Evaluation and Selection of Thin-layer Models for Drying Kinetics of Apricot (cv.*NASIRY*)

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ABSTRACT

This paper presents the thin layer drying behavior of apricot (cv.*NASIRY*) at the air temperatures of 40, 50, 60, 70ºC and air velocity of 1 and 2 m/s. In order to select a suitable form of the drying curve, 12 different thin layer drying models were fitted to experimental data. Fick's second law was used as a major equation to calculate the moisture diffusivity with some simplification. The high values of coefficient of determination and the low values of reduced chi-square and root mean square error indicated that the *Logarithmic* and *Midilli et al.* models could satisfactorily describe the drying curve of apricot for drying air velocity of 1 and 2 m/s, respectively. According to the results the calculated value of effective moisture diffusivity varied from 1.78-5.11×10^{-10} m^2/s and the value of activation energy varied from a minimum of 24.01 to a maximum of 25 kJ/mol.

Key word: Apricot; Thin layer drying; Effective moisture diffusivity; Activation energy

1. INTRODUCTION

Drying is one of the oldest methods of food preservation (Doymaz, 2007). Longer shelf-life, product diversity and substantial weight and volume reduction are the reasons for popularity of dried fruits and vegetables. In most regions in Iran, sun-drying is used for drying apricot fruits. We have some restricted parameters in using of sun drying such as short day and low temperature, it is necessary that the traditional techniques be replaced with industrial drying methods (Ertekin and Yaldiz, 2004). Using industrial drying methods, the dried apricot fruit retains its natural color, puffy body and does not undergo any undesirable changes in chemical properties and quality over a relatively long time. Simulation models of the drying process are used for developing new designs, improving existing drying systems, predicting the airflow over the product, or even for the control of the process (Aghbashlo et al., 2008). There are many mathematical models in the literature (Table1) that have been proven to be useful in design and analysis of heat transfer processes during drying. All parameters used in simulation models are directly related to the drying conditions (Babalis and Belessiotis, 2004). The drying kinetics is greatly affected by air velocity, air temperature, material thickness, and etc (Akpinar and Bicer, 2005; Erenturk and Erenturk, 2007). Although much information has been reported about modeling of thin-layer drying for apricot fruits (Togrul and Pehlivan, 2002; Bozkir, 2006), there is no information about modeling of thin-layer drying of apricot in Iran. Therefore, the objectives of this work were: (i) to selection the most appropriate thin layer drying model, (ii) to determine the moisture diffusivity and activation energy of Iranian apricot (cv. *Nasiry*).

2. MATERIALS AND METHODS

2.1 Drying Experiments

A laboratory scale hot-air dryer was used for this study (Figure1). It consists of fan, heaters, straightened, monitor, microcontroller, digital balance, tray, and sensors for temperature and humidity (Yadollahinia, 2006).

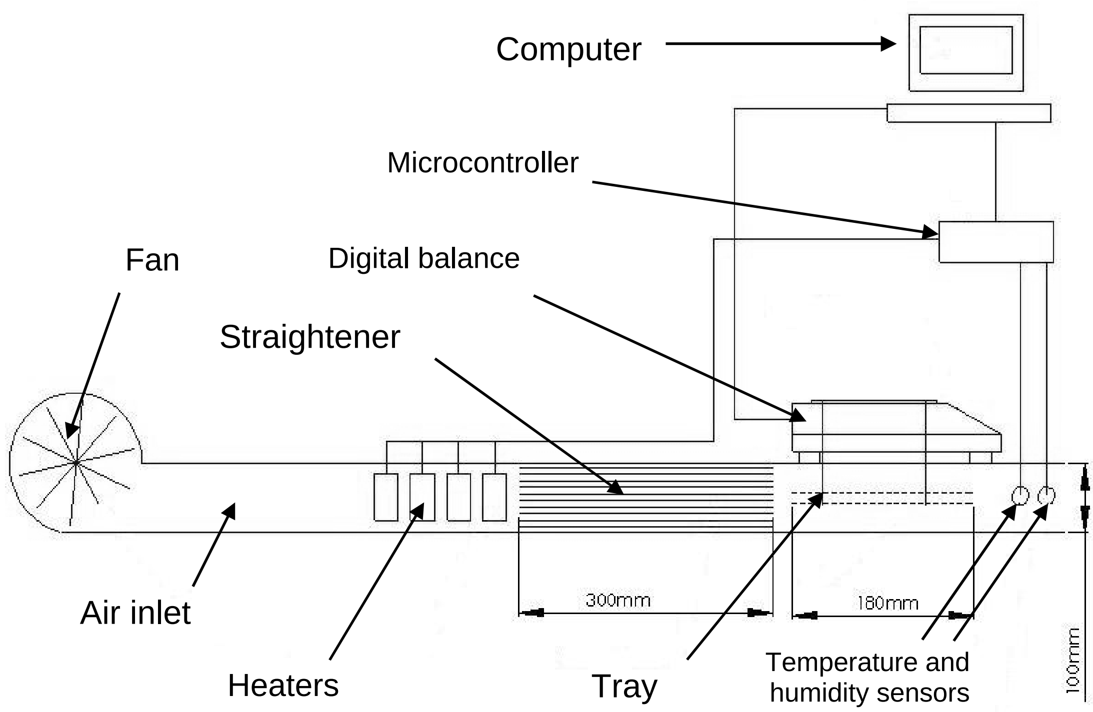

Figure1. Schematic of thin-layer drying equipment.

Fresh apricots (cv. *Nasiry*) were obtained from orchard located in Shahroud, Iran (170 km from Semnan Province) in July 2008. Before the drying process commenced, samples were washed in clean running tap water. They were then sorted based on uniformity of ripeness, after which their cores were separated. Two hundred grams of apricot were placed as half on the tray in the dryer to dry. The drying experiment was carried out at air temperature of 40, 50, 60, 70ºC and air velocity of 1 and 2 m/s. The samples were weighted using a digital balance with 0.01 g sensitivity (GF3000, A&D, Japan) every 5 s during the process. Moisture contents of apricots were determined at 78ºC for 48 h with oven method (AOAC, 1984).

2.2 Mathematical modeling of drying curves

The moisture ratio (*MR*) of apricot during drying experiments was calculated using the following Equation:

$$MR = (M - M_e)/(M_o - M_e) \tag{1}$$

where M, M_o, and M_e are moisture content at any drying time, initial and equilibrium moisture content (kg water/kg dry matter), respectively. The values of M_e are relatively small compared to those of M or M_o, hence the error involved in the simplification is negligible (Aghbashlo et al., 2008), hence moisture ratio was calculated as:

$$MR = M / M_o \tag{2}$$

For drying model selection, drying curves were fitted to 12 well known thin layer drying models which are given in Table 1. The goodness of fit was determined using three parameters: coefficient of determination (R^2), reduced chi-square (χ^2) and root mean square error (*RMSE*) using Equations (3-5), respectively (Togrul and Pehlivan, 2003). The statistical analyses were carried out using SPSS 15 software.

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

$$\chi^2 = \frac{\sum_{i=1}^{N} \left(MR_{\exp,i} - MR_{\text{pre},i} \right)^2}{N - m} \tag{4}$$

$$RMSE = \left(\frac{1}{N} \sum_{i=1}^{N} \left[MR_{\mathrm{pre},i} - MR_{\mathrm{exp},i} \right]^2 \right)^{\frac{1}{2}} \qquad (5)$$

In the above Equations $MR_{pre,i}$ is the ith predicted moisture ratio, $MR_{exp,i}$ is the ith experimental moisture ratio, N is number of observations and m is number of constants. The higher values for R^2 and lower values for χ^2 and $RMSE$ are chosen as the criteria for goodness of fit (Demir *et al*., 2004).

Table1.Thin layer drying curve models considered.

Model name	Type	Reference
Newton	$MR = \exp(-kt)$	Mujumdar (1987)
Page	$MR = \exp(-kt^n)$	Diamante and Munro (1993)
Modified Page	$MR = \exp\left[-(kt)^n\right]$	Whith *et al*. (1978)
Henderson and Pabis	$MR = a\exp(-kt)$	Zhang and Litchfleld (1991)
Logarithmic	$MR = a\exp(-kt) + c$	Yagcioglu *et al*.(1999)
Tow term	$MR = a\exp(-k_0 t) + b\exp(-k_1 t)$	Henderson (1974)
Tow- term exponential	$\mathrm{MR} = \mathrm{a}\exp(\mathrm{-kt}) + (1 - \mathrm{a})\exp(\mathrm{-kat})$	Sharaf-eldeen *et al*. (1980)
Wang and Singh	$MR = 1 + at + bt^2$	Wang and singh (1978)
Diffusion approach	$MR = a\exp(-kt) + (1-a)\exp(-kbt)$	Yaldiz and Ertekin (2001)
Modified Henderson and Pabis	$\mathrm{MR} = \mathrm{a}\exp(\mathrm{-kt}) + \mathrm{b}\exp(\mathrm{-gt}) + \mathrm{c}\exp(\mathrm{-ht})$	Karathanos (1999)
Verma *et al*.	$MR = a\exp(-kt) + (1-a)\exp(-gt)$	Verma *et al*. (1985)
Midilli *et al*.	$\mathrm{MR} = \mathrm{a}\exp(\mathrm{-kt^n}) + \mathrm{bt}$	Midilli *et al*. (2002)

2.3 Calculation of moisture diffusivity and activation energy

Fick's second law of diffusion can be used to model the drying behavior of fruits and vegetables. The following analytical solution for diffusion in an infinite planar slab for long drying time is given by Akpinar (2006):

$$MR = \frac{M}{M_0} = \frac{8}{\pi^2} \sum_{n=1}^{\infty} \frac{1}{(2n-1)^2} \exp\left(-\frac{(2n-1)^2 \pi^2 Dt}{4L^2} \right) \qquad (6)$$

where MR is moisture ratio, M is moisture content at any time (kg water/kg dry mater), M_0 is the initial moisture content (kg water/kg dry mater), n = 1, 2, 3, . . . the number of terms taken into consideration, t is the time of drying in second, D is effective moisture diffusivity in m^2/s and L is the half thickness of the fresh slice (m). Only the first term of equation (6) is used for long drying times (Lopez *et al*., 2000), hence**:**

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

From equation (7), a plot of ln (MR) versus time gives a straight line with a negative slope of K_2 given by:

$$k_2 = \frac{\pi^2 D}{4L^2} \qquad (8)$$

The activation energy was calculated using an Arrhenius type equation (Lopez *et al*., 2000; Akpinar *et al*., 2003):

$$D = D_0 \exp\left(-\frac{E_a}{RT_a}\right) \qquad (9)$$

Where E_a is the energy of activation (kJ/mol), R is universal gas constant (8.3143 kJ/mol K), T_a is absolute air temperature (K), and D_0 is the pre-exponential factor of the Arrhenius equation (m^2/s).

The activation energy can be determined from the slope of the Arrhenius plot of ln (D) versus $1/T_a$. From Equation (9), a plot of ln D versus $1/T_a$ gives a straight line whose slope is K_3, given by:

$$K_3 = E_a / R \qquad (10)$$

3. RESULTS AND DISCUTION

The drying process was stopped after no further change in weights was observed. At this point moisture content decreased from 390 % to11 % (db). Moisture content data were converted to moisture ratio and then fitted to the 12 thin layer drying models. Tables 2 and 3 show the results of fitting the experimental data to the thin layer drying models listed in Table 1 (R^2, *RMSE* and χ^2), with the best-fitting model in bold type for air velocity of 1 and 2 m/s, respectively. The criterion for selection of the best model describing the thin layer drying kinetics was the model with the highest R^2 average values, and the lowest *RMSE* and χ^2 average values.

Table 2. Statistical results obtained from the selected models for air velocity of 1 m/s.

Model name	R^2	χ^2	RMSE
Newton	0.991	0.0005	0.0235
Page	0.996	0.0001	0.0126
Modified Page	0.991	0.0005	0.0223
Henderson and Pabis	0.994	0.0004	0.0193
Logarithmic	**0.998**	**0.0001**	**0.0114**
Tow term	0.997	0.0002	0.0142
Tow- term exponential	0.995	0.0003	0.0163
Wang and Singh	0.962	0.0020	0.0417
Diffusion approach	0.997	0.0011	0.0238
Modified Henderson and Pabis	0.997	0.0003	0.0152
Werma et al.	0.996	0.0002	0.0139
Midilli et al.	0.998	0.0006	0.0182

Table 3. Statistical results obtained from the selected models for air velocity of 2 m/s.

Model name	R^2	χ^2	RMSE
Newton	0.985	0.0007	0.0224
Page	0.997	0.0005	0.0187
Modified Page	0.985	0.0008	0.0237
Henderson and Pabis	0.991	0.0004	0.0182
Logarithmic	0.999	0.0001	0.0111
Tow term	0.999	0.0014	0.0228
Tow- term exponential	0.994	0.0002	0.0142
Wang and Singh	0.945	0.0037	0.0590
Diffusion approach	0.998	$5.42*10^{-5}$	0.0070
Modified Henderson and Pabis	0.999	$7.21*10^{-5}$	0.0079
Werma *et al.*	0.995	0.0002	0.0135
Midilli *et al.*	**0.999**	$\mathbf{3.47*10^{-5}}$	**0.0057**

From Tables 2 and 3 it can be concluded that the best models for air velocity of 1 and 2 m/s are *Logarithmic* and *Midilli et al.* with 0.998, 0.0001 and 0.0114, and 0.999, 3.47×10^{-5} and 0.0057 values for R^2, χ^2 and RMSE, respectively. The *Logarithmic* model and *Midilli et al.* model constants are reported in Tables 4 and 5 for air velocity of 1 and 2 m/s, respectively.

Table 4. Values of the drying constant and coefficients of the best model (*Logarithmic* model) for air velocity of 1m/s.

Temperature (ºC)	R^2	a	k(min^{-1})	C
40	0.999	0.93029	0.00223	0.04172
50	0.996	0.93020	0.00335	0.06758
60	0.999	0.90974	0.00416	0.02938
70	0.998	0.97151	0.00578	0.02276

Table 5.Values of the drying constant and coefficients of the best model (*Midilli et al*. model) for air velocity of 2m/s.

Temperature (ºC)	R^2	a	k(min^{-1})	b	n
40	0.999	0.98063	0.00265	0.00001	0.96436
50	0.996	0.99784	0.00349	0.00005	0.97903
60	0.999	0.95774	0.00566	0.00001	0.94037
70	0.998	0.99274	0.00494	0.00004	1.02558

Figures 2 and 3 present the variation of experimental and predicted moisture ratio using the best models with drying time for dried apricot. Both the *Logarithmic* and *Midilli et al.* models give good estimation for the drying process at 1m/s and 2 m/s, respectively.. As evident from the Figures 2 and 3, with increase in air temperature a decrease in drying time is observed. These results are in agreement with other results reported for drying of apricot fruit (Togrul and Pehlivan, 2003; Togrul and Pehlivan, 2002).

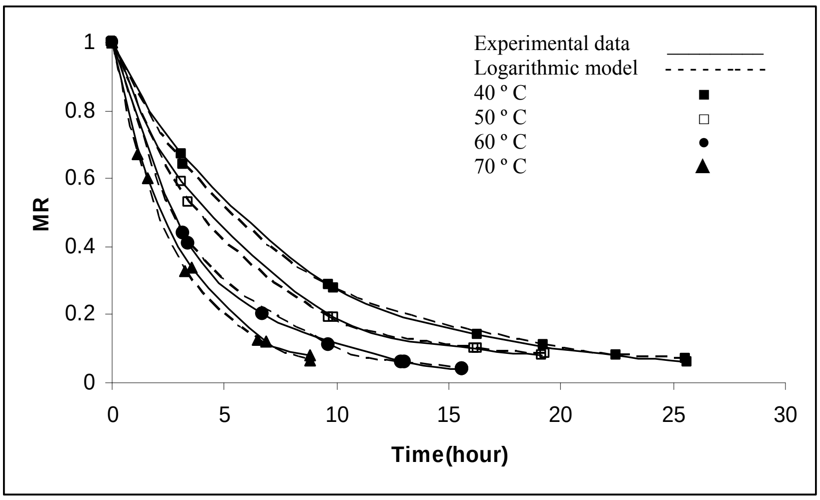

Figure 2. Experimental and predicted moisture ratio by the *Logarithmic* model versus drying time for air velocity of 1m/s.

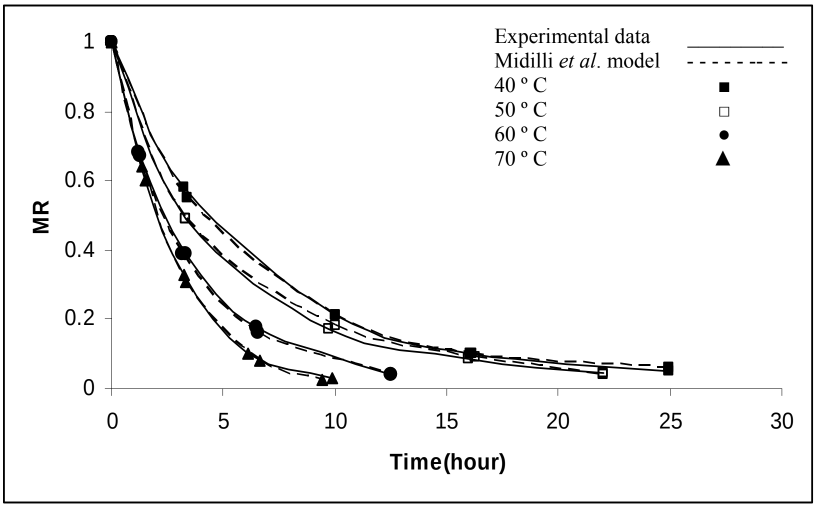

Figure 3. Experimental and predicted moisture ratio by the *Midilli et al.* model versus drying time for air velocity of 2m/s.

The effective moisture diffusivity was calculated using Equation (8), and was established to vary from 1.78-5.11$\times10^{-10}$ m^2/s. The maximum value of moisture diffusivity is 5.11$\times10^{-10}$ m^2/s when air velocity is 1 m/s and air temperature is 70ºC. The minimum value of moisture diffusivity is 1.78$\times10^{-10}$ at 2 m/s air velocity and 40ºC air temperature. As seen, the maximum value of D was found for the minimum air velocity. This is due to the fact that in low air velocity (1 m/s), air has a better contact with sample's surface that results in more absorption of moisture, consequently the moisture gradient of the sample with ambient increases that leads to an increase in moisture diffusivity. But in high air velocity level (2 m/s), air passing through sample is to some extent turbulent, therefore moisture gradient tends to decrease and moisture diffusivity reduces accordingly. Similar finding was reported by Aghbashlo et al., (2008) for barberries fruit. Togrul and Pehlivan 2003 reported that this value varied within 6.51-8.32$\times10^{-9}$ for single apricot. The energy of activation for each value of air velocity was calculated using Equation (10). Bablis *et al.* (2004) reported values of activation energy in the range of 30.8 - 48.47 kJ/mol for figs, while Aghbashlo et al., (2008) reported that this value varied within 110.837-130.61 kJ/mol for air velocities in the range of 0.5 to 1.5 m/s for barberries fruit. In this study, the value of E_a varied from 24.01 to 25 kJ/mol for two values of air velocities for apricot fruit.

Table 6. Activation energy for different level of air velocity.

Air velocity(m/s)	Ea(kJ/mol)
1	24.01
2	25

4. CONCLLUSIONS

From the above discussion it can be concluded that:

- The drying of apricot occurred in falling rate period.
- For drying air velocity of 1m/s, the *Logarithmic* model was the best model with R^2 of 0.998.
- For drying air velocity of 2 m/s, the *Midilli et al*. model gave the best results with R^2 of 0.999.
- The values of effective moisture diffusivity varied from 1.78×10^{-10} to 5.11×10^{-10} m^2/s.
- The value of E_a varied from 24.01 to 25.0 kJ/mol for different values of air velocity.

5. ACKNOWLEDGMENT

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