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MATHEMATICAL MODELS TO DETERMINE OF THIN LAYER DRYING KINETIC OF GINGER SLICES

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In the present work, the effects of some parametric values on the thin layer drying process of ginger slices were investigated. Drying was done in the laboratory by using cyclone type convective dryer. The drying air temperature was varied as 40, 50, 60 and 70 ˚C and the air velocity is 0.8, 1.5 and 3 m/s. All drying experiments had only falling rate period. The drying data were fitted to the twelve mathematical models and performance of these models was investigated by comparing the determination of coefficient (R^2), reduced chi-square (χ^2) and root mean square error (RMSE) between the observed and predicted moisture ratios. Among these models, drying model developed by Midilli et al. model showed good agreement with the data obtained from the experiments. From the Midilli et al. model for ginger slices, R^2, χ^2 and RMSE were determined between 0.99587 and 0.99971, 0.0006156 and 0.00003721 and, 0.019792 and 0.005597, respectively. Using regression analysis, the relationship between the coefficients of Midilli et al. model with drying air temperature and velocity was investigated.

Key Words: *Ginger, Drying kinetic, Thin layer drying, Mathematical models, Regression analysis*

1. Introduction

Fresh ginger is rich in oleoresins, a volatile antioxidant that has wide use in food as well as medicines. Similarly, dried ginger has also wide use as spice and medicine, thus has a potential for domestic and export market. Therefore, drying of ginger needs special attention to preserve the quality in the end product by suitable technique [1].

Drying of materials having high moisture content is a complicated process involving simultaneous heat and mass transfer [2]. The materials are dried by thin layer drying due to faster drying with minimum loss of nutrients. Thin-layer drying describes the process of drying in a single layer of sample particles. Three types of thin-layer drying models are used to describe the drying phenomenon of farm product. The theoretical model considers only the internal resistance to moisture transfer between product and heating air whereas semi-theoretical and empirical models consider only the external resistance [3-4]. Theoretical model needs assumptions of geometry of a typical food, its mass diffusivity and conductivity [5-6]; empirical model neglects the fundamentals of drying process and presents a direct relationship between average moisture and drying time by means of regression analysis [7-8], and semi-theoretical model is a tradeoff between the theoretical and empirical ones, derived from simplification of Fick's second law of diffusion or modification of the simplified model, which are widely used, such as the Lewis, Page, Modified Page, Henderson and Pabis, Logarithmic, Two term, Two term exponential, Diffusion approach, Modified Henderson and Pabis, Verma and Midilli *et al.* models [9-10]. Recently, very little studies have been conducted on the investigation of drying behavior of ginger using different drying methods and systems [1, 11-18]. Determination of drying kinetics and convective heat transfer coefficients of ginger slices was introduced in the literature in a previous work by authors [17-18]. The main objective of this study was to describe the thin layer drying kinetics of ginger at each experimental condition, using twelve empirical models. Relations between experimental conditions with coefficients of the selected model were to investigate.

2. Material and methods

2.1. Experimental set up

Figure 1 illustrates the schematic diagram of the cyclone type dryer, developed for experimental work [19]. The system was introduced in the literature [20]. Briefly, it consists of fan, resistance and heating control systems, air-duct, drying chamber in cyclone type, and measurement instruments.

In the measurements of temperatures, J type iron-constantan thermocouples were used with a manually controlled 20-channel automatic digital thermometer (Elimko 6400, Ankara, Turkey), with reading accuracy of ±0.1 °C. A thermo hygrometer (Extech 444731, Shenzhen, China) was used to measure humidity levels at various locations in the system. Moisture loss was recorded at 20-minute intervals during drying by means of a digital balance (Bel, Mark 3100, Monza, Italy) an accuracy of ±0.01 g (Fig. 1).

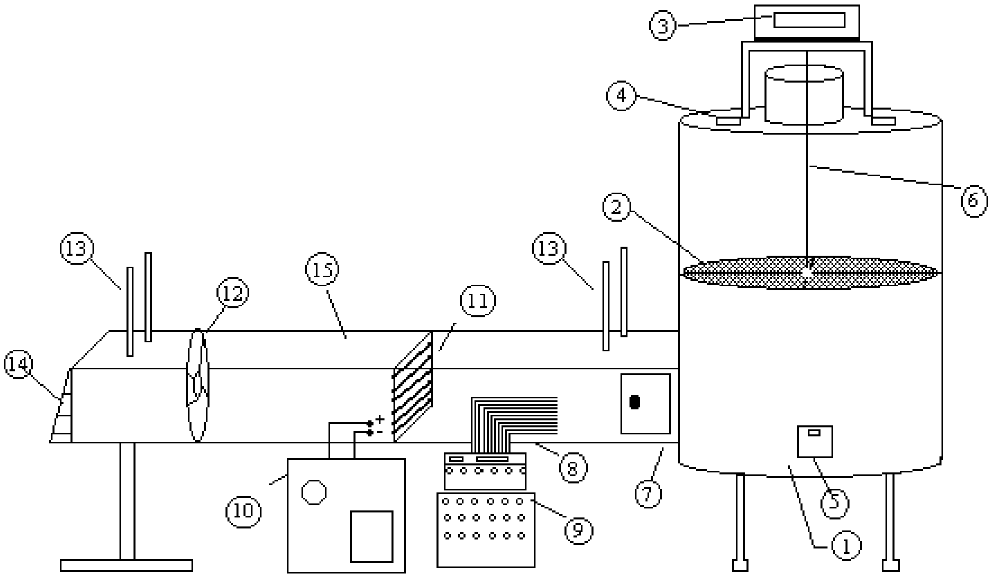

Figure 1. Experimental set-up (1- drying chamber, 2- tray, 3- digital balance, 4- observation windows, 5- digital thermometer, 6-the balance suspension bar, 7- control panel, 8- thermocouples, 9- digital thermometer and channel selector, 10-rheostat, 11- heater, 12- fan, 13- wet and dry thermometers, 14- adjustable flap, 15- duct)

2.2. Experimental procedure

Fresh ginger slices were used in the experiments. Before the drying process, the gingers were cut into slices of 4 mm thickness and 30 mm in diameter with a mechanical cutter. After the dryer had reached steady state temperature conditions for operation, 150 g ginger slices are put on the tray of dryer and dried there. The initial and final moisture contents of the ginger slices were determined at 80 °C using an infrared moisture analyzer (Mettler LJ16, Greifensee, Switzerland).

Drying experiments were carried out at 40, 50, 60, and 70°C drying air temperatures and 0.8, 1.5 and 3 m/s air velocities. Drying was continued until the average final moisture content (0.06 g water/g dry matter) from the average initial moisture content (4.8 g water/g dry matter). During the experiments, ambient temperature and relative humidity, and the inlet and outlet temperatures of the drying air in the dryer chamber were recorded.

2. 3. Mathematical modelling of drying curves

The moisture ratio (*MR*) of the ginger slices during the thin layer drying experiments was calculated using the following equation:

$$MR = \frac{M_t - M_e}{M_o - M_e} \tag{1}$$

where M_t, M_o and M_e are the anytime, the initial and equilibrium moisture contents (% dry basis) respectively [21].

Table 1. Thin layer drying curve models for the variation of moisture ratio (*MR*) with time (*t*)

Model no	Model name	Model	References
1	Newton	$MR = exp(-kt)$	[22]
2	Page	$MR = exp(-kt^n)$	[23]
3	Modified Page	$MR = exp\left[-(kt)^n\right]$	[24]
4	Henderson and Pabis	$MR = a.exp(-kt)$	[25]
5	Logarithmic	$MR = a.exp(-kt) + c$	[26]
6	Two term	$MR = aexp(-k_o t) + bexp(-k_1 t)$	[27]
7	Two-term exponential	$MR = aexp(-k\,t) + (1-a)exp(-k\,a\,t)$	[28]
8	Wang and Singh	$MR = 1 + at + bt^2$	[8]
9	Diffusion approach	$MR = aexp(-kt) + (1-a)exp(-k\,b\,t)$	[26]
10	Modified Henderson and Pabis	$MR = aexp(-kt) + bexp(-g\,t) + cexp(-ht)$	[29]
11	Verma *et al.*	$MR = aexp(-kt) + (1-a)exp(-g\,t)$	[30]
12	Midilli *et al.*	$MR = a.exp(-kt^n) + bt$	[3]

The experimental moisture ratio data of ginger obtained were fitted to the 12 commonly used thin-layer drying models in Tab. 1 [8, 22-30]. Non-linear least square regression analysis was performed using Levenberg-Marquardt procedure in Statistica 6.0 computer program. The goodness of fit of the selected mathematical models to the experimental data was evaluated with the correlation coefficient (R^2), the reduced chi-square (χ^2) and the root mean square error (RMSE). The goodness of fit will be better, if R^2 values are higher and χ^2 and RMSE values are lower. These can be calculated as:

$$R^2 = \frac{\sum_{i=1}^{n}\left(MR_i - MR_{pre,i}\right) . \sum_{i=1}^{n}\left(MR_i - MR_{exp,i}\right)}{\sqrt{\left[\sum_{i=1}^{n}\left(MR_i - MR_{pre,i}\right)^2\right] . \left[\sum_{i=1}^{n}\left(MR_i - MR_{exp,i}\right)^2\right]}} \tag{2}$$

$$\chi^2 = \frac{\sum_{i=1}^{n}\left(MR_{exp,i} - MR_{pre,i}\right)^2}{N-n} \tag{3}$$

$$RMSE = \left[\frac{1}{N}\sum_{i=1}^{N}\left(MR_{pre,i} - MR_{exp,i}\right)^2\right]^{1/2} \tag{4}$$

where, $MR_{exp,i}$ is the *ith* experimentally observed moisture ratio, $MR_{pre,i}$ the *ith* predicted moisture ratio, N the number of observations and n is the number constants [7, 31, 32].

3. Results and discussion

The times to reach the final moisture content from the initial moisture content at the various drying air temperature and velocity of the ginger slices were found to be between 8700 and 24900 seconds. The temperature is the major effect on the drying process, and, air velocity has less important effect on the drying of ginger slices. In order to normalize the drying curves, the data involving dry basis moisture content versus time were transformed to a dimensionless parameter called as moisture ratio versus time (Fig. 2). The moisture content data at the different experimental mode were converted to the most useful moisture ratio expression and then curve fitting computations with the drying time were carried on the 12 drying models evaluated by the different researches (Tab. 1). The results of statistical analyses undertaken on these models for the thin layer drying of ginger slices (Tabs. 2-4) were evaluated based on R^2, $\chi^2$and *RMSE*. Generally, the R^2, χ^2 and RMSE values changed between 0.91989 and 0.99971, 0.00003721 and 0.0124073, and 0.005597 and 0.086280, respectively. For the thin layer drying of ginger slices, the Midilli et al. model was the best descriptive model (Tabs. 2-4). From the Midilli *et al*. model for ginger slices, R^2, χ^2*and RMSE* were determined between 0.99587 and 0.99971, 0.0006156 and 0.00003721 and, 0.019792 and 0.005597, respectively. The Midilli et al. model gave a higher R^2 and lower χ^2, *RMSE* (Tables 2-4) all the experimental conditions and, thus, was selected to represent the thin layer drying behaviour of the ginger slices. According to the statistical indicators, the worst results were obtained with Page model (all temperature at V=0.8 m/s, T= 70 ℃ and 60 ℃ at V=1.5 m/s, T= 60 ℃ at V=3 m/s), Wang and Singh model (V=1.5 m/s and 3 m/s at T= 50 ℃), Modified Henderson and Pabis model (V=1.5 m/s and 3 m/s at T= 40 ℃) and Two term model (T= 70 ℃ at V=3 m/s).

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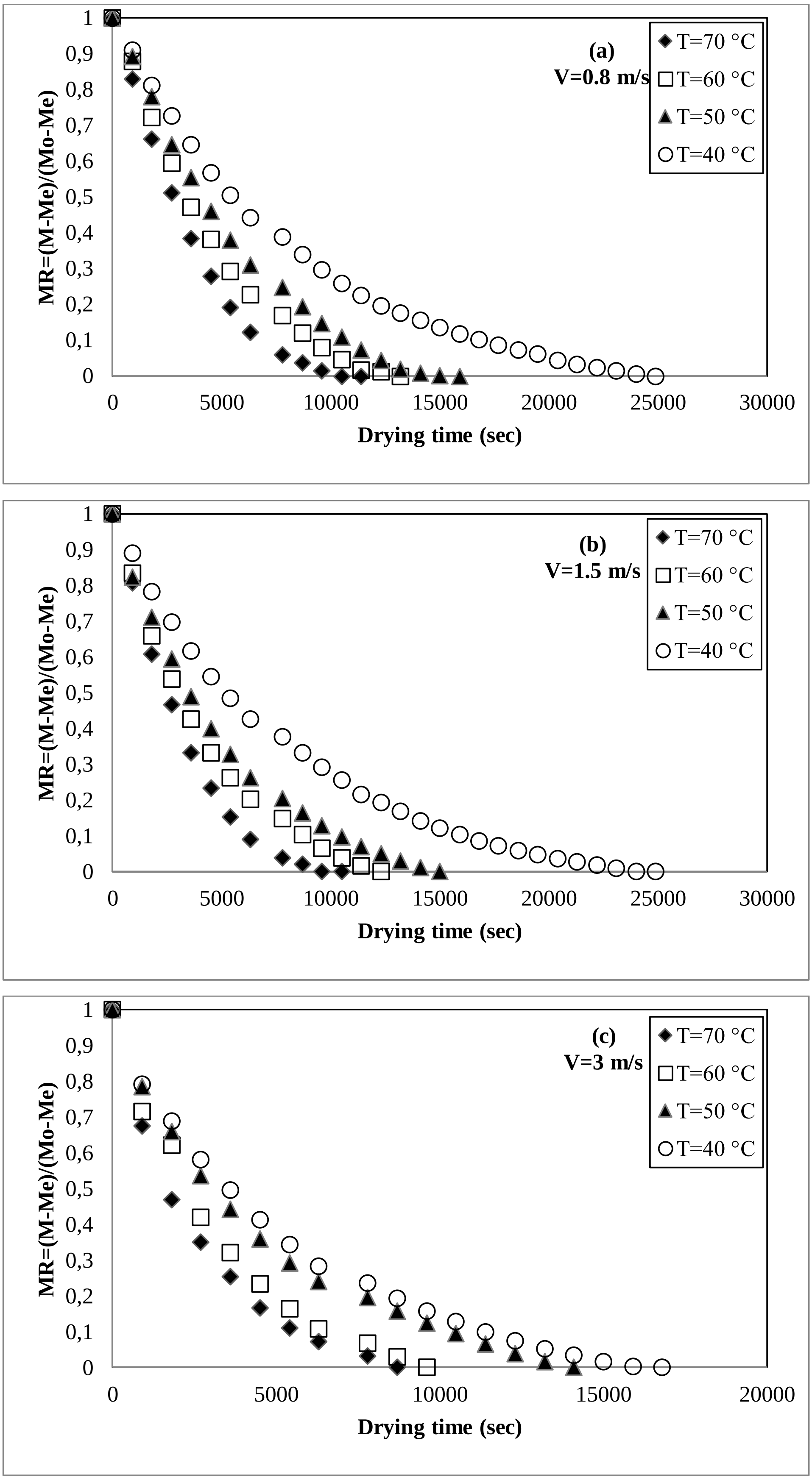

Figure 2. Variation of moisture ratio with drying time at different air temperatures and constant air velocities

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The values of the selected model coefficients *(a, k, n and b of Midilli et al. model)* are reported in Tab. 1. The regression analysis was used to set up the relations between these parameters with the temperatures and velocities. Thus, the regression equations of these parameters against drying temperature, *T (°C) and V (m/s)* for accepted model using linear equation are as follows:

$$a, k, n, b = f$$

$$a = 1.01746 + 0.000916V - 0.00029T \qquad R^2=0.50 \qquad (5)$$

$$k = -0.000220 + 0.000417V - 0.000002T \qquad R^2=0.82 \qquad (6)$$

$$n = 0.887897 - 0.12359V + 0.006242T \qquad R^2=0.93 \qquad (7)$$

$$b = -0.00000497 - 0.0000022V + 1.10^{-19}T \qquad R^2=0.82 \qquad (8)$$

k, n, b coefficients were dependent on drying air temperature and velocity. But, the values of *"a"* coefficient varied between *1.00 and 0.99* at all drying air velocities and temperatures. Therefore, *"a"* coefficient was not affected by drying air velocity and temperature. It remained stable. The R^2 values for *k, n, b* equations were between *0.82 and 0.93*, thus the coefficients of selected model could be calculated using these equations to estimate moisture ratio of ginger.

Validation of the established model was made by comparing the computed moisture contents with the measured moisture contents in any particular drying run under certain conditions. The performance of the model for the thin layer drying of ginger slices was illustrated in Fig. 3. The experimental data are generally banded around the straight line representing data found by computation, which indicates the suitability of the mathematical model in describing drying behavior of ginger slices.

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Table 2. Modelling of moisture ratio according to the drying time at 40, 50, 60, and 70˚C drying air temperatures and 3 m/s air velocity

		V=3 m/s, T=70 ºC				*V=3 m/s, T=60ºC*				*V=3 m/s, T=50ºC*				*V=3 m/s, T=40ºC*			
Model no	*Constants*	*Constants*	*R^2*	*χ^2*	*RMSE*	*Constants*	*R^2*	*χ^2*	*RMSE*	*Constants*	*R^2*	*χ^2*	*RMSE*	*Constants*	*R^2*	*χ^2*	*RMSE*
1	k	0.00041	0.99751	0.0002569	0.015206	0.00033	0.99191	0.0008447	0.027712	0.00023	0.99543	0.0004059	0.01950	0.00019	0.99359	0.0005560	0.022952
2	k	0.00068	0.99697	0.0003515	0.016769	0.000532	0.98840	0.0013452	0.033176	0.000582	0.99252	0.0007116	0.02495	0.000566	0.98968	0.0009482	0.029127
	n	0.93371				0.93976				0.89018				0.88202			
3	k	0.00041	0.99760	0.0002781	0.014918	0.00032	0.99362	0.0007399	0.024605	0.00023	0.99584	0.0003959	0.01861	0.00020	0.99460	0.0004957	0.021060
	n	0.97573				1.08629				0.98961				0.98038			
4	a	0.99718	0.99751	0.0002897	0.015225	1.01479	0.99178	0.0009529	0.027922	1.00372	0.99559	0.0004199	0.01916	0.98187	0.99496	0.0004625	0.020344
	k	0.00041				0.00033				0.00023				0.00020			
5	a	0.00244	0.99805	0.0002591	0.013469	1.06033	0.99539	0.0006020	0.020924	0.99208	0.99301	0.0007160	0.02411	1.00331	0.99317	0.000666	0.023689
	k	0.00039				0.00029				0.00025				0.00021			
	c	-0.01056				-0.05220				0.021784				0.009205			
6	a	0.428445	0.91989	0.0124073	0.086280	0.300440	0.99186	0.0012133	0.027786	0.590417	0.99568	0.0004793	0.01896	0.670941	0.99509	0.0005111	0.020088
	ko	0.000215				0.000313				0.000247				0.000199			
	b	0.428444				0.714003				0.406408				0.316897			
	k_1	0.00104				0.000340				0.000211				0.000199			
7	a	0.032905	0.99788	0.0002457	0.014020	0.009119	0.99169	0.0009636	0.028078	0.025142	0.99625	0.0271496	0.15412	0.023351	0.99528	0.0004334	0.019693
	k	0.011950				0.035261				0.008855				0.008418			
8	a	-0.0003	0.97072	0.0034011	0.052162	-0.0002	0.98595	0.0016292	0.036510	-0.0001635	0.97012	0.0003568	0.01766	-0.0001	0.97138	0.0026289	0.048499
	b	0.00000002				0.00000001				0.000000007				0.00000001			
9	a	0.032908	0.99788	0.0002808	0.014020	-0.134117	0.99343	0.0008574	0.024972	0.025943	0.99625	0.0003841	0.01766	0.024709	0.99528	0.0004603	0.019690
	k	0.019897				0.001020				0.027390				0.012465			
	b	0.019763				0.350979				0.008124				0.015751			
10	a	0.257540	0.99242	0.0017608	0.026539	-0.151314	0.99313	0.0014337	0.025528	0.315149	0.99245	0.0010056	0.02507	0.302676	0.95450	0.0054654	0.061151
	k	0.001304				0.001232				0.000209				0.000089			
	b	0.386343				0.577350				0.315149				0.305973			
	g	0.000318				0.000369				0.000207				0.000485			
	c	0.386343				0.565309				0.315149				0.305973			
	h	0.000318				0.000361				0.000209				0.000212			
11	a	-1.94983	0.99748	0.0003339	0.015288	-1.83309	0.99281	0.0009385	0.026126	-2.21304	0.99596	0.000414214	0.01834	-0.771462	0.99553	0.0004365	0.019173
	k	0.000487				0.000447				0.000182				0.000147			
	g	0.000457				0.000402				0.000195				0.000174			
12	**a**	**1.007039**	**0.99932**	**0.0001060**	**0.007977**	**0.993331**	**0.99587**	**0.0006156**	**0.019792**	**1.001472**	**0.99903**	**0.0001081**	**0.00900**	**1.01886**	**0.99833**	**0.0001740**	**0.011720**
	k	**0.001423**				**0.000330**				**0.000681**				**0.001323**			
	n	**0.830290**				**0.986345**				**0.858524**				**0.76493**			
	b	**-0.000009**				**-0.000006**				**-0.000005**				**-0.00001**			

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Table 3. Modelling of moisture ratio according to the drying time at 40, 50, 60, and 70°C drying air temperatures and 1.5 m/s air velocity

		V=1.5 m/s, T=70 ºC				*V=1.5 m/s, T=60ºC*				*V=1.5 m/s, T=50 ºC*				*V=1.5 m/s, T=40 ºC*			
Model no	*Constants*	*Constants*	*R^2*	*χ^2*	*RMSE*	*Constants*	*R^2*	*χ^2*	*RMSE*	*Constants*	*R^2*	*χ^2*	*RMSE*	*Constants*	*R^2*	*χ^2*	*RMSE*
1	k	0.00032	0.98654	0.0015488	0.037680	0.00024	0.99288	0.0007296	0.026028	0.00020	0.99357	0.0006125	0.02401	0.00014	0.99517	0.0004087	0.019854
2	k n	0.000384 0.97628	0.98381	0.0020483	0.041315	0.000333 0.966188	0.99057	0.0010466	0.029951	0.00026 0.974723	0.99308	0.0007033	0.02491	0.000468 0.866752	0.98330	0.0014674	0.036914
3	k n	0.00031 1.25280	0.99865	0.0001714	0.011952	0.00025 1.11608	0.99712	0.0003198	0.016558	0.00021 1.08236	0.99689	0.0003155	0.01668	0.00014 0.97522	0.99203	0.0007004	0.025503
4	a k	1.05414 0.00034	0.98901	0.0013907	0.034044	1.03912 0.00026	0.99430	0.0006328	0.023289	1.03077 0.00022	0.99474	0.0005346	0.02172	1.02955 0.00014	0.99493	0.0004450	0.020329
5	a k c	1.09832 0.00029 -0.06576	0.99684	0.0004440	0.018250	1.07147 0.00023 -0.05510	0.99891	0.0001325	0.010205	1.05714 0.00022 -0.003207	0.99391	0.000663	0.02336	1.06894 0.00015 -0.004938	0.99215	0.0007170	0.025303
6	a ko b k_1	1.826842 0.00046 -0.81942 0.000814	0.99781	0.0003463	0.015194	-0.093563 0.000366 1.133483 0.000266	0.99470	0.0007068	0.022469	0.511996 0.000219 0.511996 0.000221	0.99476	0.0006145	0.02167	0.511125 0.000139 0.511125 0.000139	0.99546	0.000431	0.019240
7	a k	0.002693 0.118472	0.98625	0.0017401	0.038080	0.002447 0.101508	0.99313	0.000763	0.025579	0.004844 0.043302	0.99448	0.000560	0.02224	0.005825 0.023317	0.99520	0.0004220	0.019795
8	a b	-0.00022689 0.00000001	0.99706	0.0003721	0.017611	-0.00018056 0.000000008	0.99106	0.0009932	0.029177	-0.0001512 0.00000001	0.98742	0.001278	0.03358	-0.00009559 0.000000002	0.98195	0.0015859	0.038374
9	a k b	-0.157991 0.019359 0.018969	0.99483	0.0007272	0.023354	-0.078678 0.012659 0.021209	0.99630	0.0004478	0.018758	-0.039406 0.015704 0.013950	0.99563	0.0004760	0.01979	-0.021106 0.012453 0.011208	0.99570	0.0003930	0.018732
10	a k b g c h	2.197149 0.000479 -0.787999 0.000912 -0.408693 0.000556	0.99721	0.0005878	0.017144	0.433591 0.000257 0.143389 0.000257 0.453699 0.000257	0.99451	0.0009148	0.022863	0.352955 0.000221 0.352955 0.000221 0.352955 0.000221	0.99307	0.0009598	0.02492	0.361445 0.000448 0.361445 0.000109 0.361445 0.000109	0.97929	0.0021508	0.041109
11	a k g	-2.85701 0.000713 0.000548	0.99620	0.0005340	0.020014	-2.79873 0.00045 0.00038	0.99480	0.0006295	0.022239	-1.60525 0.000115 0.000143	0.99895	0.00011471	0.00971	-1.09901 0.000064 0.000093	0.99453	0.0004996	0.021121
12	**a k n b**	**0.997348 0.000057 1.203643 -0.000003**	**0.99960**	**0.0000628**	**0.006474**	**1.002727 0.000168 1.036276 -0.000004**	**0.99945**	**0.0000727**	**0.007208**	**0.997912 0.000202 0.993314 -0.000004**	**0.99947**	**0.00006199**	**0.00688**	**1.001703 0.000186 0.955617 -0.000002**	**0.99951**	**0.00004647**	**0.006311**

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Table 4. Modelling of moisture ratio according to the drying time at 40, 50, 60, and 70°C drying air temperatures and 0.8 m/s air velocity.

		V=0.8 m/s, T=70 °C				*V=0.8 m/s, T=60 °C*				*V=0.8 m/s, T=50 °C*				*V=0.8 m/s, T=40 °C*			
Model no	*Constants*	*Constants*	*R^2*	*χ^2*	*RMSE*	*Constants*	*R^2*	*χ^2*	*RMSE*	*Constants*	*R^2*	*χ^2*	*RMSE*	*Constants*	*R^2*	*χ^2*	*RMSE*
1	k	0.00029	0.98278	0.0019857	0.042813	0.00023	0.98446	0.0016982	0.039812	0.00017	0.97721	0.0024287	0.04789	0.00012	0.98998	0.000872	0.029009
2	k n	0.000299 0.99344	0.98193	0.0022736	0.043862	0.000365 0.943322	0.97677	0.0027334	0.048672	0.000326 0.93564	0.97210	0.0031586	0.05298	0.000227 0.91869	0.95136	0.0044011	0.063927
3	k n	0.00028 1.32422	0.99855	0.0001828	0.012437	0.00022 1.24845	0.99757	0.0002860	0.015743	0.00018 1.27243	0.99651	0.0003948	0.01873	0.00013 0.93744	0.98999	0.0009058	0.029002
4	a k	1.06646 0.00031	0.98615	0.0017423	0.038396	1.08252 0.00024	0.98829	0.0013780	0.034559	1.08153 0.00020	0.98617	0.0015653	0.03730	1.03025 0.00013	0.99638	0.0003275	0.017439
5	a k c	1.10837 0.00026 -0.05773	0.99496	0.0006975	0.023164	1.15574 0.00020 -0.08890	0.99640	0.0004590	0.019162	1.13930 0.000199 -0.037992	0.98870	0.0013644	0.03371	1.03225 0.00015 0.030236	0.99037	0.0009058	0.028439
6	a ko b k_1	0.528448 0.000301 0.528448 0.000301	0.98561	0.0020750	0.037901	0.212004 0.000217 0.861260 0.000251	0.98844	0.0016081	0.034340	0.534480 0.000201 0.534480 0.000200	0.98649	0.0017486	0.03687	0.519899 0.000137 0.51989 0.000137	0.99624	0.0003682	0.017765
7	a k	0.000022 12.76146	0.98281	0.0021633	0.042784	0.002749 0.081617	0.98417	0.0018626	0.040178	0.002776 0.067483	0.98144	0.002101	0.04322	0.003375 0.038500	0.99507	0.0004459	0.020348
8	a b	-0.0002045 0.00000001	0.99811	0.0002376	0.014181	-0.0001634 0.00000001	0.99627	0.0004383	0.019491	-0.00013474 0.000000005	0.99722	0.0003142	0.01671	-0.00009299 0.000000002	0.98718	0.0011605	0.032826
9	a k b	-0.169596 0.021105 0.015716	0.99331	0.0009256	0.026684	-0.144924 0.060982 0.004216	0.99454	0.0006964	0.023604	-0.131699 0.024650 0.008604	0.99114	0.0010705	0.02986	-0.049925 0.012030 0.011376	0.99704	0.0002787	0.015777
10	a k b g c h	0.022357 0.000208 1.473202 0.000392 -0.504322 0.001000	0.99685	0.0006225	0.018308	0.553523 0.000240 0.255082 0.000243 0.255117 0.000245	0.98878	0.0019078	0.033833	0.354767 0.000200 0.354708 0.000200 0.354770 0.000200	0.98651	0.0020362	0.03684	0.343493 0.000134 0.341936 0.000134 0.345333 0.000134	0.99639	0.0003864	0.017425
11	a k g	-2.97038 0.000709 0.000530	0.99341	0.0009125	0.026494	-1.14587 0.000160 0.000184	0.98594	0.0017925	0.037868	-1.27293 0.000068 0.000107	0.99820	0.0002170	0.01344	-0.80896 0.000027 0.00006	0.97917	0.0019601	0.041834
12	**a** **k** **n** **b**	**0.995118** **0.000033** **1.252341** **-0.000002**	**0.99971**	**0.00003721**	**0.005597**	**1.007890** **0.000059** **1.148874** **-0.000003**	**0.99926**	**0.0001029**	**0.008688**	**1.006970** **0.000062** **1.114616** **-0.000004**	**0.99903**	**0.0001254**	**0.00987**	**1.007395** **0.000112** **1.009843** **-0.000002**	**0.99962**	**0.00004524**	**0.005648**

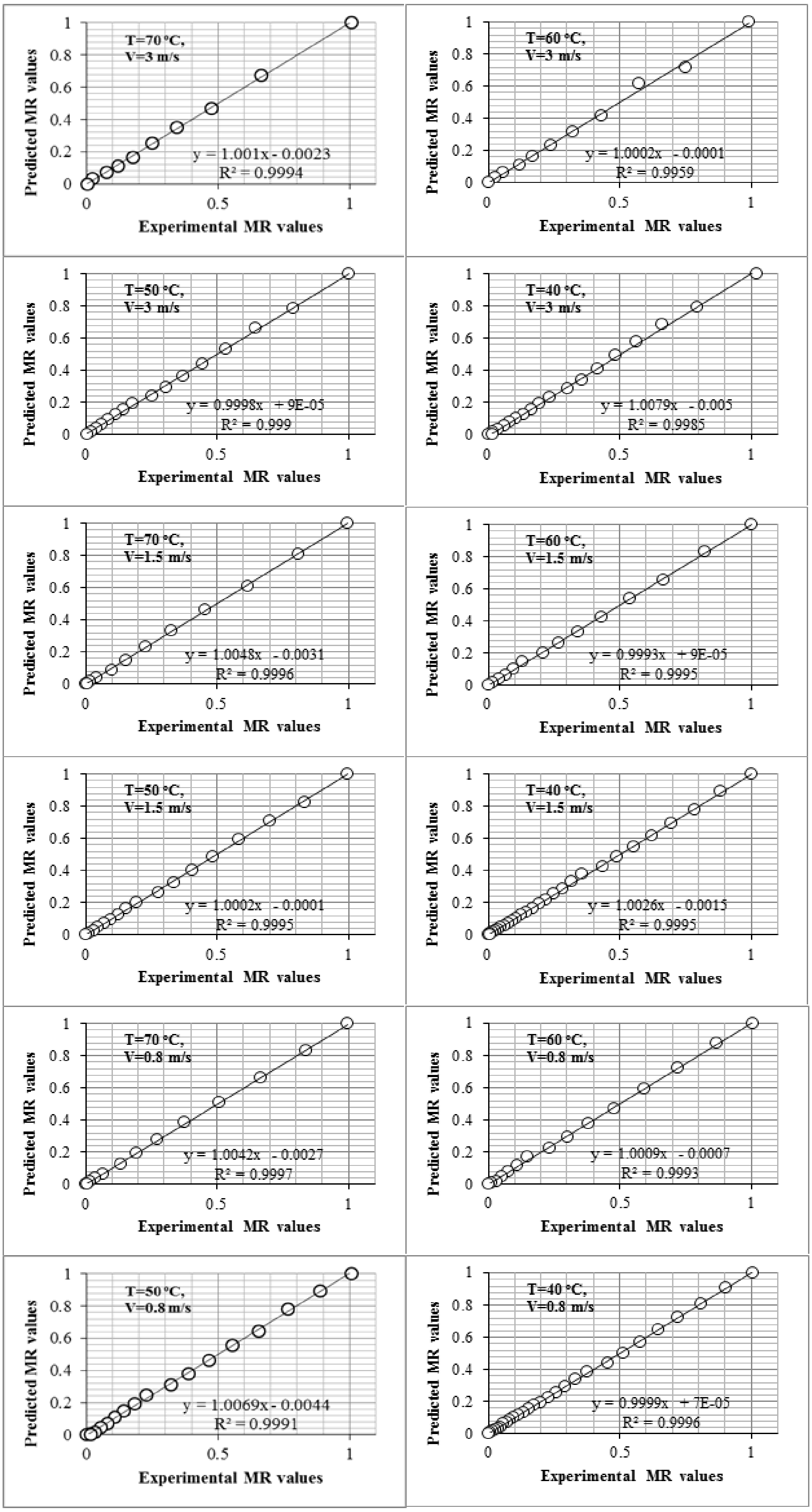

Figure 3. Comparison of experimental moisture ratios with those predicted from the Midilli *et al.* model for each one of the experimental conditions

4. Conclusions

The influence of drying air temperature and velocity on modeling of drying of ginger slices was investigated in this study. Drying of ginger slices occurred in falling rate period; no constant rate period of drying was observed for the present study, which implies that moisture removal from the material was governed by diffusion phenomenon. In order to explain the drying behaviour and to develop the mathematical modeling of ginger slices, 12 models were applied to thin layer forced drying processes. According to the statistical indicators, *Midilli et al. model* was found to be the most suitable for describing drying curve of the thin layer forced drying process of ginger slices. Among the twelve empirical models investigated in this study, the worst results were obtained with *Page, Wang and Singh, Modified Henderson and Pabis and Two term models* while the *Midilli et al. model* reasonably described the processes.

Nomenclature

a, b, c, g, h, n	empirical constants in the drying models
k, k_o, k_1	empirical coefficients in the drying models (s^{-1})
n	number constants
N	number of observations
M_e	moisture content in equilibrium state (dry basis)
M_o	moisture content at $t = 0$ (dry basis)
M_t	moisture content at t (dry basis)
MR	moisture ratio (dimensionless)
MR_{exp}	experimental moisture ratio (dimensionless)
MR_{pre}	predicted moisture ratio (dimensionless)
R^2	regression coefficient
RMSE	root mean square error
t	time (s, hr, min)
V	velocity (m/s)
T	temperature (^oC)
χ^2	chi-square

References

[1] Nema, P. K., Mohapatra, D., Daniel, A., Mishra, S., Modeling Pulse Microwave Drying Kinetics of Ginger (*Zingiber officinale R.*), *Journal of Food Research and Technology*, *1(2)* (2013), pp.46-58.

[2] Yilbas, B.S., Hussain, M.M., Dincer, I., Heat and Moisture Diffusion in Slab Products to Convective Boundary Condition, *Heat Mass Transf.*, 39 (2003), pp.471–476.

[3] Midilli, A., Kucuk, H., Yapar, Z., A New Model for Single Layer Drying, *Drying Technology*, *20(7)* (2002), pp.1503-1513.

[4] Panchariya, P.C., Popovic. D., Sharma, A.L., Thin-layer Modelling of Black Tea Drying Process, *J Food Eng. 52* (2002), pp.349–357. doi: 10.1016/S0260-8774(01)00126-1.

[5] Demirtas, C., Ayhan, T., Kaygusuz, K., Drying Behavior of Hazelnuts, *J Sci Food Agric.*, *76* (1998), pp.559–564. doi: 10.1002/(SICI)1097-0010(199804)

[6] Ece, M.C., Cihan, A., A Liquid Diffusion Model for Drying Rough Rice, *Trans Am Soc Agric Eng.*, *36* (1993), pp.837–840.

[7] Ozdemir, M., Devres, Y.O., The Thin Layer Drying Characteristics of Hazelnuts During Roasting, *J Food Eng.*, *42* (1999), pp.225–233. doi: 10.1016/S0260-8774(99)00126-0.

[8] Wang, C.Y., Singh, R.P., A Single Layer Drying Equation for Rough Rice, *ASAE Paper no: 3001* (1978).

[9] Kumar, N., Sarkar, B.C., Sharma, H.K., Mathematical Modelling of Thin Layer Hot Air Drying of Carrot Pomace, *J Food Sci Technol.*, *49(1)* (2012), pp.33–41.

[10] Silva, W.P., Silva, C.M.D.P.S., Gama, F.J.A., Gomes, J.P., Mathematical Models to Describe Thin-Layer Drying and to Determine Drying Rate of Whole Bananas, *Journal of the Saudi Society of Agricultural Sciences*, *13* (2014), pp.67–74.

[11] Parlak, N., Fluidized Bed Drying Characteristics and Modeling of Ginger (*zingiber officinale*) slices, *Heat Mass Transfer*, *51* (2015), pp.1085–1095.

[12] Schweiggert, U., Hofmann, S., Reichel, M., Schieber, A., Carle, R., Enzyme-assisted Liquefaction of Ginger Rhizomes (Zingiber officinale Rosc.) for the Production of Spray-Dried and Paste-Like Ginger Condiments, *Journal of Food Engineering*, *84* (2008), pp.28–38.

[13] Singhanat, P., Saentaweesuk, S., Effect of Two Stage, Tray And Heat Pump Assisted-Dehumidified Drying on Drying Characteristics and Qualities of Dried Ginger, *Food and Bioproducts Processing*, *89* (2011), pp.429–437.

[14] Eze, J.I., Agbo, K., Comparative Studies of Sun and Solar Drying of Peeled and Unpeeled Ginger, *Am. J. Sci. Ind. Res*, *2(2)* (2011), pp.136-143.

[15] Prasad, J., Vijay, V.K., Experimental Studies on Drying of Zingiber Officinale, Curcuma longa l. and Tinospora Cordifolia in Solar-Biomass Hybrid Drier, *Renewable Energy*, *30* (2005), pp.2097–2109.

[16] Thorat, I.D., Mohapatra, D., Sutar, R.F., Kapdi, S.S., Jagtap, D.D., Mathematical Modeling and Experimental Study on Thin-Layer Vacuum Drying of Ginger (Zingiber Officinale R.) Slices, *Food Bioprocess Technol*, DOI 10.1007/s11947-010-0429-y, 2010.

[17] Akpinar, E.K., Toraman, S., Estimation of The Moisture Diffusivity and Activation Energy in Thin Layer Drying of Ginger Slices, *World Academy of Science, Engineering and Technology*, *78* (2013) 2013-06-27.

[18] Akpinar, E.K., Toraman, S., Determination of Drying Kinetics and Convective Heat Transfer Coefficients of Ginger Slices, *Heat Mass Transfer*, 2015, DOI 10.1007/s00231-015-1729-6.

[19] Akpinar, E.K. The Development of a Cyclone Type Dryer for Agricultural Products, PhD Thesis, Firat University, Elazig, Turkey, 2002.

[20] Akpinar, E., Midilli, A., Bicer, Y., Single Layer Drying Behavior of Potato Slices in a Convective Cyclone Dryer and Mathematical Modeling, *Energy Conversion and Management, 44* (2003), pp.1689-1705.

[21] Doymaz, I., Evaluation of Some Thin-Layer Drying Models of Persimmon Slices (Diospyros kaki L.), *Energy Conversion and Management*, *56* (2012), pp.199-205.

[22] Mujumdar, A.S., Handbook of Industrial Drying, Marcel Dekker, New York, 1987.

[23] Diamante, L.M., Munro, P.A., Mathematical Modelling of Thin Layer Solar Drying of Sweet Potato Slices, *Solar Energy*, 51 (1993), pp.271-276.

[24] Overhults, D.G., White, H.E., Hamilton, H.E., Ross, I.J., Drying Soybeans with Heated Air, *Transactions of the ASAE*, *16* (1973), pp.112-113.

[25] Zhang, Q., Litchfield, J.B., An Optimization of Intermittent Corn Drying in A Laboratory Scale Thin Layer Dryer, *Drying Technology*, *9* (1991), pp.383-395.

[26] Yaldız, O., Ertekin, C., Thin Layer Solar Drying of Some Vegetables, *Drying Technology*, *19* (2001), pp.583-596.

[27] Henderson, S.M., Progress in Developing The Thin Layer Drying Equation, *Transactions of the ASAE*, *17* (1974), pp.1167-1172.

[28] Sharaf-Eldeen, Y.I., Blaisdell, J.L., Hamdy, M.Y., A Model For Ear Corn Drying, *Transaction of the ASAE*, *23* (1980), pp.1261-1271.

[29] Karathanos, V.T., Determination of Water Content of Dried Fruits by Drying Kinetics, *Journal of Food Engineering*, *39* (1999), pp.337-344.

[30] Verma, L.R., Bucklin, R.A., Endan, J.B., Wratten, F.T., Effects of Drying Air Parameters on Rice Drying Models, *Transaction of the ASAE*, *28* (1985), pp.296-301.

[31] Akpinar, E.K., Determination of Suitable Thin Layer Drying Curve Model For Some Vegetables And Fruits, *Journal of Food Engineering*, *73(1)* (2006), pp.75-84.

[32] Gunhan, T., Demir, V., Hancioglu, E., Hepbasli, A., Mathematical Modelling of Drying of Bay Leaves, *Energy Conversion and Management*, *46(11-12)* (2005), pp.1667-1679.