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Convective Drying of Apple: Mathematical Modeling and Determination of some Quality Parameters

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ABSTRACT

In present study, the effects of drying air temperatures (50, 60 & 70°C) and velocities (0.6, 1.2 & 1.8 m s^{-1}) on the drying kinetics of apple slices were investigated using a hot-air tray dryer. In addition, the effects of the drying variables on the quality characteristics (such as shrinkage & color) of dried apple were evaluated. In order to select the appropriate drying model, ten mathematical drying models were fitted to the experimental data. According to the statistical criteria (R^2, SSE & RMSE) the Aghbashlo *et al.* (2009) model was found to be the best model to describe the drying behavior of apple slices. Multiple regression analysis was used to find the correlation of the new model coefficients with the temperature and air velocity. The ANOVA results indicated that the drying-air conditions had no significant effect on final shrinkage, Hunter color values and total color differences of dried apple. © 2010 Friends Science Publishers

Key Words: Apple drying, Mathematical modeling, Quality parameters

INTRODUCTION

Drying of fruit is an important sector of the agricultural industry. The major objective in drying of fruit is the reduction of moisture content to a certain level, which allows safe storage and preservation. Drying is regarded as a complicated process and the most difficult operation in food processing. This is due to simultaneous heat and mass transfer and considerable undesired quality changes in the product during the drying process. The methods and the variables of drying, influence both the quality and physicochemical characteristics of the dried products (Krokida & Maroulis, 1997). The quality of the dried products is characterized by the appearance, color and other physical properties such as shrinkage and porosity. The drying kinetics is greatly affected by air temperature and velocity and material characteristics. Many studies have been carried out on the changes of the quality characteristics such as color and shrinkage during drying of agricultural products (Demir *et al.*, 2004; Mayor & Sereno, 2004; Sacilik & Elicin, 2004; Talla *et al.*, 2004; Koc *et al.*, 2008).

Apple is one of the most important fruits produced in Iran, especially in Azarbaijan province. It is largely consumed as fresh product. Fresh apple is perishable product due to its high moisture content. Drying of apple is an alternative process to preservation it during the time. The most common drying method is open air-sun drying, which is used for drying apple, vegetables and other fruits. There are many problems associated with sun drying method, such as lack of sufficient control during drying, being extremely weather dependent, contamination with dust, soil and insects and undesirable changes in the quality of products. These problems could be overcome if industrial dryers are used.

Modeling of drying processes and kinetics is a tool for process control and necessary to choose suitable method of drying for a specific product. The developed models are used for designing new drying systems as well as selection of optimum drying conditions and for accurate prediction of simultaneous heat and mass transfer phenomena during drying process. It also leads to produce the high quality product and increases the energy efficiency of drying system. Thin-layer drying models have been used to describe the drying process of several agricultural products, such as apple (Sacilik & Elicin, 2006; Okyay Menges & Ertekin, 2006), raw mango slices (Goyal *et al.*, 2006), grape (Yaldiz *et al.*, 2001), pistachio (Midilli & Kucuk, 2003), eggplant (Ertekin & Yaldiz, 2004). These models are categorized as theoretical, semi-theoretical and empirical models (Khazaei & Daneshmandi, 2007). The solution of Fick's second law was used widely as a theoretical model in thin layer drying of food products such as wheat (Gaston *et*

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al., 2004) and pistachio nuts (Kashaninejad *et al*., 2007). Semi-theoretical models such as Page, Newton, Henderson and Pabis and Logarithmic models are only valid under the drying and product conditions for which these models were developed. Simple empirical models such as Pleg (Pleg, 1988), Weibull (Marabi *et al*., 2004) and Midilli (Midilli *et al*., 2002) are used for water absorption process as well as single layer drying process, which can adequately describe the drying kinetics.

The aim of the present work was to investigate the thin-layer convective drying behavior of apple slices. The effects of air temperature and velocity on the final quality of dried apples, such as color and shrinkage were investigated. As well, the empirical model proposed by Aghbashlo *et al.* (2009) was evaluated to describe the thin-layer drying kinetic of apple slices. The effects of drying variables on the some pervious models have not been included. However the drying kinetics is greatly affected by the air temperature, air velocity, material size, drying time and etc. (Erenturk & Erenturk, 2007; Khazaei *et al*., 2008). But the selected model coefficients (k_1 & k_2) include the effect of drying variables on drying kinetics.

MATERIALS AND METHODS

Materials: The apples (Golden Delicious cultivar) used in this study were obtained from an orchard in Marand, Iran. It is stored in a refrigerator at 4°C. After stabilization period for 2 h at the ambient temperature, samples of uniform size were selected and peeled. After removing their center, the apples were cut to the rectangle-shaped slices, with the dimensions of 5.3×23×38 mm. To prevent non-enzymatic browning, the apple slices were dipped in an ascorbic-acid solution of 1% w.w^{-1} at room temperature.

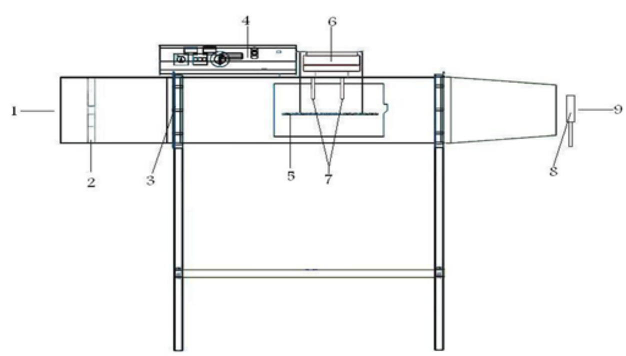
The initial moisture content of the apples was determined in a mechanical convection oven at 102±1°C, until a constant weight was attained. Four replications were conducted to obtain a reasonable average.

Drying equipment: Drying was performed in a pilot plant tray-dryer (UOP 8 Tray dryer, Armfield, UK). A schematic view of the experimental dryer is shown in Fig. 1. The dryer mainly consists of three basic units, a fan providing desired drying air velocity, electrical heaters controlling the temperature of drying air and drying chamber. The dryer was equipped with a data acquisition system and a control unit for temperature, air velocity and relative humidity. Air was flowed by an axial flow blower (90 W) and the velocity of air flow was controlled by changing the rotating speed of fan (SPC1-35, Autonics, Taiwan) and measured using a vane probe type anemometer (AM-4202, Lutron, Taiwan) with an accuracy of±0.1 m s^{-1}. Air was heated, while flowing through three spiral type electrical heaters, having 5, 5 and 2 kW capacity. These electrical heaters turned off or on separately via a temperature control unit (TZ4ST-Autonics, Taiwan), depending on the changes in the temperature, to stabilize a constant temperature during the

Abbreviations

a, b, c, n, k, k_1, k_2	Coefficients and constants in drying models
a^*	redness of the color
b^*	yellowness of the color
L^*	lightness of the color
C	color density
N	number of observations
MR	moisture ratio
M	moisture content ($g_{water}.g_{dry\ solid}^{-1}$)
RMSE	root mean square error
Sh	volumetric shrinkage
SSE	sum of squares error
V	volume at time t (m^3)
R^2	coefficient of determination
min	minute
T	air temperature (°C)
V	air velocity (m.s^{-1})
t	time (min)
ΔE	total color difference
T_{abs}	absolute temperature (°K)
T_g	glass transition temperature
Subscripts	
o	initial
i	dried apple
exp	experimental
pre	predicted
e	equilibrium

Fig. 1: Schematic diagram of the convection drying equipment (UOP 8 TRAY DRYER, ARMFIELD UK)
(1) Air inlet; (2) Fan; (3) Heaters; (4) Temperature and air flow velocity controlling; (5) Perforated tray; (6) Digital balance; (7) Relative humidity sensor and thermocouple to data logger; (8) Digital anemometer; (9) Air outlet



each experiment with an accuracy of ±0.1°C. Weighing system consisted of an electronic balance (AND GF3000, Japan) having an accuracy of 0.01 g. During the drying process, the air temperature and relative humidity in the drying chamber were logged on a data acquisition system (Delta T, England).

Experimental procedure: Experiments were performed at air temperatures of 50, 60 and 70°C and air velocities of 0.6, 1.2 and 1.8 m s^{-1}. Each experiment was repeated three times. The dryer was ran empty for about 30 min to achieve a steady state condition. Then the apple slices (about 180 g) were put on the tray in single layer. The tray was connected to the balance. The weight loss of the samples was recorded every 40 s. Drying time was defined as the time required to reduce the moisture content of the apple samples to 0.25% d.b. Additional samples (200 g) were put on a separate tray within drying chamber. These samples were used to observe and measure the change of physical and quality properties of apple slices at the end of drying process. Some drying samples were taken out from this tray by opening quickly the door of drier when the moisture content of apple slices fell to 0.3 ($g_{water}.g_{dry\ solid}^{-1}$). Considering that the weight of dry matter of samples was constant during the drying, the moisture content of samples in the drier was calculated at every time using the weight of samples that was recorded by the balance.

The color measurement of the fresh and dried apple slices was made using the apparatus recommended and described by the Yam (Yam & Papadakis, 2004). Surface color of the samples was measured using the apparatus constructed in the Agriculture Machinery Engineering, University of Tabriz, Iran. It consists of a chamber with a trapezoidal cross section that was equipped by two D65 (daylight) lamps as the light source for illumination of sample. An analog camera (Proline, PR-565S; UK) was used to record the images. At first, a sample was put in the chamber. After zooming the lens and focusing, the images were taken by camera. Color measurements for each drying condition were made on three randomly selected slices and at 10 different locations on each slice before and after drying to determine color coordinates i.e., the L^*, a^* and b^* values.

Color density (C) and the total color difference (ΔE) were determined using the following equations (Demir *et al*., 2004):

$$C = \sqrt{a^{*2} + b^{*2}} \quad (1).$$

$$\Delta E = \sqrt{(L_0^* - L_i^*)^2 + (a_0^* - a_i^*)^2 + (b_0^* - b_i^*)^2} \quad (2).$$

The subscripts 0 and i denote the color parameters of fresh and dried apple slices, respectively. The higher ΔE represents greater color change from the fresh apple.

The volume of apple slices (before & after drying) was measured using toluene displacement method (Mohsenin, 1986). For each measurement, three slices were randomly selected. Shrinkage of apple slices at the end of drying process was calculated using the following equation (Koc *et al*., 2008):

$$Sh = 1 - \frac{V}{V_0} \quad (3).$$

Where V_0 and V denote the initial and dried volume of the same apple slice, respectively.

Mathematical modeling of the drying curves: In this study some of mathematical models as well as the latest proposed model, were used to describe the drying kinetic of apple slices. The obtained drying curves were fitted with

Table I: Thin-layer mathematical drying models

Model	Mathematical equation	Reference
Newton	$MR = \exp(-kt)$	Ayensu (1997)
Page	$MR = \exp(-kt^n)$	Page (1949)
Modified page	$MR = \exp\left[-(kt)^n\right]$	White *et al*. (1981)
Henderson	$MR = a\exp(-kt)$	Rahman *et al*. (1998)
Logarithmic	$MR = a\exp(-kt) + c$	Togrul & Pehlian (2004)
Midilli *et al*.	$MR = a\exp(-kt^n) + bt$	Midilli *et al*. (2002)
Approximation of diffusion	$MR = a\exp(-kt^n) + (1-a)\exp(-kbt)$	Yaldiz *et al*. (2001)
Wang & Singh	$MR = 1 + at + bt^2$	Ozdemir & Devres (1999)
Weibull	$MR = \exp(-(\frac{t}{b})^a)$	Marabi *et al*. (2004)
Aghbashlo *et al*.	$MR = \exp(-\frac{k_1 t}{1 - k_2 t})$	Aghbashlo *et al*. (2009)

nine different moisture ratio models and Aghbashlo *et al*. (2009) model (Table I). However the dimensionless moisture ratio (MR) was simplified to M/M_0 instead of $(M-M_e)(M_0-M_e)^{-1}$ for long drying time, because the values of the M_e are relatively small compared to M or M_0. Hence the error involved in the simplification is negligible (Diamente & Munro, 1991, 1993; Yaldiz *et al.*, 2001; Midilli & Kucuk, 2003; Doymaz, 2004; Ertekin & Yaldiz, 2004; Togrul & Pehlivan, 2004).

The non-linear least square regression based on Levenberg-Morquardt algorithm was used to estimate the parameters of the models (by fitting the model equations to experimental data). The coefficient of determination (R^2), the root mean square error (RMSE) and sum of squares error (SSE) were used as criteria for verifying the goodness of fit (Ertekin &Yaldiz, 2004; Doymaz, 2005; Togrul, 2005; Sacilik & Elicin, 2006).

The best model for describing the thin-layer drying characteristics of apple slices was chosen as the one with the highest value of R^2 and the least values of RMSE and SSE (Ozdemir & Devres, 1999; Ertekin & Yaldiz, 2004; Togrul, 2005). Then the relationships between coefficients of the best model and the drying variables were determined using multiple regression analysis. All possible combinations of the different drying variables were tested and included in the regression analysis (Ertekin & Yaldiz, 2004; Togrul, 2005; Sharma *et al*., 2005; Okyay Menges & Ertekin, 2006).

RESULTS AND DISCUSSION

Drying curves: The initial moisture content of apple was found to be 88.2% wet base (w.b.). The moisture content versus drying time and the variation of drying rate with moistures content at various air temperatures and velocity are shown in (Figs. 2 & 3), respectively. It is observed that moisture content of samples decreases exponentially with the drying time. As shown in (Fig. 2), increasing the air temperature reduced the time required to reach a certain level of moisture content. The drying time to reduce the moistures content of apple slices from 7.5 to 0.3 (g_{water} $g_{dry\ solid}^{-1}$) at air velocity of 1.2 m s^{-1} were 366, 292 and 221 min at temperature of 50, 60 and 70°C, respectively. These time values at other air temperature and velocities were shown in Table II. The lowest drying time to reach the moisture content of 0.3 (g_{water} $G_{dry\ solid}^{-1}$) was obtained at the air temperature of 70°C and air velocity of 1.8 m s^{-1}. The analysis of variance indicated that the air temperature as well as the air velocity had a significant effect on the drying time (P value=0.0001). Similar results were reported for apple drying by several authors (Tugrul, 2005; Sacilik & Elicin, 2006; Okyay Menges & Ertekin, 2006).

Fig. 3 illustrates that drying rate decreases continuously with decreasing moisture content. In this curve, a constant drying rate period was not observed and drying process occurred in the falling rate period only and the diffusion mechanism controlled moisture movement in the apple slices. These results were in agreement with other studies on drying of apple (Togrul, 2005; Sacilik & Elicin, 2006; Schultz *et al*., 2007).

The average drying rate values at 50, 60 and 70°C and air velocity of 1.2 m s^{-1} were as 0.0164, 0.025 and 0.0336 (g_{water} $g_{dry\ solid}^{-1}$. min^{-1}), respectively. When the temperature was increased from 50 to 70°C, the drying rate almost doubled. As expected, the drying rate increased with increasing in drying air temperature and consequently decreased the required drying time. It is a fact that the higher temperature difference between the drying air and apple slices increases the heat transfer coefficient, which influences the heat and mass transfer rate. Several authors reported similar results during drying of fruits and vegetables such as hazelnut (Ozdemir & Devres, 1999), figs (Babalis & Belessiotis, 2004) and apple (Togrul, 2005; Sacilik & Elicin, 2006).

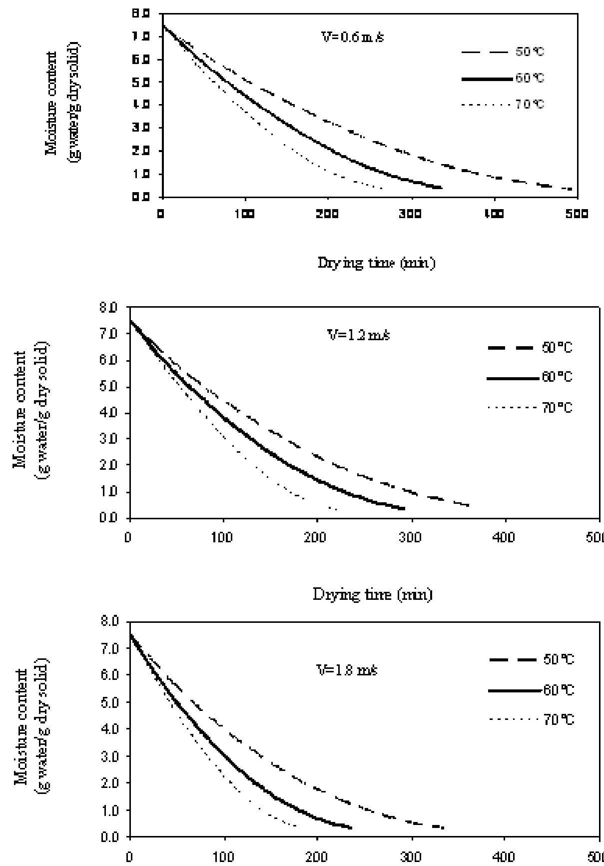
The drying rate versus moisture content at air velocities of 0.6, 1.2 and 1.8 m s^{-1} and air temperature of 60°C are shown in Fig. 4. It is clear that, the difference between drying rates related to different air velocities was high at the high moisture contents of apple. But at low moisture content, this difference was negligible. When the air velocity was increased from 0.6 to1.8 m s^{-1}, the average drying rate increased about 1.5 times at high moisture content. With increasing the air velocity, the momentum transfer increases, which affects the surface heat transfer coefficient. This led to increase the heat transfer rate between air flow and apple slices especially in the primary stages of drying, when the moisture content was high. Consequently, the heat and related mass transfer increased. The effect of air velocity on the drying rate was not considerable at the late stages of drying process, because at these stages the drying rate was controlled only by the diffusion coefficient and the temperature difference.

Modeling of drying curves: The moisture content data

Table II: Final drying time at different air velocity and temperature

Drying air temperature	Drying time (min)		
	Drying air velocity (m s^{-1})		
	0.6	1.2	1.8
50°C	493	366	335
60°C	336	292	235
70°C	266	221	179

Fig. 2: Drying curves of apple slices at different air temperatures and velocities



obtained at different air temperatures and velocities were converted to dimensionless moisture ratio (MR) and then fitted to ten thin layer drying models (Table I). Fig. 5 shows the drying curves for apple slices at different air temperatures when air velocity was constant. In these figure, the experimental and predicted moisture ratio values by Aghbashlo *et al*. (2009) model were included. This model was selected as the best model (see discussion later). Ten thin layer drying models were evaluated according to the statistical criteria, R^2, RMSE and SSE (Table ΠΙ). By comparing the average values of these criteria, it is obvious that the Aghbashlo *et al*. (2009) model had the highest R^2 and the lowest RMSE and SSE values. Generally R^2, RMSE and SSE values of the selected model in all experiments were varied between 0.9997-0.9999, 0.0019-0.0039 and

Fig. 3: Drying rate vs. moisture content of apple slices at different air temperatures and velocities

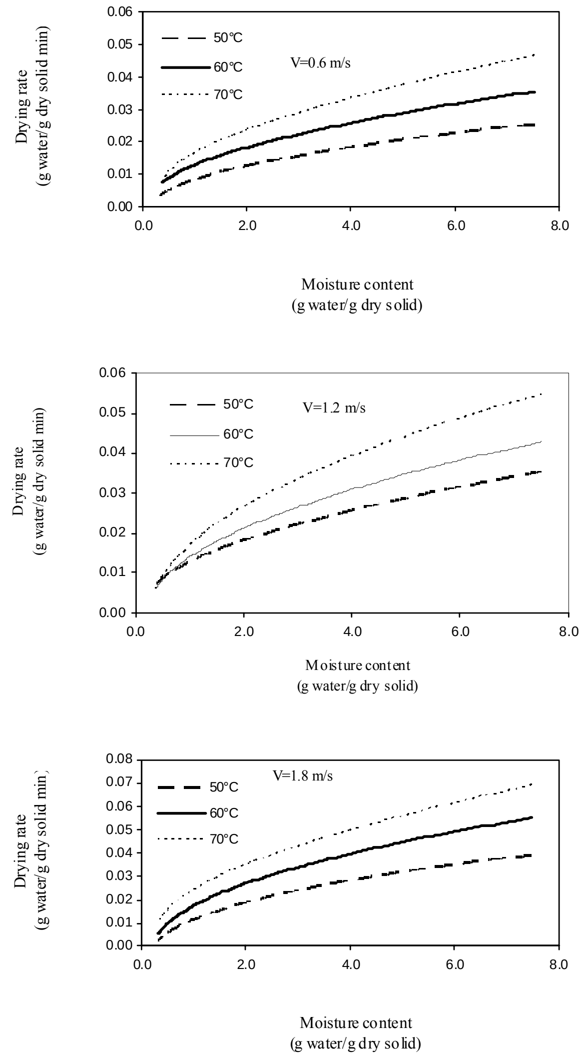
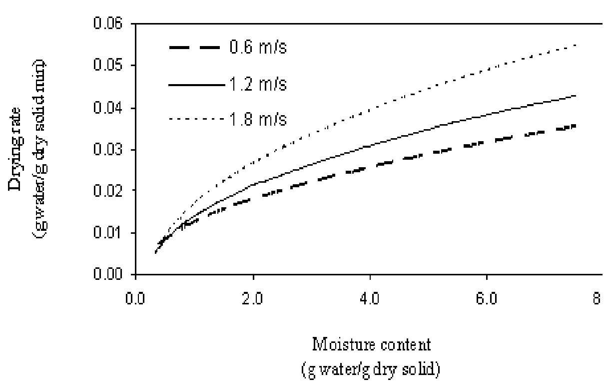


Fig. 4: Drying rate vs. moisture content of apple slices at air temperature of 60°C (0.6, 1.2 and 1.8 m s^{-1})



0.001-0.0082, respectively. Accordingly, the Aghbashlo *et al.* (2009) model was selected as the suitable model to represent the thin layer drying behavior of apple slices. The coefficients of the model are shown in Table IV.

Fig. 5: Experimental and predicted moisture ratios of apple slices vs. drying time at different air temperatures and velocities

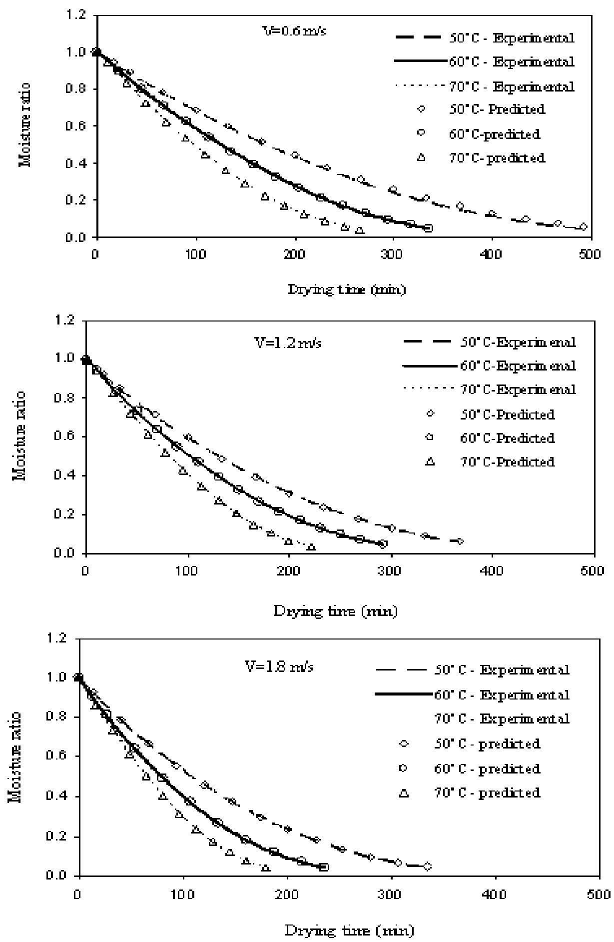
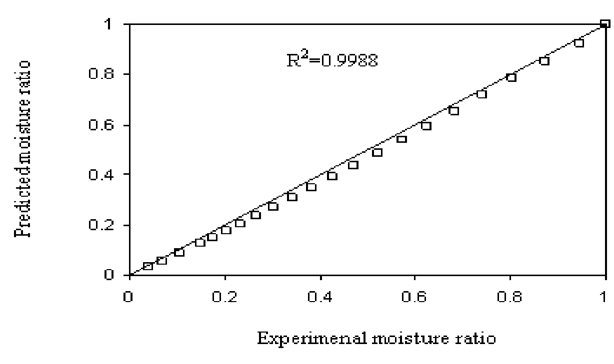


Fig. 6: Experimental versus predicted moisture ratio values by the Aghbashlo model at air temperature of 55°C and air velocity of 1.5 m s^{-1}



Variation of experimental and predicted moisture ratio by Aghbashlo *et al.* (2009) model with drying time (min) are shown in Fig. 5. It is clear that the Aghbashlo *et al.*

(2009) model provided a good agreement between experimental and predicted moisture ratios. To take into account the effect of drying air temperature T (°K) and air velocity V (m s^{-1}) on the coefficients of selected model, the values of coefficients were regressed against drying-air conditions using multiple regressions. The multiple combinations of different parameters, which gave the highest $\bar{R}^2$ value, were finally included in the selected model. The coefficients of the accepted model and the final MR equation of thin layer drying of apple slices were as follows:

$$K_1 = 8.865 \times V^{0.4147} \exp(\frac{-2462.69}{T_{abs}}) \quad \bar{R}^2 = 0.968 \qquad (5).$$

$$K_2 = 50411 \times V^{0.29997} \exp(\frac{-499676}{T_{abs}}) \quad \bar{R}^2 = 0.981 \qquad (6).$$

$$MR = f(T,V,t) = \exp(-\frac{8.865 \times V^{0.4147} \exp(\frac{-2462.69}{T_{abs}}) \times t}{1 - 5041.1 \times V^{0.29997} \times \exp(\frac{-4996.76}{T_{abs}}) \times t}) \qquad (7).$$

Some other extra experiments were conducted at air

Table III: Results of statistical analysis on ten thin-layer drying models

Model	Drying air velocity (m s^{-1})	Drying air temperature								
		50°C			60°C			70°C		
		R^2	RMSE	SSE	R^2	RMSE	SSE	R^2	RMSE	SSE
Newton	0.6	0.9800	0.0395	1.1540	0.9746	0.0449	1.0149	0.9715	0.0485	0.9383
	1.2	0.9862	0.0318	0.5546	0.9809	0.0385	0.6492	0.9680	0.0519	0.8926
	1.8	0.9862	0.0325	0.5304	0.9815	0.5164	0.0382	0.9732	0.0469	0.9732
page	0.6	0.9968	0.0156	0.1803	0.9966	0.0164	0.1352	0.9970	0.0156	0.0964
	1.2	0.9973	0.0140	0.1073	0.9971	0.0148	0.0959	0.9964	0.0174	0.1002
	1.8	0.9976	0.0135	0.0914	0.9974	0.0142	0.0713	0.9970	0.0156	0.0649
Modified page	0.6	0.9968	0.0156	0.1803	0.9966	0.0164	0.1352	0.9970	0.0964	0.0156
	1.2	0.9973	0.0140	0.1073	0.9971	0.0148	0.0959	0.9964	0.0174	0.1740
	1.8	0.9973	0.0135	0.0913	0.9974	0.0142	0.0713	0.9970	0.0156	0.0649
Henderson and Papis	0.6	0.9862	0.0328	0.7951	0.9833	0.0363	0.6642	0.9820	0.0386	0.5914
	1.2	0.9903	0.0267	0.3914	0.9874	0.0312	0.4275	0.9795	0.0415	0.5711
	1.8	0.9905	0.0269	0.3647	0.9877	0.0312	0.3428	0.9828	0.0376	0.379
Logarithmic	0.6	0.9993	0.0070	0.0368	0.9993	0.0069	0.0243	0.9988	0.0099	0.0390
	1.2	0.9996	0.0043	0.0105	0.9995	0.0060	0.0159	0.9987	0.0103	0.0350
	1.8	0.9996	0.0051	0.0132	0.9993	0.0071	0.0181	0.9989	0.0094	0.0234
Midilli *et al.*	0.6	0.9991	0.0081	0.0477	0.9997	0.0046	0.0108	0.9996	0.0057	0.0130
	1.2	0.9997	0.0038	0.0080	0.9997	0.0046	0.0090	0.9995	0.0065	0.0137
	1.8	0.9998	0.0037	0.0070	0.9997	0.0046	0.0074	0.9996	0.0055	0.0080
Deffusion	0.6	0.9972	0.0148	0.1607	0.9745	0.0449	1.0150	0.9715	0.0486	0.9384
	1.2	0.9859	0.0322	0.5695	0.9804	0.0391	0.6667	0.9680	0.0519	0.8926
	1.8	0.9858	0.0330	0.5451	0.9810	0.0388	0.5296	0.9728	0.0474	0.6003
Wang & Singh	0.6	0.9999	0.0023	0.0039	0.9998	0.0026	0.0033	0.9995	0.0059	0.0136
	1.2	0.9995	0.0057	0.0178	0.9999	0.0026	0.0029	0.9994	0.0069	0.0159
	1.8	0.9994	0.0064	0.0204	0.9998	0.0021	0.0016	0.9997	0.0046	0.0057
Weibull	0.6	0.9968	0.0156	0.1803	0.9966	0.1352	0.0116	0.9970	0.0156	0.0964
	1.2	0.9973	0.0134	0.1073	0.9971	0.0148	0.0959	0.9964	0.0174	0.1002
	1.8	0.9976	0.0135	0.0914	0.9974	0.0142	0.0713	0.9970	0.0156	0.0649
Aghbashlo *et al.*	0.6	0.9999	0.0028	0.0056	0.9990	0.0020	0.0020	0.9999	0.0024	0.0022
	1.2	0.9997	0.0039	0.0082	0.9999	0.0028	0.0034	0.9999	0.0025	0.0021
	1.8	0.9998	0.0029	0.0042	0.9999	0.0019	0.0013	0.9999	0.0019	0.0010

Table IV: Coefficients of the Aghbashlo model at different drying conditions

Velocity	0.6 (m s^{-1})		1.2 (m s^{-1})		1.8 (m s^{-1})	
Temperature	K_1	K_2	K_1	K_2	K_1	K_2
50°C	0.003417	0.000803	0.004667	0.001019	0.005580	0.001177
60°C	0.004513	0.001466	0.005727	0.001515	0.007404	0.001898
70°C	0.005758	0.001986	0.006732	0.002511	0.008688	0.002877

Table V: Summary of the analysis of variance for the effect of air temperature and velocity on quality characters of dried apple slices

Source of variation	Degree of freedom	Mean squares					
		L^*	a^*	b^*	C	ΔE	Final shrinkage
Temperature	2	2.789 ^{ns}	0.640 ^{ns}	23.972 ^{ns}	23.793 ^{ns}	0.153 ^{ns}	2.661 ^{ns}
Velocity	2	0.8 8 ^{ns}	1.267 ^{ns}	3.647 ^{ns}	3.79 ^{ns}	15.096 ^{ns}	1.455 ^{ns}
Temperature × Velocity	4	2.460 ^{ns}	0.006 ^{ns}	10.079 ^{ns}	10.102 ^{ns}	0.765 ^{ns}	0.933 ^{ns}
Error	18	2.766	1.688	9.299	9.368	6.326	3.717

ns: no significant

temperatures of 55 and 65°C and air velocities of 0.9 and 1.5 m s^{-1} to validate the developed model. Fig. 6 shows the comparison of the predicted and the experimental moisture ratio values at particular drying air temperature and velocity (55°C & 1.5 m s^{-1}). It is clear that the established model provided a good agreement between the experimental and the predicted moisture ratio values, which is bound around a 45° straight line.

Determination of quality of apple slices during drying: The air temperature and velocity had no significant effect on final shrinkage and Hunter color values as well as C and ΔE of dried apple slices (Table V). The mean values of shrinkage for apple slices at all drying conditions changed between 79.32 to 81.34%. The shrinkage values at all drying conditions were high. This indicated that the air temperatures used in this study and related temperature of apple slices were not in the range of the rubber-glass transition temperature. Therefore a porous outer rigid crust that fixes the slices volume at early stages of drying process did not formed. Consequently the apple slices shrinked at all drying conditions. The limitation of shrinkage related to T_g and formation of rigid crust during drying process was reported by several authors (Del Valle & Cuadros, 1998; Mayor & Sereno, 2004).

Desired color properties of dried apple slices are related to higher values of L^*, lower values of a^* and minimum total color differences (ΔE) of dried and fresh apple (Lee *et al*., 2003; Sacilik & Elicin, 2006). In this study L^* value of dried apple slices at drying air temperature of 50°C was higher than that of 70°C. In other word, higher drying air temperature led to darker apple slices (Sacilik & Elicin, 2006). But there was no recognized difference between ΔE values at various drying air conditions.

CONCLUSION

The drying behavior of the apple slices was investigated in a thin layer hot-air dryer at air temperatures of 50, 60 and 70°C and air velocities of 0.6, 1.2 and 1.8 m s^{-1}. The drying of apple occurred in the falling rate period and the diffusion mechanism controlled moisture movement. Drying air temperature and air velocity affected the drying rate and time. The drying rate increased with increasing the drying-air temperature and velocity. New model proposed by Aghbashlo *et al*. (2009) was adequate for describing the thin-layer drying behavior of apple slices. The final color characteristics and shrinkage values of dried apple slices were not affected significantly by air temperature and velocity at studied range of drying conditions.

REFERENCES

Aghbashlo, M., M.H. Kianmehr, S. Khani and M. Ghasemi, 2009. Mathematical modeling of carrot thin-layer drying using new model. *Int. Agrophysic.*, 23: 313–317

Ayensu, A., 1997. Dehydration of food crops using a solar dryer with convective heat flow. *Solar Ener.*, 59: 121–126

Babalis, J.S. and G.V. Belessiotis, 2004. Influence of drying condition on the drying constants and moisture diffusivity during the thin layer drying of figs. *J. Food Eng.,* 65: 449–458

Del Valle, J.M., T.R. Cuadros and J.M. Agulera, 1998. Glass transitions and shrinkage during drying and storage of osmosed apple pieces. *Food Research Int.*, 31: 191–204

Demir, V., T. Gunhan, A.K. Yagcioglu and A. Degirmencioglu, 2004. Mathematical modeling and the determination of some quality parameters of air–dried bay leaves. *Biosyst. Eng.,* 88: 325–335

Diamente, L.M. and P.A. Munro, 1991. Mathematical modeling of hot air drying of sweat potato slices. *Int. J. Food Sci. Technol.,* 26: 99–106

Diamente, L.M. and P.A. Munro, 1993. Mathematical modeling of the thin layer solar drying of sweet potato slices. *Solar Energy*, 51: 271–276

Doymaz, I., 2004. Effect of dipping treatment on air drying of plums. *J. Food Eng.,* 64: 465–470

Doymaz, I., 2005. Drying behavior of green beans. *J. Food Eng.*, 69: 161–165

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

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

Gaston, A.L., R.M. Abalone, S.A. Giner and D.M. Bruce, 2004. Effect of modeling assumptions on the effective water diffusivity in wheat. *Biosyst. Eng.*, 88: 175–185

Goyal, R.K., A.R.P. Kingsly, M.R. Manikantanl and S.M. Ilyas, 2006. Thin-layer drying kinetics of raw mango slices. *Biosyst. Eng.,* 95: 43–49

Kashaninejad, M., A. Mortazavi, A. Safekordi and L.G. Tabil, 2007. Thin-layer drying characteristics and modeling of pistachio nuts. *J. Food Eng.*, 78: 98–108

Khazaei, J. and S. Daneshmandi, 2007. Modeling of thin-layer drying kinetics of sesame seed: mathematical and neural networks modeling. *Int. Agrophysics,* 21: 335–348

Khazaei, J., A. Arabhosseini and Z. Khosrobeygi, 2008. Application of superposition technique for modeling drying behavior of avishan (*Zataria Multiflora*) Leaves. *Trans. ASABE,* 51: 1383–1393

Koc, B., I. Eren and F.K. Ertekin, 2008. Modelling bulk density, porosity and shrinkage of quince during drying: The effect of drying method. *J. Food Eng.*, 85: 340–349

Krokida, M.K. and Z.B. Maroulis, 1997. Effect of drying method on shrinkage and porosity. *Dry. Technol.*, 15: 1145–1155

Lee, J.Y, H.J. Park, C.Y. Lee and W.Y. Choi, 2003. Extending shelf–life of minimally processed apples with edible coating and antibrowning agents. *Lebensmittel-Wissenchaft Technol.*, 36: 323–329

Marabi, A., C. Dilak, J. Shah and I.S. Saguy, 2004. Kinetics of solid leaching during rehydration of particulate dry vegetables. *J. Food Sci.,* 69: 91–96

Mayor, L. and A.M. Sereno, 2004. Modelling shrinkage during convective drying of food materials: a review. *J. Food Eng.*, 61: 373–386

Midilli, A., H. Kucuk and Z. Yapar, 2002. A new model for single–layer drying. *Dry. Technol.,* 20: 1503–1513

Midilli, A. and H. Kucuk, 2003. Mathematical modeling of thin layer drying of pistachio by using solar energy. *Energy Convers. Manage.*, 44: 1111–1122

Mohsenin, N.N., 1986. *Physical Properties of Plant and Animal Materials.* Gordon and Breach Sci. Publ. New York

Okyay Menges, H. and C. Ertekin, 2006. Mathematical modeling of thin layer drying of golden apples. *J. Food Eng.*, 77: 119–125

Ozdemir, M. and Y.O. Devres, 1999. The thin layer drying characteristics of hazelnuts during roasting. *J. Food Eng.,* 42: 225–233

Page, G.E., 1949. Factors influencing the maximum rates of air drying shelled corn in thin layers. *M.Sc. Thesis*, Purdue University, West Lafayette, Indiana

Pleg, M., 1988. An empirical model for the description of moisture sorption curves. *J. Food Sci.,* 53: 1216–1217

Rahman, M.S., C.O. Perera and C. Thebaud, 1998. Desorption isotherm and heat pump drying kinetics of peas. *Food Res. Int.*, 30: 485–491

Sacilik, K. and A.K. Elicin, 2006. The thin layer drying characteristics of organic apple slices. *J. Food Eng.,* 73: 281–289

Schultz, E.L., M.M. Mazzuco, R.A.F. Machado, A. Bolzan, M.B. Quadri and M.G.N. Quadri, 2007. Effect of pre–treatment on drying, density and shrinkage of apple slices. ***J. Food Eng.***, 78: 1103–1110

Sharma, G.P., R.C. Verma and P. Pathare, 2005. Mathematical modeling of infrared radiation thin layer drying of union slices. ***J. Food Eng.,*** 71: 282–286

Talla, A., J.R. Puiggali, W. Jomaa and Y. Jannot, 2004. Shrinkage and density evolution during drying of tropical fruits: application to banana. ***J. Food Eng.,*** 64: 103–109

Togrul, I.T. and S. Pehlivan, 2004. Modeling of thin layer drying kinetics of some fruit under open-air sun drying process. ***J. Food Eng.,*** 65: 413–425

Togrul, H., 2005. Simple modeling of infrared drying of fresh apple slices. ***J. Food Eng.,*** 71: 311–323

White, G.M., T.C. Bridges, O.J. Loewer and I.J. Ross, 1981. Thin layer drying model for soybeans. ***Trans. ASAE***, 24: 1643–1649

Yaldiz, O., C. Ertekin and H.I. Uzun, 2001. Mathematical modeling of thin layer solar drying of sultan grapes. *Energy*, 26: 457–465

Yam, K.L. and S.E. Papadakis, 2004. A simple digital imaging method for measuring and analyzing color of food surfaces. ***J. Food Eng.***, 61: 137–142

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