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Mathematical Modeling of Moisture Content of Apple Slices (Var. Golab) During Drying

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Abstract: Drying is one of the primary methods of food preservation. Determining coefficients used in drying models is essential to predict the drying behavior. The present study was conducted to compute drying characteristics of apple slices. Thin layer drying kinetics of apple slices (variety-Golab) was experimentally investigated in a convective dryer and the mathematical modeling was performed by using thin layer drying models in the literature. Drying characteristics of apple slices were determined using heated ambient air at temperatures between 40 and 80°C, velocities at 0.5 m/s and thickness of thin layer 2, 4, 6 mm. Beside the effects of drying air temperature, effects of slice thickness on the drying characteristics, drying time and quality of dried product were also determined. Drying curves obtained from the experimental data were fitted to twelve different thin layer drying models. All the models were compared according to three statistical parameters, i.e. Root Mean Square Error (RMSE), chi-square (X^2) and modeling efficiency (EF). The results showed that increasing drying air temperature resulted to shorter drying times. Midilli model had the highest value of EF (0.999611), the lowest values of 0.031806 and 0.001088 for RMSE and X^2 respectively. The Midilli model was found to be the best model for describing the drying curves of apples. The effects of drying air temperature and thickness on the drying constant and coefficient were also shown.

Key words: Thin-layer drying, moisture content, modeling, apple slice, midilli model

INTRODUCTION

Among fruits, apple is the more important one economically and industrially. It is consumed in different forms as fresh fruit, concentrated juice or thin dried slices (Wang *et al*., 2007). Apple was introduced into Iran many years ago. Iran with more than 2,000,000 tones produce in year, presently ranks 6th among the apple producing countries of the world (ASB, 2005). Drying, a complex process involving heat and mass transfer phenomena and frequent in most food processing industries (Cohen and Yang, 1995), is probably the main and the most expensive step after harvesting. It improves the product shelf life without addition of any chemical preservative and reduces both the size of package and transport cost. Fruits and vegetables are regarded as highly perishable foods due to their high moisture content (Simal *et al*., 1994). The fruits contain a high percentage of their fresh weight as water. Accordingly, they exhibit relatively high metabolic activity compared with other plant-derived foods such as seeds. This metabolic activity continues after harvesting, thus making most fruits highly perishable commodities (Atungulu *et al*., 2004). Mathematical modeling and simulation of drying curves under different conditions is important to obtain a better control of this unit operation and an overall improvement of the quality of the final product. Models are often used to study the variables involved in the process, predict drying kinetics of the product and to optimize the operating parameters and conditions (Karathanos and Belessiotis, 1999). Drying process of food materials mostly occur in the falling rate period (Wang and Brennan, 1992). Thin layer drying equations are used to estimate drying times of several products and also to generalize drying curves. Several investigators have proposed numerous mathematical models for thin layer drying of many agricultural products.

For example, apple (Wang *et al*., 2007), organic apple (Sacilik and Elicin, 2006), Golden apple (Menges and Ertekin, 2005), kiwifruit (Mohammadi *et al*., 2009), rough rice (Cihan, *et al*., 2007), red chilli (Kaleemullah and Kailappan, 2005), apricot (Togrul and Pehlivan, 2002, 2003), plum (Doymaz, 2004), eggplant (Ertekin and Yaldiz, 2004), grape (Yaldiz *et al*., 2001), green pepper, stuffed pepper, pumpkin, green bean and onion (Yaldiz and Ertekin, 2001). Convection drying as well as other techniques for drying is used in order to preserve the original characteristics of apples. Dried apples could be consumed directly or treated as secondary raw material (Velic *et al*., 2004).

The aim of this work was to study the effect of drying air temperature on the drying characteristics and dehydration ratio for the apple drying process and to select the most-suitable model (in terms of fitting ability) to describe the thin-layer drying of apple (variety-Golab). Beside, investigate the effects of drying conditions and slices thickness on the coefficients of the selected model.

MATERIALS AND METHODS

In this study, the apples were selected from a local market and from Golab variety; Iranian variety. The drying experiments were carried out using the laboratory dryer in the Department of Agricultural Machinery, Faculty of Bio-systems Engineering, University of Tehran. Figure 1 shows a schematic diagram of the dryer used for experimental work; it consists of an electrical fan, an airflow control unit, heaters, drying chamber and instruments for various measurements (Yadollahinia, 2006). Table 1 shows measurement instruments including their rated accuracy. The airflow control unit regulates the velocity of the drying air through the 30 cm diameter drying chamber. The dryer is capable of providing any desired drying air temperature in the range of 20-120°C and velocity in the range of 0.1-3.0 m/s with high accuracy. Apples were washed, peeled and sliced in thicknesses of 2, 4 and 6 mm using a slicer machine. The uniform thickness of t±0.01 mm was prepared by adjusting the opening of the slicer with a vernier caliper having a least count of 0.01 mm. The product was spread as a thin layer on a screen. The desired drying air temperature was attained by electrical resistance heating elements and controlled by the heating control unit. The air was forced through the heating elements and after reaching the desired temperature was passed through the drying chamber. The drying air temperature and velocity were measured directly in the drying chamber. The air velocity was measured using a hot wire digital anemometer (Testo, 405 V1, Germany) with the accuracy of ±0.1 m/s and the temperature using T-type thermocouple (Testo 925, Germany) with the accuracy of ±1°C. Weighing of samples inside the drying chamber was carried out manually using an electronic balance with a capacity of 0-3000 g and accuracy of ±0.01 g.

Table 1: Specifications of measurement instruments including their rated accuracy

Instrument	Model	Accuracy	Make
Digital balance	GF3000	±0.02 g	A and D, Japan
T-sensor	LM35	±1°C	NSC, USA
RH-sensor	Capacitive	±3%	PHILIPS, UK
V-sensor	405-V1	±3%	Testo, UK

Thin layers of apples were dried using drying air temperatures from 40-80°C at 10°C interval. The drying air velocity was adjusted to 0.5 m/s. The drying samples were cut into 2, 4 and 6 mm slice thicknesses with a slicer (Ertekin, 2002). Moisture content determination was done by drying the samples at 105°C until the weight became constant (Yagcioglu *et al*., 1999).

To determine the initial moisture content, the drying process was continued until the weight became constant. After that the samples were placed in an oven at 105°C for 12 h to find the moisture content according to the following equation:

$$M = \frac{W_w - W_d}{W_d} \qquad (1)$$

Where M is the apple slice moisture content (g water/ g dry base, d.b.), W_w is the wet weight and W_d is the dried weight. The initial moisture content of apple was obtained as 5.0-6.4 (d.b.). The reproducibility of the initial moisture content measurements was within the range of ±5%.

The experimental drying data for apple were fitted to the thin layer drying models in Table 2 by using SPSS version 13.0 software and nonlinear regression technique. For mathematical modeling, the thin layer drying equations in Table 2 were tested to select the best model for describing the drying curve of the apple slices.

The reduced chi-square (X^2), Root Mean Square Error (RMSE) and increased modeling Efficiency (EF) were used as the primary criteria to select the best equation to account for variation in the drying curves of the dried samples (Goyal *et al*., 2007; Menges and Ertekin, 2006; Yaldiz, 2001). The reduced chi-square is the mean square of the deviations between the experimental and calculated values for the models and was used to determine the goodness of the fit. The RMSE gives the deviation between the predicted and experimental values and it is preferred tending to zero. The EF also gives the ability of the model to predict the drying behavior of the product and its highest value is one. These statistical values were calculated from the following equations:

$$X^2 = \frac{\sum_{i=1}^{n}(MC_{exp,i} - MC_{pre,i})^2}{N - n} \qquad (2)$$

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

$$EF = \frac{\sum_{i=1}^{N}(MC_{i,exp} - MC_{i,exp_{mean}})^2 - \sum_{i=1}^{N}(MC_{i,pre} - MC_{i,exp})^2}{\sum_{i=1}^{N}(MC_{i,exp} - MC_{i,exp_{mean}})^2} \qquad (4)$$

Where $MC_{exp,i}$ is the ith experimental moisture content, $MC_{pre,i}$ is the ith predicted moisture content, N is the number of observations, n is the number of constants in drying model and $MC_{expmean}$ is the mean value of experimental moisture content.

RESULTS AND DISCUSSION

The results of the effects of drying air temperature on drying time showed that, an increase in drying air temperature resulted in a decrease in the drying time (Fig. 2-4). The drying rate, DR, is expressed as the

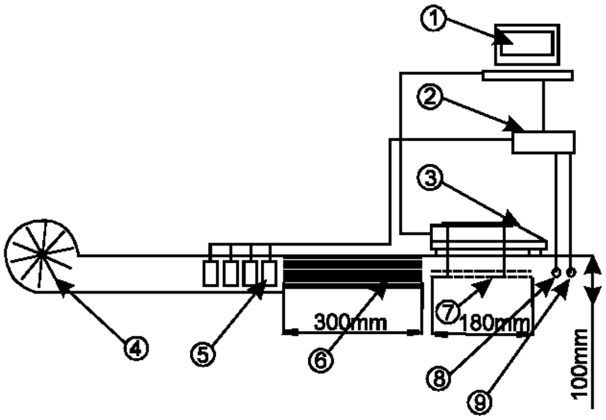

Fig. 1: Schematic diagram of the drying system for measurement of the thin-layer parameters of apple slices. 1. PC; 2. microcontroller; 3. digital balance; 4. fan; 5. heating elements; 6. duct and tunnel; 7. trays; 8. temperature sensor; 9. relative humidity sensor

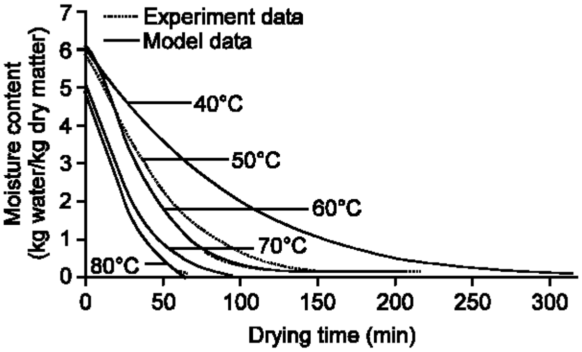

Fig. 2: Experimental and computed moisture content obtained using the Midilli model for 2mm thickness

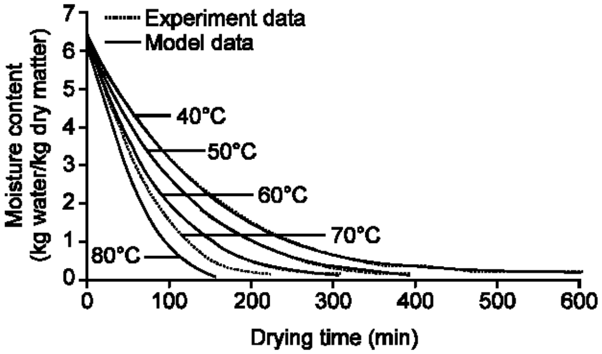

Fig. 3: Experimental and computed moisture content obtained using the Midilli model for 4mm thickness

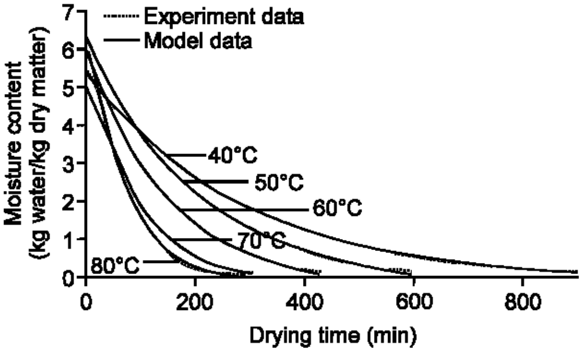

Fig. 4: Experimental and computed moisture content obtained using the Midilli model for 6mm thickness

amount of the evaporated moisture over time. The drying rates of apple slices were calculated by using Eq. (5):

$$DR = \frac{M_{t+dt} - M_t}{dt} \qquad (5)$$

Where, M_t and M_{t+dt} are the moisture content at t and moisture content at t+dt (kg moisture/kg dry matter), respectively, t is drying time (min).

As shown in Fig. 5, the drying rate increased with increasing drying air temperature and reached its maximum values at 80°C. Drying rate decreased continuously with decreasing moisture content or increasing drying time. Similar results have been reported by Mohammadi *et al.* (2009) for kiwifruit, Bala *et al.* (2003) for pineapple, Prachayawarakorn *et al.* (2008) for banana and for different crops by researchers (Kingsly and Singh, 2006; Doymaz, *et al.*, 2005).

Figure 5 shows the drying rate against moisture content of the samples at temperatures of 40-80°C of drying air, velocity of 0.5 m/s and thickness of 2 mm and the average initial moisture content of around 5 kg water per kg dry matter was dried to the final moisture content of about 0.1 (d.b.) until no further changes in their mass were observed.

The moisture content of apple slices at various drying air temperatures were fitted in twelve models and the results of statistical analysis. In seven cases (Table 3), the value of EF was greater than 0.99 indicating a good fit (Madamba *et al.*, 1996).

From the results of RMSE and chi-square values of all thin layer drying models for all drying conditions, the Midilli *et al.* (2002) model gave the lowest values while the EF showed the highest amount and thus it was chosen to represent the thin layer drying of apple slices (Table 3). The drying constants (k) and (b) and coefficients (a) and (n) values and also statistical parameters RMSE, chi-square and EF for Midilli model are shown in Table 4.

Table 2: Mathematical models applied to drying curves

Model no.	Model name	Model	References
1	Newton	$MC = \exp(-kt)$	Westerman, *et al.*, 1973
2	Page	$MC = \exp(-kt^n)$	Page, 1949
3	Modified page	$MC = \exp[-(kt)^n]$	Yaldiz *et al.*, 2001
4	Henderson and Pabis	$MC = a \exp(-kt)$	Yagcioglu *et al.*, 1999
5	Logarithmic	$MC = a \exp(-kt) + c$	Yaldiz and Ertekin, 2001
6	Two term	$MC = a \exp(-k_0t) + b \exp(-k_1t)$	Rahman *et al.*, 1998
7	Two term exponential	$MC = a \exp(-kt) + (1-a) \exp(-kat)$	Yaldiz *et al.*, 2001
8	Wang and Singh	$MC = M_0 + at + bt^2$	Ozdemir and Devres, 1999
9	Approximation of diffusion	$MC = a \exp(-kt) + (1-a) \exp(-kbt)$	Yaldiz and Ertekin, 2001
10	Verma *et al.*, 1985	$MC = a \exp(-kt) + (1-a) \exp(-gt)$	Verma *et al.*, 1985
11	Modified Henderson and Pabis	$MC = a \exp(-kt) + b\exp(-gt) + c\exp(-ht)$	Karathanos, 1999
12	Midilli *et al.*, 2002	$MC = a \exp(-kt^n) + bt$	Midilli *et al.*, 2002

Table 3: Average values of the drying constants and coefficients of different models determined through regression method for apples

Model no	Model	RMSE	X^2	EF
1	Henderson and Pabis	0.119948	0.017245	0.994147
2	Logarithmic	0.066098	0.005329	0.998157
3	Two term	0.063644	0.006371	0.9984
4	Diffusion approximation	0.150933	0.026381	0.990949
5	Verma *et al.*, 1985	0.150933	0.026381	0.990949
6	Modified Henderson and Pabis	0.039814	0.002189	0.999272
7	Midilli *et al.* 2002	0.031806	0.001088	0.999611

Table 4: Statistical results of midilli *et al.* model and its' constants and coefficients at different drying conditions

Temp (°C)	Thick (mm)	a	k (h^{-1})	n	b (h^{-1})	RMSE	EF	X^2
40	2	5.8448745	0.0057494	1.1371442	-0.0000545	0.0199960	0.9998470	0.0004000
	4	6.0618205	0.0034929	1.1396066	0.0001637	0.0445160	0.9991930	0.0019830
	6	5.3512121	0.0029670	1.0338640	-0.0001214	0.0294840	0.9995770	0.0008700
50	2	5.8543541	0.0081589	1.2176847	0.0003838	0.0345970	0.9995360	0.0011990
	4	6.1716514	0.0058045	1.0834187	-0.0002169	0.0266360	0.9997490	0.0007100
	6	6.4377456	0.0066792	0.9509924	-0.0005036	0.0264200	0.9997550	0.0006980
60	2	6.1652773	0.0068544	1.3367405	0.0006994	0.0489440	0.9992470	0.0024010
	4	6.1437120	0.0057027	1.1534235	0.0000189	0.0267590	0.9997520	0.0007170
	6	6.1108584	0.0069572	1.0025187	-0.0005135	0.0191570	0.9998620	0.0003670
70	2	4.9844434	0.0125730	1.2557620	-0.0005419	0.0283610	0.9996260	0.0008070
	4	6.2276923	0.0048952	1.2300531	-0.0004356	0.0368330	0.9995910	0.0013590
	6	5.0839836	0.0047576	1.1545942	-0.0003089	0.0214790	0.9997780	0.0004620
80	2	5.9792793	0.0109339	1.3115646	-0.0038247	0.0399840	0.9995200	0.0016060
	4	6.0895068	0.0052056	1.2798966	-0.0010316	0.0361030	0.9996080	0.0013060
	6	6.0039491	0.0043459	1.2392664	-0.0002131	0.0378130	0.9995220	0.0014310

$$\frac{MC}{MC_0} = a \exp\left(-kt^n\right) + bt$$

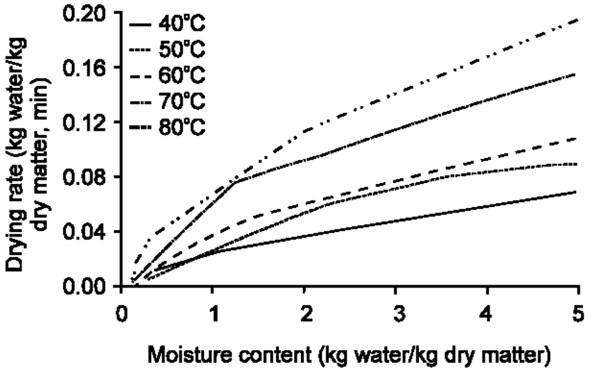

Fig. 5: Influence of temperature on drying rate of apple slices at five temperatures, air velocity of 0.5 m/s and slice thickness of 2mm

It is clear that, in Midilli model, RMSE and chi-square values were very low and changed between 0.0191570 and 0.0489440 and 0.0003670 and 0.0024010, respectively. Modeling Efficiency (EF) also ranged from 0.9991930 and 0.9998620. This model represented the experimental values satisfactorily.

Conclusion: The drying behavior of apple slices in a laboratory dryer was investigated for three thicknesses of apple slices at five different drying air temperatures. The time required to dry apple slices from an initial moisture content of 5.0-6.4 (d.b.) to the final moisture content of about 0.1 (d.b.) for 2 mm thickness was 320, 220, 150, 100 and 60 min and for thickness of 4 mm, was 600, 400, 320, 320 and 150 min and for thickness of 6mm, was 700, 600, 320 and 300 min, at 40, 50, 60, 70 and 80°C of drying air temperature, respectively.

Nomenclature			
MC	moisture content	MCexp;i	ith experimental moisture content
T	drying air temperature (°C)	MCpre;i	ith predicted moisture content
V	drying air velocity (m/s)	N	Number of observations
M_e	equilibrium moisture content (kg water/kg dry matter)	n	number of constants in the model
M_0	initial moisture content (kg water/kg dry matter)	MCexp;mean	mean value of experimental moisture content
X^2	Chi-square	k, k_0, k_1, g, h	drying constants (h^{-1})
RMSE	root mean square error	a, b, c, d, e, f , n	coefficients
EF	modeling efficiency	t	drying time (min)

Drying rate increased with the increase in drying air temperature, thus reducing the drying time. Results showed that the Midilli *et al.* model among of twelve drying models, could be used to describe the drying characteristics of the apple slices, in the drying conditions and slice thicknesses. This model had the highest value of EF (0.99961), the lowest RMSE (0.03180) and X^2 (0.00109). Determining constants and coefficients of this model is essential to predict the drying behavior.

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