadow. The D_{eff} values of tomato slices in this research are similar to those estimated by other researchers: for instance 3.72-12.27×10^{-9} m^2 s^{-1} for tomato slices dried from 45℃ to 75℃ (Akanbi et al. 2006); and 2.3-9.1×10^{-9} m^2 s^{-1} for tomato slices dried at 60℃ to 110℃ (Giovanelli et al. 2002).

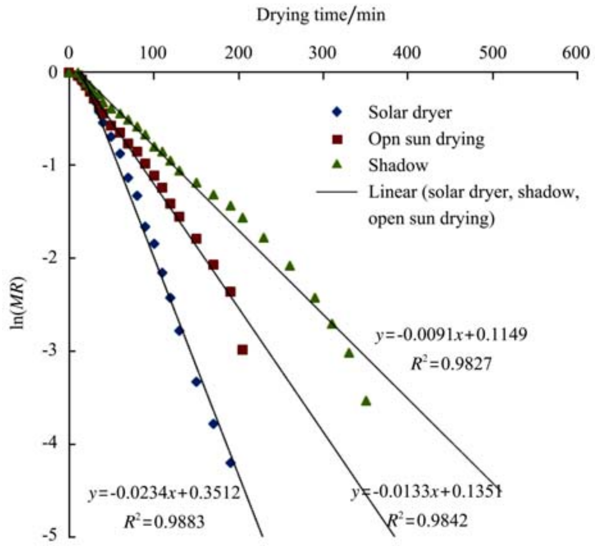

Figure 7 Effect of temperature on moisture diffusivity in tomato slice with thickness 3 mm

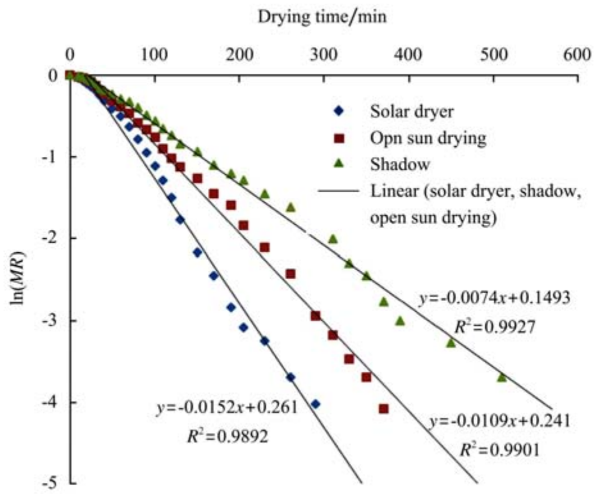

Figure 8 Effect of temperature on moisture diffusivity in tomato slice with thickness of 5 mm

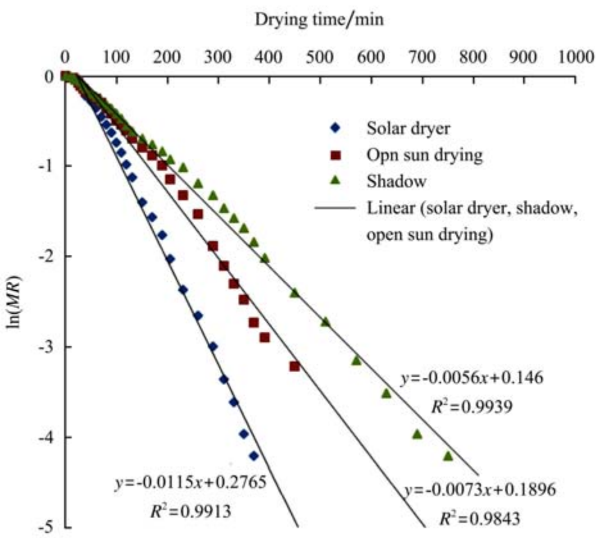

Figure 9 Effect of temperature on moisture diffusivity in tomato slice with thickness of 7 mm

4 Conclusions

In order to explain the drying behavior of tomato slices, nine different thin layer drying model were fitted to experimental data and compared according to their R^2, *RMSE* and χ^2. According to the results of thin layer drying of tomatoes, the Page model was found as the best model which could be used to predict the moisture content of the product during drying process with high ability between drying thicknesses and air velocity.

Nomenclature

m	number of drying constants
MR	moisture ratio (dimensionless)
MR_{exp}	experimental moisture ratio
MR_{pre}	predicted moisture ratio
M_t	moisture content at time t ($kg_{water}\ kg_{dry\ mater}^{-1}$)
M_e	equilibrium moisture content ($kg_{water}\ kg_{dry\ mater}^{-1}$)
M_0	initial moisture content ($kg_{water}\ kg_{dry\ mater}^{-1}$)
N	number of observation
n, k	coefficients
R^2	correlation coefficient
$RMSE$	root mean square error
T	temperature (℃)
T_{abs}	absolute temperature (K)
t	time (min)
χ^2	chi-square
v	air velocity (m s^{-1})
D_{eff}	effective diffusivity ($m^2\ s^{-1}$)
H	half thickness of slab (m)

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