Mathematical Modeling of Kinetics of Thin-layer Drying of Apple (var. Golab)

E. Meisami-asl, S. Rafiee

Department of Agricultural Machinery, Faculty of Bio-Systems Engineering, College of Agricultural and Natural Resource, University of Tehran, Karaj, Iran.
Corresponding author e-mail address: elham_112@yahoo.com

ABSTRACT

Mathematical models of thin-layer drying of apple were studied and verified with experimental data. Fourteen different mathematical drying models were compared according to three statistical parameters, i.e. root mean square error (RMSE), chi-square (χ^2) and modeling efficiency (EF). The thin-layer drying kinetics of apple slices was experimentally investigated in a laboratory convective dryer and the mathematical modeling, using thin-layer drying models present in the literature, was performed. The main objective of the study was the verification of models already developed. Experiments were performed at air temperature between 40 and 80 °C, velocity of 0.5, 1 and 2 m/s, and thickness of thin layer of 2, 4, 6 mm. Besides the effects of drying air temperature and velocity, effects of slice thickness on the drying characteristics and drying time were also determined. Drying curves obtained from the experimental data were fitted to the-thin layer drying models. The results have shown that, model introduced by Midilli *et al*. (2002) obtained the highest value of EF = 0.99972, the lowest value of RMSE = 0.00292 and χ^2 = 10^{-5}. Therefore this model was the best for describing the drying curves of apples. The effects of drying air temperature, velocity and thickness on the drying constant and coefficient were shown to compare the circumstances of drying.

Keywords: Modeling, thin-layer, drying, apple slice, temperature, moisture content

Nomenclature

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

1. INTRODUCTION

Among fruits, apple is the most important one economically and industrially. It is consumed in different forms, such as fresh fruit, concentrated juice or thin dried slices. Apple was introduced in Iran many years ago. Iran, with more than 2 million tons production in a year, presently ranks to 6th among the apple producing countries of the world (ASB, 2005). Drying is a complex process involving heat and mass transfer phenomena and frequently used in food processing industry (Cohen and Yang, 1995). It is probably the main and the most expensive step after harvesting. It extends the product shelf life without addition of any chemical preservative and reduces both package size and transportation cost.

Fruits such as apple and vegetables like carrot are regarded as highly perishable food due to their high moisture content (Simal *et al.*, 1994). The fruits (such as apple) contain a high percentage of their fresh weight as water. Accordingly, they exhibit relatively high metabolic activity compared to 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 better control of this unit operation and 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 optimize the operating parameters and circumstances (Karathanos and Belessiotis, 1999).

Drying is one of the widely used methods of fruit and vegetable preservation. Thin-layer drying equations are used to estimate drying time 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, carrot (Aghabashlo *et al.*, 2008), apple (Wang *et al.*, 2006), rough rice (Cihan *et al.*, 2007), red chili (Kaleemullah and Kailappan, 2005), bitter orange leaves (Ait Mohamed *et al.*, 2005), organic apple (Sacilik and Elicin, 2005), prickly pear peel (Lahsasni *et al.*, 2004), eggplant (Ertekin and Yaldiz, 2004), plum (Doymaz, 2004), apricot (Togrul and Pehlivan, 2002; Togrul and Pehlivan, 2003), grape (Yaldiz *et al.*, 2001), green pepper, stuffed pepper, pumpkin, green bean and onion (Yaldiz and Ertekin, 2001).

The objective of this study was to determine the effect of drying air temperature on the drying characteristics and dehydration ratio for the apple drying process. In addition to this, choosing a suitable model for thin-layer drying of apple (Golab variety) and investigation of the effects of drying air temperature, velocity and thickness on the model coefficients describing drying characteristics of apple slices were investigated.

2. MATERIALS AND METHODS

Apples, of ‘Golab’ variety that is Iranian variety, were selected from a local market. The initial moisture content of apples was obtained as 5.0-6.4 %(d.b.). The drying experiments were carried out using the laboratory dryer in the Department of Agricultural Machinery, Faculty of Bio-systems Engineering, University of Tehran, Iran. The dryer is capable of providing any desired drying air temperature in the range of 20 to 120 °C and velocity in the range of 0.1 to 3.0 m/s with high accuracy (±0.01 m/s). Figure 1 shows a schematic diagram of the dryer used for experimental work; it consisted 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 regulated the velocity of the drying air flowing through the 30 cm diameter drying chamber. Apples were washed, peeled and sliced in thicknesses of 2, 4 and 6 mm using a slicing machine. The uniform thickness of apples (±0.01 mm) was prepared by adjusting the opening of the slicer with a vernier caliper having the least count of 0.01 mm. The product was spread as a thin layer on a screen. The desired drying air temperature (40, 50, 60, 70 and 80 ºC) was attained by electrical resistance heating elements and controlled by the heating control unit. The air was forced by electrical fan to pass through the heating elements and after reaching the desired temperature (40 to 80 ºC) passed through the drying chamber. The drying air temperature and velocity were measured directly in the drying chamber where drying air was getting out. 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, and by connecting to the computer, the weighing program could save the weight of samples at any time interval. The air velocity was measured using a hot wire digital anemometer with the accuracy of ±0.1 m/s, and the temperature using a T-type thermocouple with the accuracy of ±1 °C.

Thin layers of apples (thickness of 2, 4 and 6 mm) were dried using drying air temperatures from 40 to 80 °C at 10 °C interval and drying air velocity was 0.5, 1 and 2 m/s (Ertekin, 2002). Moisture content determination was done by drying the samples at 105 °C until the weight became constant (Yagcioglu *et al.*, 1999).

Table 1. Specifications of measurement instruments including their rated accuracy

Instrument	Model	Accuracy	Company
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

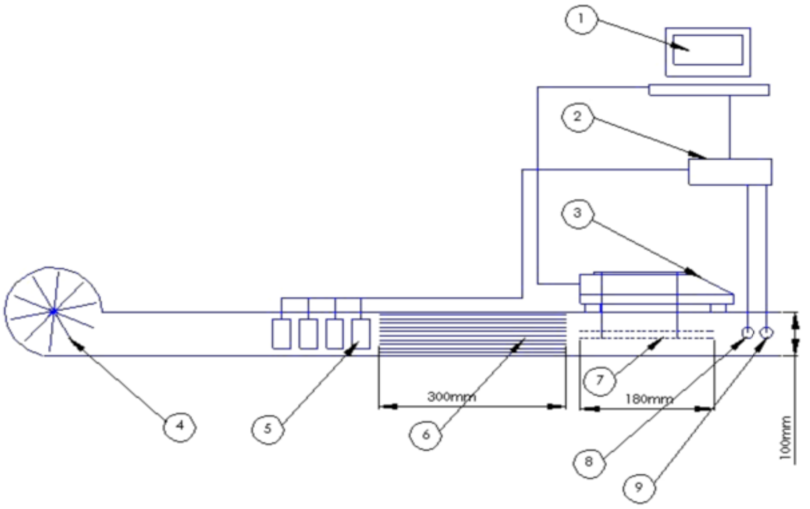


Figure 1. Schematic diagram of the drying system for measurement of the thin-layer parameters of apple slices. 1. PC; 2. microcontroller; 3. digital balance; 4. fan; 5. heating elements; 6. duct and tunnel; 7. trays; 8. temperature sensor; 9. relative humidity sensor.

Drying curves were fitted to the experimental data using fourteen different moisture ratio equations (table 2). 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).

In 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.

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	$MR = \exp(-kt^n)$	(Page, 1949)
3	Modified page	$MR = \exp\left[-(kt)^n\right]$	(Yaldiz *et al.*, 2001)
4	Henderson and Pabis	$MR = a\exp(-kt)$	(Yagcioglu *et al.*, 1999)
5	Logarithmic	$MR = a\exp(-kt) + c$	(Yaldiz and Ertekin, 2001)
6	Two term	$MR = a\exp(-k_0t) + b\exp(-k_1t)$	(Rahman *et al.*, 1998)
7	Two term exponential	$MR = a\exp(-kt) + (1-a)\exp(-kat)$	(Yaldiz *et al.*, 2001)
8	Wang and Singh	$MR = M_0 + at + bt^2$	(Ozdemir and Devres,1999)
9	Approximation of diffusion	$MR = a\exp(-kt) + (1-a)\exp(-kbt)$	(Yaldiz 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	Aghabashlo model	$MR = \exp(-\frac{k_1t}{1+k_2t})$	(Aghabashlo *et al.*, 2008)
13	Weibull	$MR = \exp(-(t/a)^b)$	(Corzo *et al.*, 2008)
14	Midilli et al.	$MR = a\exp(-kt^n) + bt$	(Midilli *et al.*, 2002)

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 for the models and was used to determine the goodness of fit. RMSE gives the deviation between predicted and experimental values. 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:

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

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

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

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 (Sacilik and Elicin, 2005).

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

$$DR = \frac{M_{t+dt} - M_t}{dt} \tag{4}$$

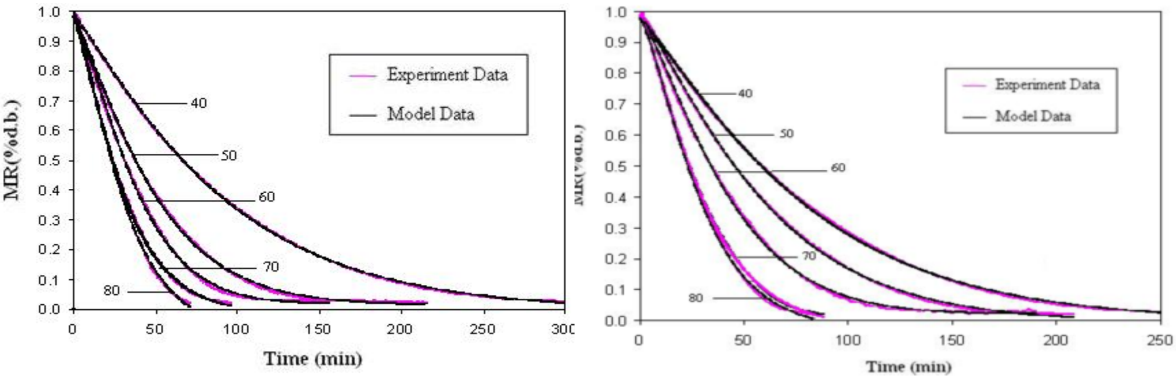
Where, M_t and M_{t+dt} are the moisture ratio at t and moisture ratio at t+dt, respectively; t is drying time (min).

3. RESULTS AND DISCUSSION

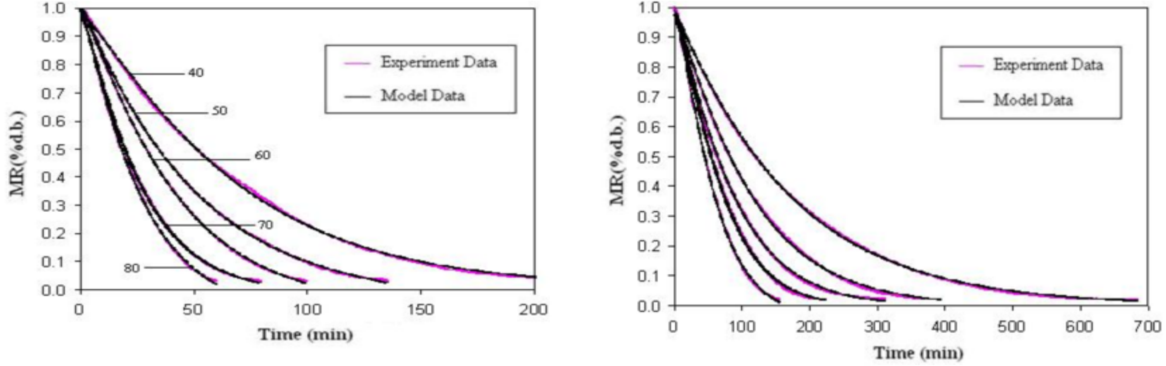
The effect of drying air temperature on drying time showed, that increase in drying air temperature resulted in decrease in drying time (figure 2). To reach the safe final moisture content (near zero), for example with a drying air velocity of 0.5 m/s for thickness of 2 mm, the drying time was 75 min at a drying air temperature of 80 °C which increased to 300 min at 40 °C.

The drying rate reached its maximum values at higher drying air temperatures. Drying rate decreased continuously with decreasing moisture content or increasing drying time (figure 3). The moisture removing to inside the apple slices with increasing drying air temperatures, and because of this, the drying rate clearly decrease.

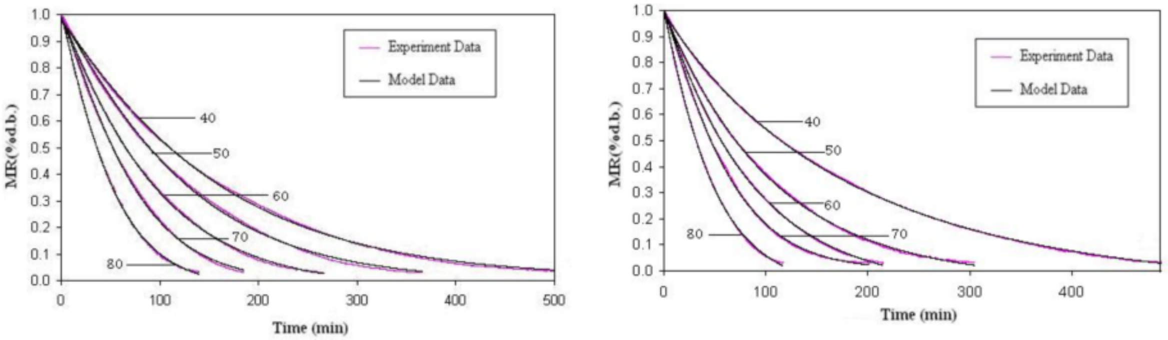
All the drying processes occurred in falling rate drying period, starting from the initial moisture content and reaching to the final moisture content (figure 3). Similar results have been reported for different crops by researchers (Akpinar, 2006; Akanbi *et al.*, 2006). As are indicated in these curves, there is no constant rate drying period in the drying of apple slices. The most effective force governing the moisture movement was diffusion.



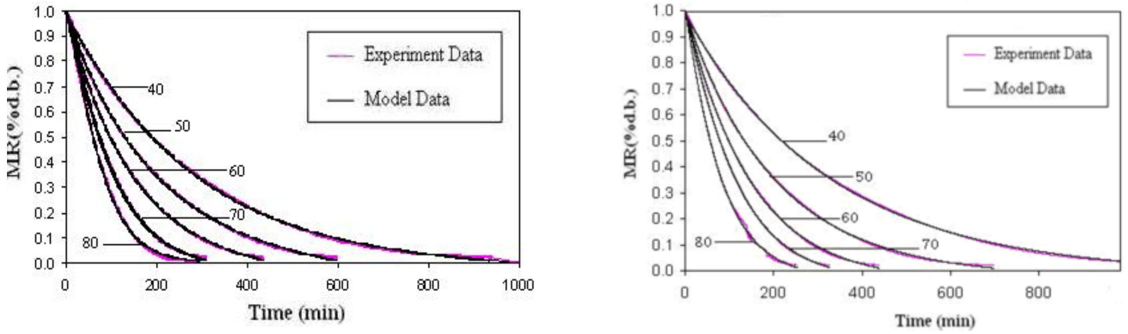
a- Air velocity at 0.5 m/s and thickness of 2 mm b- Air velocity at 1.0 m/s and thickness of 2 mm



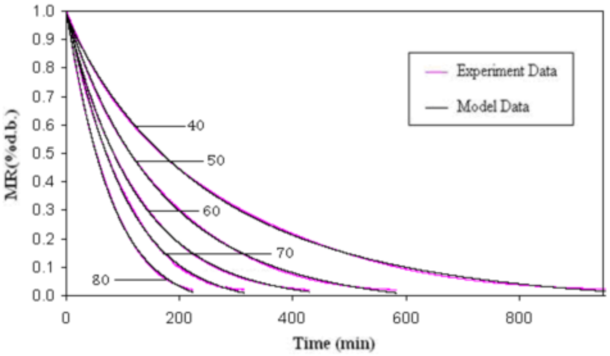
c- Air velocity at 2.0 m/s and thickness of 2 mm d- Air velocity at 0.5 m/s and thickness of 4 mm



e- Air velocity at 1.0 m/s and thickness of 4 mm f- Air velocity at 2.0 m/s and thickness of 4 mm



g- Air velocity at 0.5 m/s and thickness of 6 mm h- Air velocity at 1.0 m/s and thickness of 6 mm



i- Air velocity at 2.0 m/s and thickness of 6 mm

Figure 2. Effect of drying air temperature on drying time for Midilli *et al.* model.

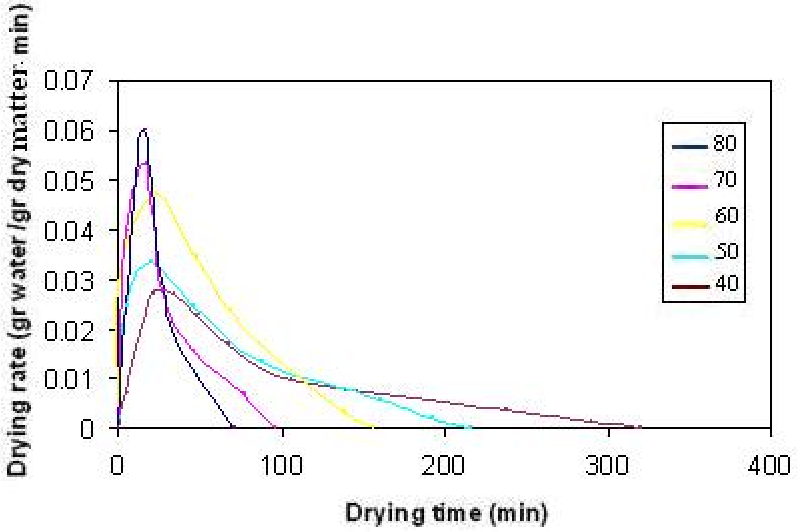


Figure 3. Drying rate changes with drying time for 2 mm thickness and 0.5 m/s velocity

According to the results of RMSE and chi-square values of all the thin-layer drying models for all drying conditions, the Midilli *et al.* 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 RMSE varied between 0.00292 and 0.03074 for all examined models, while the value varied between 0.000047 and 0.007724 for Midilli *et al.* model according to the different experimental conditions.

Table 3 showed that Midilli *et al.* model, in drying condition of 2 m/s air velocity, gave the lowest value of RMSE (0.00292) and chi-square (1.350×10^{-5}) and gave the highest value of EF (0.99972), among other drying air velocities. The drying constants (k) and (b) and coefficients (a) and (n), also statistical parameters RMSE, chi-square and EF for Midilli *et al.* model are shown in table 4.

Table 3. Average values of the statistical parameters of drying for different models for apple slices

Model	V=0.5 m/s			V=1 m/s			V=2 m/s		
	RMSE	χ^2	EF	RMSE	χ^2	EF	RMSE	χ^2	EF
Newton	0.02514	8.081×10^{-4}	0.99025	0.02271	6.372×10^{-4}	0.99218	0.01990	4.670×10^{-4}	0.99395
Page	0.00850	7.855×10^{-5}	0.99899	0.00839	7.328×10^{-5}	0.99905	0.00824	7.185×10^{-5}	0.99902
Modified page	0.00850	7.840×10^{-5}	0.99899	0.00839	7.332×10^{-5}	0.99905	0.00824	7.185×10^{-5}	0.99902
Henderson and Pabis	0.01959	4.701×10^{-4}	0.99429	0.01740	3.671×10^{-4}	0.99539	0.01532	1.881×10^{-2}	0.99642
Logarithmic	0.01069	1.450×10^{-4}	0.99819	0.00988	1.210×10^{-4}	0.99849	0.00658	4.967×10^{-5}	0.99933
Two term	0.01696	4.211×10^{-4}	0.99505	0.01564	3.200×10^{-4}	0.99612	0.01323	2.280×10^{-4}	0.99705
Two term exponential	0.02518	8.100×10^{-4}	0.99023	0.02274	6.320×10^{-4}	0.99216	0.01965	4.631×10^{-4}	0.99402
Wang and Singh	0.03074	1.253×10^{-3}	0.98324	0.02978	1.109×10^{-3}	0.98472	0.02616	8.780×10^{-4}	0.98707
Approximation of diffusion	0.00789	7.293×10^{-5}	0.99908	0.00722	6.215×10^{-5}	0.99921	0.00881	1.360×10^{-4}	0.99827
Verma et al.	0.01763	4.510×10^{-4}	0.99454	0.01172	1.710×10^{-4}	0.99785	0.01154	1.600×10^{-4}	0.99785
Modified Henderson and Pabis	0.01568	3.310×10^{-4}	0.99601	0.01434	2.610×10^{-4}	0.99679	0.01066	1.540×10^{-4}	0.99798
Aghabashlo model	0.01383	5.968×10^{-4}	0.99257	0.00594	4.180×10^{-5}	0.99945	0.00855	1.790×10^{-4}	0.99758
Weibull	0.00850	7.839×10^{-5}	0.9989	0.00838	8.003×10^{-5}	0.99906	0.00824	7.190×10^{-5}	0.99902
Midilli et al.	**0.00531**	$\mathbf{3.017\times10^{-5}}$	**0.99962**	**0.00582**	$\mathbf{3.580\times10^{-5}}$	**0.99954**	**0.00292**	$\mathbf{1.350\times10^{-5}}$	**0.99972**

It is clear, that RMSE and chi-square values were very low and varied between 0.000047 and 0.007724, and 0.000000002 and 0.000062711, respectively. So from all conditions the state of 4 mm thickness, 2 m/s air velocity and drying air temperature of 40 ºC, gave the lowest value of RMSE and chi-square. Modeling efficiency (EF) also ranged from 0.999201 to 0.999917, so from all conditions the state of 2 mm thickness, 2 m/s air velocity and drying air temperature of 50 ºC gave the highest value of EF. This model represented the experimental values satisfactorily.

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

Temp (°C)	V (m/s)	Thick (mm)	a	k (h^{-1})	n	b (h^{-1})	RMSE	EF	χ^2
40	0.5	2	0.981409	0.005752	1.137005	-0.000009	0.003351	0.999841	1.125×10^{-5}
		4	0.986153	0.004651	1.043105	0.000000	0.003955	0.999763	1.564×10^{-5}
		6	0.977963	0.002967	1.033864	-0.000022	0.005388	0.999577	2.900×10^{-5}
	1	2	0.975720	0.005866	1.165685	-0.000002	0.005775	0.999547	3.339×10^{-5}
		4	0.978295	0.004396	1.070790	0.000015	0.006184	0.999456	3.826×10^{-5}
		6	0.985893	0.003039	1.003515	-0.000009	0.004647	0.99967	2.160×10^{-5}
	2	2	0.984666	0.007448	1.150785	0.000041	0.006031	0.999497	3.640×10^{-5}
		4	0.993037	0.007078	0.958842	-0.000081	0.000047	0.999790	2.288×10^{-9}
		6	0.994124	0.006249	0.915147	-0.000021	0.005301	0.999540	2.810×10^{-5}
50	0.5	2	0.971079	0.008159	1.217684	0.000063	0.005740	0.999530	3.300×10^{-5}
		4	0.981287	0.004761	1.126114	0.000000	0.005605	0.999569	3.145×10^{-5}
		6	0.998966	0.006679	0.950992	-0.000078	0.004100	0.999755	1.680×10^{-5}
	1	2	0.982535	0.006629	1.212711	-0.000018	0.005351	0.999637	2.867×10^{-5}
		4	0.979208	0.004044	1.137975	0.000001	0.007912	0.99920	6.267×10^{-5}
		6	0.994668	0.005142	0.997791	-0.000028	0.004787	0.999662	2.290×10^{-5}
	2	2	1.009834	0.016955	1.050446	-0.000222	0.002502	0.999917	6.280×10^{-6}
		4	0.991306	0.008164	1.037219	-0.000079	0.000083	0.999641	6.973×10^{-9}
		6	0.996370	0.006808	0.973283	-0.000044	0.004748	0.999664	2.260×10^{-5}
60	0.5	2	0.966514	0.006854	1.336740	0.000109	0.007673	0.999247	5.900×10^{-5}
		4	0.987042	0.005783	1.150246	0.000000	0.004305	0.999751	1.855×10^{-5}
		6	0.996025	0.006957	1.002518	-0.000083	0.003122	0.999862	9.757×10^{-6}
	1	2	0.975885	0.007253	1.287832	0.000111	0.007293	0.999283	5.328×10^{-5}
		4	0.990349	0.00687	1.097581	-0.000063	0.005378	0.999617	2.896×10^{-5}
		6	0.993441	0.005552	1.046675	-0.000067	0.004734	0.999693	2.240×10^{-5}
	2	2	0.994560	0.013282	1.167777	-0.000354	0.002782	0.999905	7.771×10^{-6}
		4	1.004158	0.009893	1.048527	-0.000198	0.000068	0.999840	4.678×10^{-9}
		6	0.994055	0.007710	1.013391	-0.000032	0.003771	0.999791	1.420×10^{-5}
70	0.5	2	0.980264	0.012573	1.255762	-0.000106	0.005578	0.999626	3.120×10^{-5}
		4	0.973446	0.003984	1.280025	0.000000	0.007063	0.999395	4.997×10^{-5}
		6	0.991111	0.004757	1.154594	-0.000060	0.004187	0.999778	1.755×10^{-5}
	1	2	0.985945	0.011776	1.275746	-0.000198	0.003999	0.999814	1.605×10^{-5}
		4	0.976638	0.005268	1.224081	-0.000009	0.007724	0.999341	5.976×10^{-5}
		6	0.993155	0.005676	1.095576	-0.000084	0.003736	0.999817	1.400×10^{-5}
	2	2	0.990608	0.020905	1.172071	-0.000079	0.002849	0.999897	8.150×10^{-6}
		4	0.987013	0.007052	1.193110	0.000019	0.000109	0.999623	1.211×10^{-8}
		6	0.990987	0.006467	1.092407	-0.000070	0.005843	0.999546	3.420×10^{-5}
80	0.5	2	0.993264	0.011251	1.301372	-0.000708	0.006361	0.999554	4.066×10^{-5}
		4	0.981582	0.005205	1.279897	-0.000166	0.005819	0.999608	3.394×10^{-5}
		6	0.971848	0.003696	1.277096	0.000003	0.007395	0.999356	5.475×10^{-5}
	1	2	0.975321	0.010417	1.327375	-0.000230	0.007724	0.999322	5.990×10^{-5}
		4	0.993481	0.011032	1.147379	-0.000123	0.004873	0.999697	2.380×10^{-5}
		6	1.003355	0.009115	1.072081	-0.000083	0.007163	0.999319	5.140×10^{-5}
	2	2	1.000955	0.025247	1.135096	-0.00092	0.004574	0.999744	2.100×10^{-5}
		4	0.991068	0.014776	1.102151	-0.00034	0.000123	0.999724	1.515×10^{-8}
		6	0.990221	0.009626	1.071738	-0.00013	0.004927	0.999674	2.430×10^{-5}

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

4. CONCLUSIONS

Drying time decreased with increasing drying air temperature. The highest dehydration ratio was obtained at a drying air temperature of 80 °C. Results of thin layer modeling showed that, the Midilli *et al.* model could be used to explain moisture transfer in apple and gave the lowest value of RMSE and chi-square, and gave the highest value of EF. This model can be used between drying air temperatures between 40 and 80 °C, velocities of 0.5, 1, 2 m/s and thickness of 2, 4, 6 mm.

5. ACKNOWLEDGMENT

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