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Determination of suitable thin layer drying curve model for apple slices (variety-Golab)

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Abstract

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 from 40 to 80 °C, velocity of 0.5 m/s and slice layers of 2, 4, 6 mm thickness. Beside, the effects of drying air temperature, effects of slice thickness on the drying characteristics and drying time were also determined. Thirteen thin-layer drying models were studied. The fitting ability of the models is compared using the root mean square error, chi-square and modeling efficiency. The results showed that, increasing the drying air temperature and decreasing slice thickness causes shorter drying times. The Midilli et al. model was found to be the best model for describing the drying curves of the apple slices. Also, the effects of drying air temperature and thickness of layers on the model constants and coefficients were predicted by multiple regression analysis. According to the results of regression method, Henderson and Pabis model could satisfactorily describe the drying curve of apples with a correlation coefficient (R^2) of 0.9762.

Keywords: Thin-layer drying, mathematical modeling, multiple regressions, apple slices

Abbreviations: MR_ moisture ratio; M_t _moisture content at any time of drying process (gr water/gr dry matter); $MR_{exp,i}$ _ith experimental moisture ratio; $MR_{pre,i}$ _ith predicted moisture ratio; T_m_ drying air temperature (°C); T_ drying time(h); M_e _ equilibrium moisture content (gr water/gr dry matter); MR_o _initial moisture content (gr water/gr dry matter); χ^2 _Chi-square; RMSE_ root mean square error; N_Number of observations; n_ number of constants in the model; $MR_{exp,mean}$ _mean value of experimental moisture ratio; EF_ modeling efficiency; k, k_0, k_1, g, h_drying constants (h^{-1}); a, b, c, d, e, f , n_ coefficients

Introduction

Apple is one of the most important fruits all around the world. Fruits and vegetables are regarded as highly perishable food due to their high moisture content (Simal et al. 1994). 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). Drying is one of the widely used methods for fruits and vegetables preservation. 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, drying of apple (Wang et al. 2006), rough rice (Cihan et al. 2007), red chilli (Kaleemullah and Kailappan 2005), apricot (Togrul and Pehlivan 2002, 2003), plum (Doymaz 2004), Organic apple (Sacilik and Elicin 2005), 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).

Depending on the applied equations, models can be classified as theoretical, semi-empirical and empirical models to express and explain the thin layer drying of agricultural products. Theoretical models could be used for different materials and conditions, but contain diffusion or heat and mass transfer equations, and thus, the usability of these models decreases. Semi-theoretical models contain parameters directly related to material properties. The empirical equations give a satisfactory fit to all the experimental data and take less computing time in comparison to the theoretical equations. These proposed, quite simple models can provide adequate representation of experimental results (Simal et al. 2004, Hossain and Bala 2002, Yagcioglu 1999). Among these models, the theoretical approaches account for only the internal resistance to moisture transfer, while the semi-empirical and empirical approaches consider only the external resistance to moisture transfer between the product and air (Yagcioglu 1999, Midilli and Kucuk 2003).

Table 1. Specifications of measurement instruments including their rated accuracy

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

The objectives of this work were to study the effects of drying conditions and the slices thickness on the drying behavior of apple slices 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 for regression analysis.

Materials and methods

The drying experiments were carried out using a 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 flowing through the 30 cm diameter drying chamber. The dryer is capable of providing any desired drying air temperature in the range of 20 to 120 °C and air velocity in the range of 0.1 to 3.0 m/s with high accuracy. Apples were washed, peeled and drying samples were cut in to 2, 4 and 6 mm slice thickness with a slicer (Ertekin 2002). The uniform thickness of t±0.01 mm was prepared by adjusting the opening of the slicer-machine 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 is forced to pass through the heating elements and after reaching the desired temperature is 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. Thin layers of apples were dried using drying air temperatures from 40 to 80 °C at 10°C interval. The drying air velocity was adjusted to 0.5 m/s. Moisture content determination was done by drying the samples at 105 °C until the weight became constant (Yagcioglu 1999).

Thirteen different moisture ratio equations (Table 2) were fitted to the experimental data by using SPSS version 13.0 software, nonlinear regression technique to select the best model for describing the drying curve of the apple slices. However, the moisture ratio (MR) was simplified to M/M_0 instead of the $(M-M_e)/(M_0-M_e)$ (Doymaz 2007, Goyal et al. 2007, Menges and Ertekin 2006). The reduced chi-square (χ^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). Reduced chi-square is the mean square of the deviations between the experimental and calculated values by the models and was used to determine the goodness of the fit. The lower the value of the reduced chi-square, the better is the fit. The RMSE gives the deviation between the predicted and experimental values and it is preferred to reach 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 can be calculated as follows:

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

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

$$EF = \frac{\sum_{i=1}^{N}(MR_{i,\exp} - MR_{i,\exp_{mean}})^2 - \sum_{i=1}^{N}(MR_{i,pre} - MR_{i,\exp})^2}{\sum_{i=1}^{N}(MR_{i,\exp} - MR_{i,\exp_{mean}})^2} \quad (3)$$

Where $MR_{exp,i}$ is the ith experimental moisture ratio, $MR_{pre,i}$ is the ith predicted moisture ratio, N is the number of observations, n is the number of constants in drying model and $MR_{exp,mean}$ is the mean value of experimental moisture ratio (Wang et al. 2006, Cihan et al 2007, Sacilik and Elicin 2005, Kaleemullah and Kailappan 2005).

The drying rate, DR, is expressed as the amount of the evaporated moisture over time. The drying rates of apple slices were calculated by using Eq. (4):

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

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

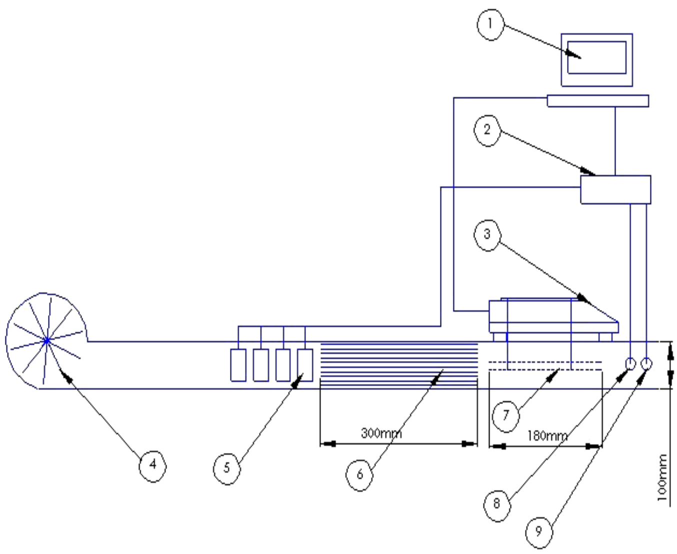

Fig 1. Schematic diagram of the drying system for measurement of the thin-layer parameters of apple slices. 1. PC; 2. microcontroller; 3. digital balance; 4. fan; 5. heating elements; 6. duct and tunnel; 7. trays; 8. temperature sensor; 9. relative humidity sensor.

Table 2. Mathematical models applied to drying curves

Model no.	Model name	Model	References
1	Newton	$MR = \exp(-kt)$	Westerman, et al., 1973
2	Page	$MR = \exp(-kt^n)$	Guarte, 1996
3	Modified page	$MR = \exp\left[-(kt)^n\right]$	Yaldız et al., 2001
4	Henderson and Pabis	$MR = a\exp(-kt)$	Yagcioglu et al., 1999
5	Logarithmic	$MR = a\exp(-kt) + c$	Yaldız and Ertekin, 2001
6	Two term	$MR = a\exp(-k_0 t) + b\exp(-k_1 t)$	Rahman et al., 1998
7	Two term exponential	$MR = a\exp(-kt) + (1-a)\exp(-kat)$	Yaldız et al., 2001
8	Wang and Singh	$MR = M_0 + at + bt^2$	Ozdemir and Devres, 1999
9	Approximation of diffusion	$MR = a\exp(-kt) + (1-a)\exp(-kbt)$	Yaldız and Ertekin, 2001
10	Verma et al.	$MR = a\exp(-kt) + (1-a)\exp(-gt)$	Verma et al., 1985
11	Modified Henderson and Pabis	$MR = a\exp(-kt) + b\exp(-gt) + c\exp(-ht)$	Karathanos, 1999
12	Hii et al.	$MR = a\exp(-kt^n) + c\exp(-gt^n)$	Hii et al., 2009
13	Midilli et al.	$MR = a\exp(-kt^n) + bt$	Ertekin and Yaldiz, 2004

Table 3. Average values of the drying constants and coefficients of different drying models

Model	RMSE	χ^2	EF	R²
Newton	0.012035	0.000808	0.990251	0.990322
Page	0.003766	0.000078	0.998988	0.998706
Modified page	0.003829	0.000078	0.998990	0.998993
Henderson and Pabis	0.009239	0.000470	0.994296	0.994349
Logarithmic	0.005760	0.000145	0.998195	0.998175
Two term	0.007863	0.000416	0.995048	0.994900
Two term exponential	0.012014	0.000810	0.990228	0.990317
Wang and Singh	0.009648	0.001253	0.983235	0.981989
Diffusion approximation	0.003705	0.000073	0.999083	0.999087
Verma et al.	0.006409	0.000450	0.994541	0.994630
Modified Henderson and Pabis	0.006502	0.000331	0.996011	0.996066
Hii et al.	0.006401	0.000049	0.999421	0.999420
Midilli et al.	0.002512	0.000030	0.999615	0.999643

In this study, for multiple regression analysis, the Henderson and Pabis model gave the best result so the relationship of the constants and coefficients of Henderson and Pabis model with drying variables like air temperature and thickness of layers was also determined by multiple combinations of the different equations as simple linear and power type (Ertekin and Yaldiz 2004):

Linear $Y = b_0 + b_1 X$

Power $Y = b_0 X^{b_1}$

Results and discussion

It was observed that, one of the main factors influencing the drying kinetics of the product, during the falling rate drying period, is the drying air temperature. The results showed that, an increase in drying air temperature resulted in a decrease in the drying time (Figures 2 to 4). To reach to the safe final moisture content, the drying time was 4500 sec at a drying air temperature of 80 °C and increased to 18000 sec at 40 °C with a drying air velocity of 0.5 m/s for thickness of 2mm ,9600 sec at 80 °C and increased to 33000 sec at 40 °C for thickness of 4mm and 18000 sec at 80 °C and increased to 45000 sec at 40 °C for thickness of 6mm, this result showed that drying time increased with increasing thickness of apple slices. The drying rate reached its maximum values at higher drying air temperatures. It is decreased continuously with decreasing moisture content or improving drying time. The moisture removal inside the apple slices were higher at higher drying air temperatures, because the migration of moisture to the surface and the evaporation rate from surface to air slows

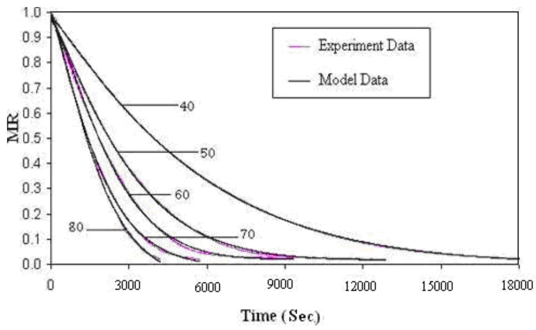

Fig 2. Effect of drying air temperature on drying time for 2mm thickness

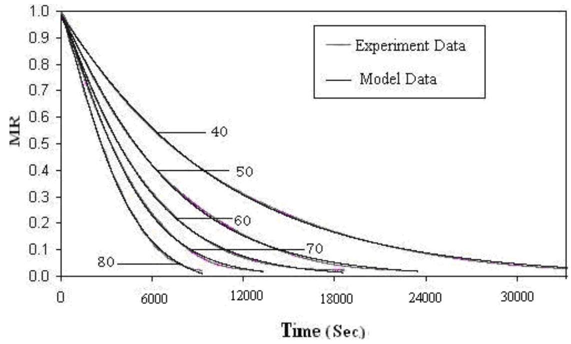

Fig 3. Effect of drying air temperature on drying time for 4mm thickness

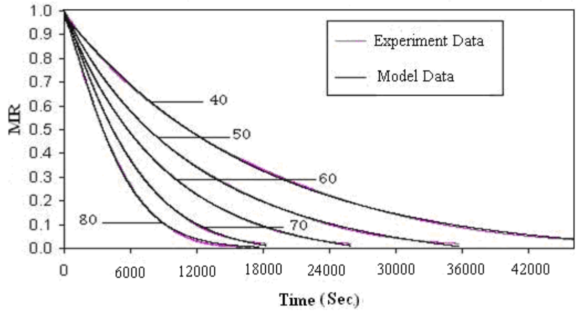

Fig 4. Effect of drying air temperature on drying time for 6mm thickness

Table 4. Results of statistical analysis on Midilli et al. model

Temp (°C)	Thick (mm)	a	k	n	b	RMSE	EF	χ^2
	2	0.9814098	0.0057528	1.1370055	0.0000093	0.0033529	0.9998471	1.12542E-05
40	4	0.9861527	0.0046509	1.0431052	0.0000000	0.0039549	0.9997633	1.56494E-05
	6	0.9779639	0.0029670	1.0338640	-0.0000220	0.0053883	0.9986334	2.90445E-05
	2	0.9710794	0.0081589	1.2176847	0.0000636	0.0057390	0.9995360	3.30000E-05
50	4	0.9812873	0.0047614	1.1261139	0.0000000	0.0056057	0.9995693	3.14514E-05
	6	0.9989657	0.0066792	0.9509924	-0.0000781	0.0041100	0.9980331	1.68000E-05
	2	0.9665145	0.0068544	1.3367403	0.0001096	0.0076730	0.9992470	5.90000E-05
60	4	0.9870417	0.0057829	1.1502458	0.0000000	0.0043053	0.9997513	1.85557E-05
	6	0.9960253	0.0069572	1.0025187	-0.0000836	0.0031225	0.9987183	9.75754E-06
	2	0.9802643	0.0125730	1.2557620	0.0001065	0.0055780	0.9996260	3.12000E-05
70	4	0.9734462	0.0039843	1.2800254	0.0000000	0.0070639	0.9993950	4.99738E-05
	6	0.9911116	0.0047576	1.1545942	-0.0000602	0.0041873	0.9993397	1.75531E-05
	2	0.9932647	0.0112510	1.3013721	0.0007083	0.0063612	0.9995547	4.06570E-05
80	4	0.9815824	0.0052056	1.2798967	-0.0001662	0.0058195	0.9996079	3.39399E-05
	6	0.9718482	0.0036960	1.2770968	0.0000034	0.0073954	0.9990919	5.47553E-05

$$\frac{M}{M_0} = a\exp\left(-kt^n\right) + bt$$

down with decreasing the moisture in the product, the drying rate clearly decrease. While the mean drying rate was 0.0010 gr water per gr dry matter per sec at a drying air temperature of 80 °C and 0.00045 gr water per gr dry matter per sec at a drying air temperature of 40 °C at a velocity of 0.5 m/s for 2 mm thickness, 0.0008 gr water per gr dry matter per sec at a drying air temperature of 80 °C and 0.0003 gr water per gr dry matter per sec at a drying air temperature of 40 °C for 4mm thickness and 0.0007 gr water per gr dry matter per sec at a drying air temperature of 80 °C and 0.00018 gr water per gr dry matter per sec at a drying air temperature of 40 °C for 6mm thickness. Similar results have been reported for apple (Wang et al. 2006), organic apple (Sacilik and Elicin 2005) and different crops by researchers (Kingsly and Singh 2006, Doymaz et al. 2005).

The drying processes occurred in falling rate drying period, starting from initial moisture content to final moisture content of 6% (w.b.) (Figures 5 to 7). Similar results have been reported for different crops by researchers (Akpinar 2006, Akanbi et al. 2006). The most effective force governing the moisture movement was diffusion.

According to the results of RMSE, chi-square values of all the thin layer drying models for all drying conditions, the Midilli et al. model gave the lowest values while EF and R^2 showed the highest amount and thus it was chosen to represent the thin layer drying of apple slices (Table 3). While RMSE was changed between 0.000562-0.032245 for all examined models, this value was changed between 0.000501469-0.001293457 for Midilli et al. model according to the different experimental conditions. The drying constants

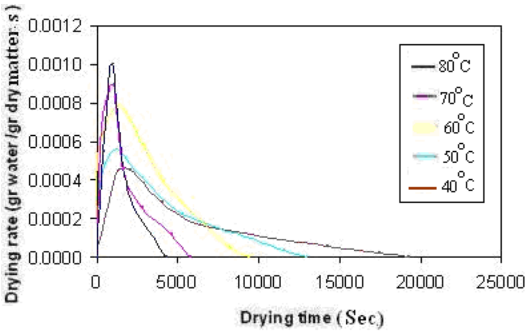

Fig 5. Drying rate changes with drying time for 2mm thickness

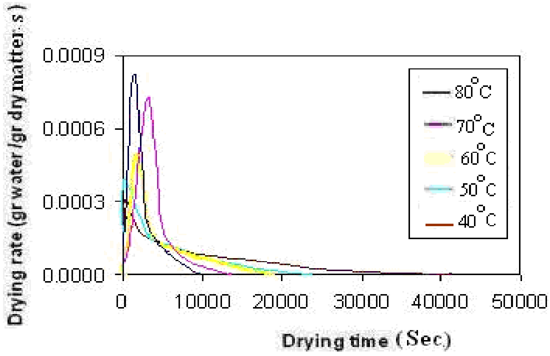

Fig 6. Drying rate changes with drying time for 4mm thickness

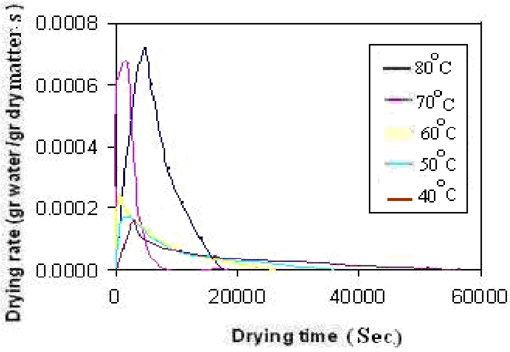

Fig 7. Drying rate changes with drying time for 6mm thickness

(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.

It is clear that, RMSE and chi-square values were very low and changed between 0.0031225-0.0076730, and 0.0000097-0.0000590, respectively. Modeling efficiency (EF) also ranged as 0.9980331-0.9998471. This model represented the experimental values satisfactorily.

To take into account for the effect of the drying variables on the Henderson and Pabis model constant of k and coefficients of a, the values of these parameters were regressed against those of the drying air temperature(T) in ºC and slice thickness (h) in mm using multiple regression analysis. All possible combinations of the different drying variables were tested and included in the regression analysis. The constants and coefficients of the Henderson and Pabis model were as follows:

$$MR = a\exp(-kt)$$

$$MR = (0.971449 + 0.002099\,T - 0.010565\,h)\exp[-(-1.061883 + T^{0.022639} - 0.004633\,h)t]$$

Where:

$a = 0.971449897 + 0.002099298T - 0.010565552h$, $R^2 = 0.9612$,

$k = -1.061883481 + T^{0.022639541} - 0.004633918h$, $R^2 = 0.9351$

These expressions can be used to estimate the moisture ratio of apple slices at any time during the drying process with a great accuracy. The consistency of the model and relationship between the coefficients and drying variables evident with

$R^2 = 0.9762$, $X^2 = 2.748 \times 10^{-4}$, $RMSE = 0.005242$, $EF = 0.9771$

Conclusions

Drying time decreased with increasing drying air temperature and decreasing thickness of apple slices. The highest drying rate was obtained at a drying air temperature of 80 °C at all thicknesses. Results of thin layer modeling showed that, the Midilli et al. model could be used to describe the drying characteristics of the apple slices, in the drying conditions and slice thickness. This model gave the lowest value of RMSE (0.002512) and X^2 (0.000030), and the highest value of EF (0.999615) and R^2 (0.999643).

According to the results of the multiple regression analysis, among the 13 thin layer-drying models, the Henderson and Pabis model could adequately describe the thin layer drying behaviour of apples. The multiple regression on the coefficients of that model for the effects of the drying air temperature and thickness of thin layers gave R^2: 0.9762, X^2: 0.0002748 and RMSE: 0.005242, and satisfactorily represented the drying of apples in the ranges of 40-80 ºC temperature, and in 0.5 m/s air velocity.

Acknowledgments

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