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Mathematical Modeling of Thin Layer Drying Kinetics of Tomato Influence of Air Dryer Conditions

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ABSTRACT

Thin-layer drying kinetics of Tomato was experimentally investigated in a pilot scale convective dryer. Experiments were performed at air temperatures of 40, 60, and 80ºC and at three relative humidity of 20%, 40% and 60% and constant air velocity of 2 m/s. In order to select a suitable form of the drying curve, 9 different thin layer drying models were fitted to experimental data. The high values of coefficient of determination and the low values of reduced sum square errors and root mean square error indicated that the Midilli et al. model could satisfactorily illustrate the drying curve of tomato. the Midilli et al. model had the highest value of R^2 (0.9997), the lowest SSE (0.22662) and RMSE (0.0040912) for relative humidity of 20% and air velocity of 2 m/s. the Midilli et al. model had the highest value of R^2 (0.99946), the lowest SSE (0.46702) and RMSE (0.0051192) for relative humidity of 40% and air velocity of 2 m/s. the Midilli et al. model had the highest value of R^2 (0.99952), the lowest SSE (0.438982) and RMSE (0.0050188) for relative humidity of 60% and air velocity of 2 m/s. The Midilli et al. model was found to satisfactorily describe the drying behavior of tomato.

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1 Introduction

Tomato (*Lycopersicon esculentum L.*) is one of the most popular vegetable crops grown all over the world, both for fresh marketing as well as for processing industry (Espinoza, 1991). Crops of tomatoes have socioeconomic importance to families, gardeners, farmers, laborers, marketers, retailers, chefs and other workers and services in the food and restaurant industries in Iran. Moreover, tomato is a crop of high commercial value. Compared to other vegetables, their fruits are less perishable and more resistant to transportation damage and have wide uses in food products, excellent organoleptic qualities, and a high nutritional value (Barbosa, 1993). The reduction of moisture is one of the oldest techniques for food preservation. Mechanical and thermal methods are two basic methods to remove the moisture in a solid material (Karimi, 2010). Raw foods have high amount of moisture and thus perishable. Many applications of drying have been successfully applied to decrease physical, biochemical and microbiological deterioration of food products due to the reduction of the moisture content to the level, which allows safe storage over a long period and brings substantial reduction in weight and volume, minimizing packaging, storage and transportation costs (Zielinska and Markowski, 2010).

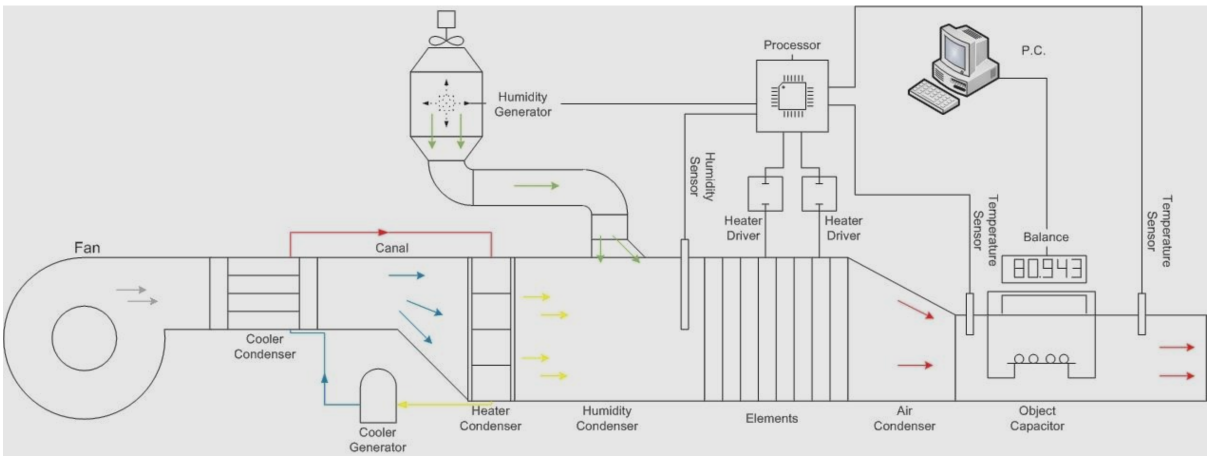

Figure 1: Scheme of pilot plan thin-layer drying equipment.

The principle of modelling is based on having a set of mathematical equations which can satisfactorily explain the system. The solution of these equations must allow calculation of the process parameters as a function of time at any point in the dryer based only on the primary condition (Kaleta and Górnicki, 2010). Hence, the use of a simulation model is an important tool for prediction of performance of drying systems. The objective of this research was the evaluation and the modeling of the drying kinetics of mass transfer during the hot-air drying process of Tomato, and the analysis of the influence of air dryer conditions on the kinetic constants of the proposed models.

2 Materials And Methods

2.1 Samples Preparation and drying unit

Drying experiment was performed using pilot scale dryer which was designed and fabricated by Amin Taheri-Garavand in the Department of Agricultural Machinery at University of Tehran. A schematic diagram of this dryer is shown in Figure 1. A portable, 0-10 m/s range digital anemometer (TESTO, 405-V1) was used to measure passing air flow velocity through the system. The airflow was adjusted by a variable speed blower. The heating structure was consisted of ten heating elements placed inside the canal. Moreover, a simple control algorithm was used to control and adjust the drying tunnel temperature and relative humidity of air used to drying. The opening side on the right was used to load or unload the tunnel and to measure drying air velocity. The trays were supported by lightweight steel rods placed under the digital balance. The used measuring instruments with their specifications are given in Table 1.

Table 1: Specifications of measurement instruments including their rated accuracy

Instrument	Model	Accuracy	Manufacturer
Digital balance	GF3000	±0.02	A&D, Japan
T-sensor	LM35	$\pm 1^{0}$C	NSC, USA
RH-sensor	SHT15	±2%	CHINA
V-sensor	405-V1	±3%	TESTO, UK

The airflow control unit was regulated 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 relative humidity in the range of 5 to 95% and air velocity in the range of 0.1 to 5.0 m/s with high accuracy. After turning on the computer, fan, scale, elements and data acquisition system, the essential velocity for the fan

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was set. A manual sensor (TESTO 405-V1) was used to measure the velocity. The control software was implemented and the required temperature and relative humidity of air for the experiment were adjusted. Experiments were carried out 20 minutes after the system was turned on to reach to its steady state condition. After that, the tray holding the samples is carefully put in the dryer. Prior to drying, samples were taken out of storage, tomato were washed and sliced in thickness of 10mm using a cutting machine. About 200 g of tomato slices were weighed and uniformly spread in a tray and kept inside the dryer. Three replications of each experiment were performed according to a pre-set air temperature and time schedule. The reproducibility of the experiments was within the range of ±5%. The hot air drying was applied until the weight of the sample reduced to a level corresponding to moisture content of about 0.5% d.b. The drying experiment was conducted at three air temperatures of 40, 60 and 80°C and at three relative humidity 20%, 40% and 60% and constant air velocity of 2.0 m/s.

The initial and final moisture contents of the tomato were determined at 78°C during 48 h with the oven method (AOAC 1984).

Table 2: Consideration of thin layer drying curve models.

Mode no.	Model name	Model	References
1	Newton	$MR = \exp(-kt)$	(Henderson, 1974)
2	Aghbashlo et al	$MR=\exp(-k_1t/1+k_2t)$	(Guarte, 1996)
3	Page	$MR = a\exp(-kt)$	(Zhang and Litchfield,1991)
4	Henderson and Pabis	$MR = \exp(-kt^n)$	(Aghbashlo et al., 2009)
5	Logarithmic	$MR = a\exp(-kt) + c$	(Karathanos, 1999)
6	Tow term	$MR = a\exp(-k_0t) + b\exp(-k_1t)$	(Yaldiz et al., 2001)
7	Wang and Singh	MR = 1+ at+ bt2	(Wang and singh, 1978)
8	Modified Henderson and Pabis	$MR = a\exp(-kt) + b\exp(-gt) + c\exp(-ht)$	(Karathanos, 1999)
9	Midilli et al.	$MR = a\exp(-kt^n) + bt$	(Midilli et al., 2002)

2.2 Mathematical modeling of drying curves

The moisture ratio (MR) of tomato during drying experiments was calculated using the following equation:

$$MR = \frac{M_d - M_e}{M_0 - M_e} \quad (1)$$

Where M, M_o, and Me are moisture content at any drying time, initial and equilibrium moisture content (kg water/kg dry matter), respectively. The values of M_e are relatively little compared to those of M or M_o, the error involved in the simplification is negligible (Aghbashlo et al., 2008), thus moisture ratio was calculated as:

$$MR = \frac{M_d}{M_0} \quad (2)$$

For drying model selection, drying curves were fitted to 9 well known thin layer drying models which are given in Table 2. The best of fit was determined using three parameters: higher values for coefficient of determination (R^2), reduced sum square errors (SSE) and root mean square error (RMSE) using Equations (3-5), respectively. The statistical analyses were carried out using SPSS 15 software.

$$R^2 = 1 - \left[\frac{\sum_{i=1}^{N} \left(MR_{per,i} - MR_{\exp,i} \right)^2}{\sum_{i=1}^{N} \left(\overline{MR}_{per} - MR_{\exp,i} \right)^2} \right] \quad (3)$$

$$SSE = \frac{\sum_{i=1}^{n} (MR_{\exp,i} - MR_{pre,i})^2}{N} \quad (4)$$

$$RMSE = \left[\frac{1}{N} \sum_{i=1}^{n} (M_{\exp,i} - M_{pre,i}) \right]^{1/2} \quad (5)$$

In the above Equations $MR_{pre,i}$ is the ith predicted moisture ratio, $MR_{exp,i}$ is the ith experimental moisture ratio, N is number of observations and m is number of constants.

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Table 3: Statistical results obtained from the selected models in air relative humidity 20% and air velocity of 2 ms^{-1}.

Model name	R^2	SSE	RMSE
Newton	0.99596	3.2558	0.012883
Aghbashlo et al	0.999	0.761066	0.0069756
Page	0.99928	0.55004	0.0060664
Henderson and Pabis	0.99828	1.80555	0.009773
Logarithmic	0.99878	0.945334	0.007509
Tow term	0.99954	0.294242	0.005067
Wang and Singh	0.9073	68.538	0.068802
Modified Henderson and Pabis	0.99376	2.61954	0.0147808
Midilli et al.	**0.9997**	**0.22662**	**0.0040912**

3 Results and Discussion

The drying process was stopped after no further change in weights was observed. At this point moisture content decreased from 93.5 % to 15 % (w.b.). Moisture content data were converted to moisture ratio and then fitted to the 9 thin layer drying models Table 3 showed that the results of fitting the experimental data to the thin layer drying models listed in Table 2 (R^2, RMSE and SSE). The best-fitting model for air relative humidity of 20% and air velocity of 2 m/s was bolded in Table 3. Criterion for selection of the best model describing the thin layer drying kinetics was according to the highest R^2 average values, and the lowest RMSE and SSE average values.

Therefore, the best model for this quantity of air velocity are the Midilli et al. model had the highest value of R^2 (0.9997), the lowest SSE (0.22662) and RMSE (0.0040912) for relative humidity of 20% and air velocity of 2 m/s.

Table 4 showed that the results of fitting the experimental data to the thin layer drying models listed in Table 2 (R^2, RMSE and SSE). The best-fitting model for air relative humidity of 40% and air velocity of 2 m/s was bolded in Table 4. criterion for selection of the best model describing the thin layer drying kinetics was according to the highest R^2 average values, and the lowest RMSE and SSE average values.

Therefore, the best model for this quantity of air velocity are the Midilli et al. model had the highest value of R^2 (0.99946), the lowest SSE (0.46702) and RMSE (0.0051192) for relative humidity of 40% and air velocity of 2 m/s.

Table 4: Statistical results obtained from the selected models in air relative humidity 40% and air velocity of 2 ms^{-1}.

Model name	R^2	SSE	RMSE
Newton	0.99016	9.04082	0.020216
Aghbashlo et al	0.99732	2.22384	0.0111926
Page	0.99806	0.92046	0.0079704
Henderson and Pabis	0.99706	3.09468	0.01295
Logarithmic	0.99834	1.44388	0.008606
Tow term	0.99892	0.763848	0.0067776
Wang and Singh	0.8126	125.132	0.25287
Modified Henderson and Pabis	0.98874	6.385678	0.017562
Midilli et al.	**0.99946**	**0.46702**	**0.0051192**

Table 5: Statistical results obtained from the selected models in air relative humidity 60% and air velocity of 2 ms^{-1}.

Model name	R^2	SSE	RMSE
Newton	0.99504	4.38732	0.0157338
Aghbashlo et al	0.99678	2.74864	0.0113034
Page	0.99746	2.07876	0.0084634
Henderson and Pabis	0.99752	2.16842	0.0064662
Logarithmic	0.99884	0.96112	0.0077736
Tow term	0.99906	0.6957	0.0066556
Wang and Singh	0.87794	95.752	0.081096
Modified Henderson and Pabis	0.96688	17.9552	0.0279632
Midilli et al.	**0.99952**	**0.438982**	**0.0050188**

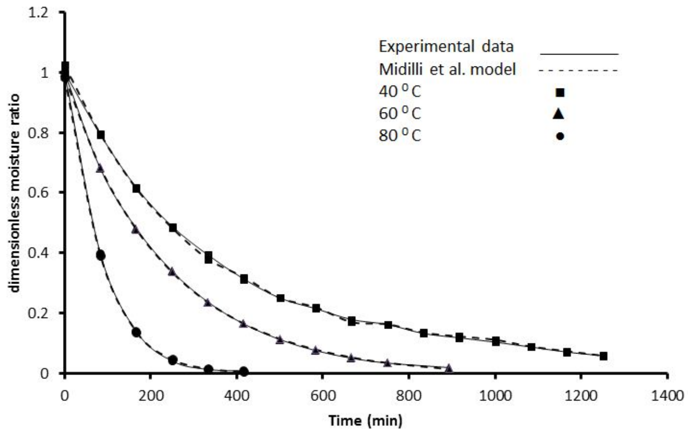

Figure 2: Experimental and predicted moisture ratio by the Midilli et al. model versus drying time for air velocity of 2m/s and relative humidity 20%.

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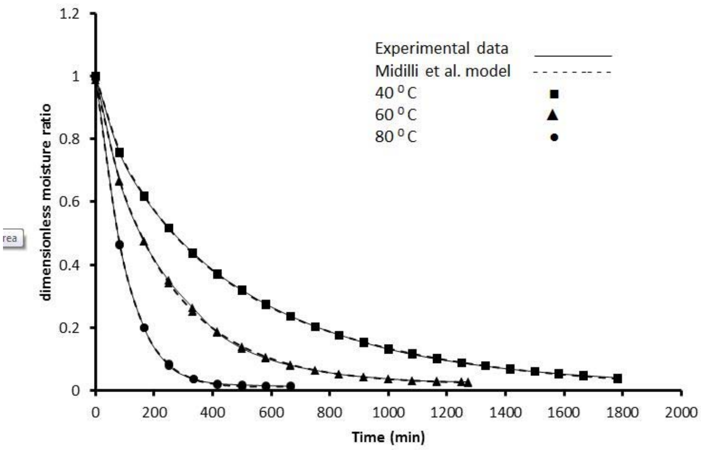

Figure 3: Experimental and predicted moisture ratio by the Midilli et al. model versus drying time for air velocity of 2m/s and relative humidity 40%.

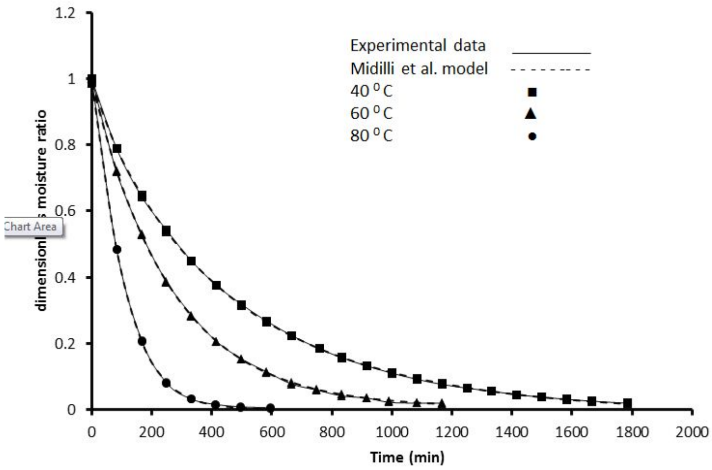

Figure 4: Experimental and predicted moisture ratio by the Midilli et al. model versus drying time for air velocity of 2m/s and relative humidity 60%.

Table 5 showed that the results of fitting the experimental data to the thin layer drying models listed in Table 2 (R^2, RMSE and SSE). The best-fitting model for air relative humidity of 40% and air velocity of 2 m/s was bolded in Table 5. criterion for selection of the best model describing the thin layer drying kinetics was according to the highest R^2 average values, and the lowest RMSE and SSE average values.

Therefore, the best model for this quantity of air velocity are the Midilli et al. model had the highest value of R^2 (0.99952), the lowest SSE (0.438982) and RMSE (0.0050188) for relative humidity of 60% and air velocity of 2 m/s.

The constants of Midilli et al. model are presented in Table 6-8 for different drying conditions.

Figures 2-4 present the variation of experimental and predicted moisture ratio using the best models with drying time for dried Tomato. the Midilli et al. Model gives a good estimation for the drying process. As can be seen from Figures 2-4, by increasing air temperature, a decrease in drying time was observed. Also Figure 1 exhibits the variation of moisture ratio as a function of time. The moisture ratio of the samples decreased continually with drying time. As expected, increase in the temperature of drying air reduces the time required to reach any given level of moisture ratio since the heat transfer Increases. in other words, at high temperatures the transfer of heat and mass is high and water loss is excessive This can be explained by increasing temperature difference between the drying air and the product and the resultant water migration. These results are in agreement with other findings reported for drying of tomato.

These figures showed that the experimental and calculated moisture ratio of the best model, where a good fit can be graphically observed when using these equations. In addition, other authors have obtained good results when applying this model in drying kinetics of food (Arumuganathan et al., 2009; Simal et al., 2005; Meisami-asl et al., 2010).

Figures 5-7 show moisture ratio versus drying time at constant air velocity and air temperature for relative humidity 20, 40 and 60%. It is clear that at a low relative humidity, the difference between total times is significant while at a high relative humidity, In other words, these figures show the effect of the air relative humidity on the moisture ratio versus drying time at constant air velocity and air temperature.

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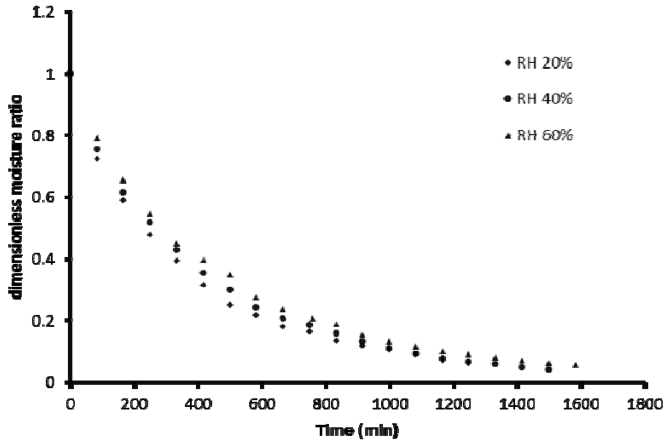

Figure 5: moisture ratio versus drying time for air temperature 40 and air velocity of 2m/s.

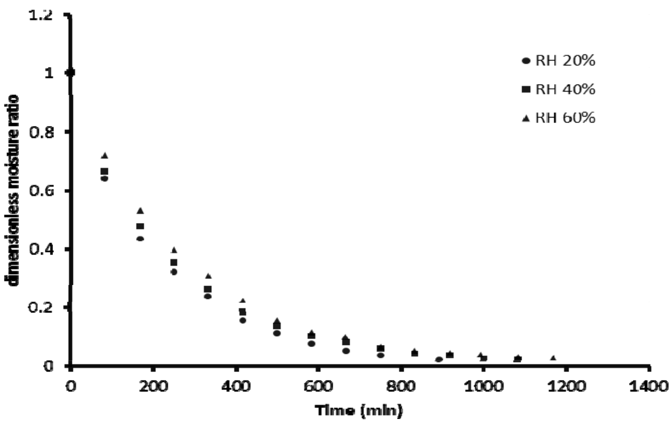

Figure 6: moisture ratio versus drying time for air temperature 60 and air velocity of 2m/s.

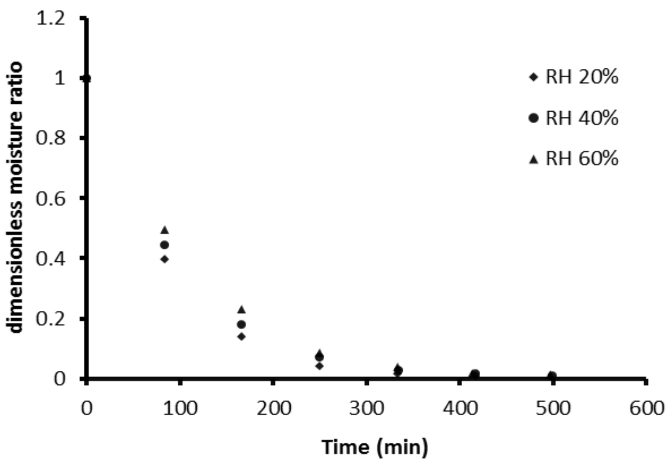

Figure 7: moisture ratio versus drying time for air temperature 80 and air velocity of 2m/s.

As can be seen from Figures 5-7, by decreasing air relative humidity, a decrease in drying time was observed. Also Figures 5-7 exhibit the variation of moisture ratio as a function of time. The moisture ratio of the samples decreased continually with drying time. As expected, decrease in the relative humidity of drying air reduces the time required to reach any given level of moisture ratio since the mass transfer Increases. In other words, at low relative humidity of air the transfer of heat and mass is high and water loss is excessive This can be explained by increasing temperature difference between the drying air and the product and the resultant water migration. These results are in agreement with other findings reported for drying of tomato.

Figure **8** exhibits moisture ratio versus drying time and air velocity for relative humidity 20%.

Table 6: Values of the drying constant and coefficients of the best model (**Midilli et al.** model) in air relative humidity 20% and air velocity of 2 ms^{-1}

Temperature (°C)	a	k	n	b
40	1.024	0.01228	0.8077	-0.000001394
60	0.9848	0.004837	0.9774	-0.00001031
80	0.9842	0.007353	1.092	0.000002443

Table 7: Values of the drying constant and coefficients of the best model (**Midilli et al.** model) in air relative humidity 40% and air velocity of 2 ms^{-1}

Temperature (°C)	a	k	n	b
40	1.001	0.01228	0.7941	-0.000002987
60	0.9874	0.00718	0.9057	-0.00001313
80	0.9923	0.006157	1.09	0.00001897

Table 8: Values of the drying constant and coefficients of the best model (**Midilli et al.** model)in air relative humidity 60% and air velocity of 2 ms^{-1}

Temperature (ºC)	a	k	n	b
40	0.9877	0.004041	0.9071	-0.000005254
60	0.9847	0.003658	1.055	0.000005024
80	0.992	0.004847	1.13	0.000003642

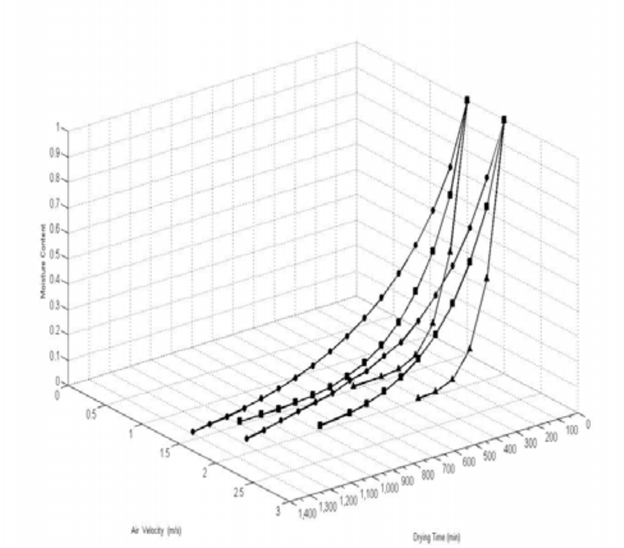

Figure 8: Moisture ratio versus drying time and air velocity for relative humidity 20% .

4 Conclusion

The drying behavior of tomato slices in a pilot dryer was investigated at three different drying air temperatures and three different drying air relative humidifies. The times to reach equilibrium moisture (15%) from the initial moisture content at three temperatures and air relative humidity were found to be between 420 and 1800 min. In order to explain the drying behavior of tomato cultivated in Iran, 9 models in the literature were applied and fitted to the experimental data. According to the statistical analysis applied to all models, it can be concluded that among these models, Midilli et al. gave the best results. In addition to, these results showed good agreement with the experiment data. It can be concluded that the influence of air temperature on drying time cause to with increase in air temperature a decrease in drying time during falling rate period is observed. According to the results, it can be stated that Midilli et al model. could describe the drying characteristics of tomato in the drying process at a temperature range 40-80 °C and air relative humidity 20-60% air velocity of 2 ms^{-1}. The effect of air temperature on drying time, by increasing air temperature, a decrease in drying time was observed. The effect of air relative humidity on drying time, by decreasing air t relative humidity, a decrease in drying time was observed.

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6 References

Aghbashlo M, Kianmehr MH, Samimi-Akhljahani H (2008) Influence of drying conditions on the effective Effective moisture diffusivity, energy of activation and energy consumption during the thin-layer drying of barberries fruit (Berberidaceae). *Energy Conversion and Management* 49: 2865–2871.

Aghbashlo M, Kianmehr MH, Khani S, Ghasemi M (2009) Mathematical modelling of thin-layer drying of carrot, *Int. Agrophysics* 23: 313-317.

Arumuganathan T, Manikantan MR, Rai RD, Anandakumar S, Khare V (2009) Mathematical modeling of drying kinetics of milky mushroom in a fluidized bed dryer. *Int. Agrophysics* 23: 1-7.

AOAC (1984). Official Methods of Analysis. Association of Official Analytical Chemists Press. Washington , DC.

Barbosa V (1993) Nutriçao e adubaçao de tomate rasteiro. In: Simpósio sobre 323-339.

Guarte RC (1996) Modelling the drying behaviour of copra and development of a natural convection dryer for production of high quality copra in the Philippines. *Ph.D. Dissertation*, 287. Hohenheim University, Stuttgart, Germany.

Henderson SM (1974) Progress in developing the thin layer drying equation. *Transactions of the ASAE* 17: 1167–1172.

Kaleta A, Górnicki K (2010) Some remarks on evaluation of drying models of red beet particles. *Energ Convers Manage* 51: 2967–2978.

Karathanos VT (1999) Determination of water content of dried fruits by drying kinetics. *J Food Eng* 39: 337–344.

Karimi F (2010) Applications of superheated steam for the drying of food products, *Int. Agrophysics* 24: 195-204

Meisami-asl E, Rafiee S, Keyhani A, Tabatabaeefar A (2010) Determination of suitable thin layer drying curve model for apple slices (variety-Golab), *Plant Omics J* 3(3):103-108

Midilli A, Kucuk H, Yapar Z (2002) A new model for single layer drying. *Dry Technol* l20 (7):1503-1513.

Simal S Femenia A Garau MC, Rosello C (2005) Use of exponential, Page's and diffusional models to simulate the drying kinetics of kiwi fruit. *J Food Eng* 66: 323–328.

Tunde-Akintunde TY, Afolabi TJ, Akintunde BO (2005) Influence of drying methods on drying of bell pepper (Capsicum annuum) *J Food Eng* 68: 439–442.

Wang CY, Singh RP (1978) A single layer drying equation for rough rice. ASAE, paper no. 3001.

Yaldiz O, Ertekin C (2001) Thin layer solar drying of some vegetables. *Dry Technol* 19: 583–596.

Zhang Q, Litchfleld JB (1991) An optimization of intermittent corn drying in a laboratory scale thin layer dryer. *Dry Technol* 9:383–395.

Zielinska M, Markowski M (2010) Air drying characteristics and Effective moisture diffusivity of carrots. *Chem Eng Process* 49: 212–218.

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