The Thin-Layer Modelling of Tomato Drying Process

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Summary

In this study thin-layer drying characteristics of tomato were investigated using a hot air convective dryer at a constant airflow velocity of 0.8 m s^{-1} and air temperature in the range of 50-70°C. The experimental drying data were fitted to the four well-known drying models *i.e.* the Page, Henderson and Pabis, logarithmic and two term models. The statistical validity of fit was measured using the coefficient of determination, mean relative percent deviation, root mean square error and reduced chi-square. Of all four models, the logarithmic model proved to be the best for predicting drying behaviour of tomato with values of coefficient of determination R^2 greater than 0.99. The effective diffusivity was determined to be in the range of 2.56-4.28x10^{-9} m^2 s^{-1} for non-treated samples and 4.29-6.28x10^{-9} m^2 s^{-1} for blanched ones in the temperature range of 50-70°C. The temperature dependence of the effective diffusivity was described by the Arrhenius-type relationship. The activation energy values for non-treated and blanched samples were 23.73 and 17.55 kJ mol^{-1}, respectively. Also, air temperature and pre-treatment affected the quality parameters of dried tomato.

Key words

drying; tomato; moisture content; effective diffusivity; activation energy; colour

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Received: October 15, 2006 | Accepted: January 26, 2007

ACKNOWLEDGEMENTS
The authors are grateful to Dr. Cem ÖZKAN at Department of Plant Protection, Faculty of Agriculture, Ankara University for his assistance in obtaining tomato.

Introduction

Tomato is considered one of the most important vegetables. It is grown worldwide on variety of soils and climatic conditions. Over 100 million tonnes of tomato are produced in the world from about four million ha of land. USA, China, Turkey, Italy, and Spain are the leading tomato growing countries. Turkey ranks third among tomato producing countries in the world after China and USA in 2002 (FAO, 2003). Tomato is a good source of vitamins and minerals. Lycopene, the predominant carotenoid pigment of tomato contributes to its characteristic red colour. It functions as an anti-oxidant and helps in lowering DNA damage. These properties have accelerated research activities to improve processing factors that lead to maintain the nutritional as well as sensory quality of tomato product. Nutritional and sensory quality of tomato products are primarily affected by cultivar, growing conditions, and processing parameters (Kaur *et al.,* 1999).

The vegetables and fruits contain a high percentage of their fresh weight as water. Accordingly, they exhibit relatively high metabolic activity compared with other plant-derived foods such as seeds. This metabolic activity continues after harvesting, thus making most fruits highly perishable commodities. One of the simplest methods used to improve the shelf life of agricultural products is to reduce their moisture content to such extent that the micro organism can not grow. Drying is a classical method of food preservation and it is a difficult food processing operation mainly due to undesirable changes in quality of dried product (Maskan, 2000). The basic objective of drying agricultural products is the removal of water in the solids up to certain level, at which microbial spoilage and deterioration chemical reactions are greatly minimised (Krokida and Marinos-Kouris, 2003). Tomato finds various uses in both fresh and processed forms. Processed forms include ketchup, sauces, pastes, juice and dried products. The dried tomato products are usually used as components for pizza and various vegetable and spicy dishes (Zanoni *et al*., 1999). The interest in production of dried tomato is continuously increasing in Turkey. Also, tomato drying methods include the foam-mat technique, spray drying, sun drying and hot air drying.

The study of the drying behaviour of tomato has been a subject of interest for various investigators such as Olorunda *et al*. (1990), Hawlader *et al*. (1991), Baloch *et al*. (1997), Shi *et al*. (1999), Zanoni *et al*. (1999), Giovanelli *et al*. (2002) and Telis *et al*. (2003). The efficient processing and long-term storage of tomato requires reducing of the moisture content to suitable levels by various drying methods. The present study was undertaken to investigate the thin layer drying characteristics of tomato using a hot air dryer and to fit the experimental data into mathematical models available in literature.

Material and methods

Materials

The tomatoes (cv. Milen) used in this study were obtained from Department of Plant Protection, Faculty of Agriculture, Ankara University, Turkey during the summer season of 2003. Ripe, well-coloured and sound tomatoes were harvested by hand and stored in a refrigerator at 4°C until drying experiments. After 1 hour stabilization at an ambient temperature, homogenous samples were rinsed with tap water and cut into halves with a knife. Tomato samples for drying experiments were classified in two groups: blanched and non-treated ones. The tomato halves were immersed in boiling water at 90°C for 1 min and then brined by steeping in 10% salt solution for 10 min. Both of these processes were named as blanched samples. The other group was only dipped in salt solution for 10 min and denoted as non-treated samples. Out of ten halves, seven halves were used for drying measurement. The average weight of the sample used was about 250 g. The remaining three halves were used for determination of the initial moisture content of the tomato samples by the vacuum oven method at 70°C for 24 h (AOAC, 1990).

Experimental apparatus

A laboratory scale hot air dryer was used in drying experiments (Figure 1). The dryer essentially consists of an adjustable centrifugal blower, with a power of 100 W, air heating duct, drying chamber and weighing system. Air supplied by the centrifugal blower was heated to the required temperature in air heating duct. The air velocity was changed by regulating the variable transformer, which changed the fan speed. The air velocity was measured using a hot-wire anemometer with the measurement range of 0-5 m s^{-1}. Air velocity was measured directly in the drying chamber. A 2850 W electrical heater was placed inside air heating duct. The air heating duct was constructed from galvanised metal sheets in the form of a

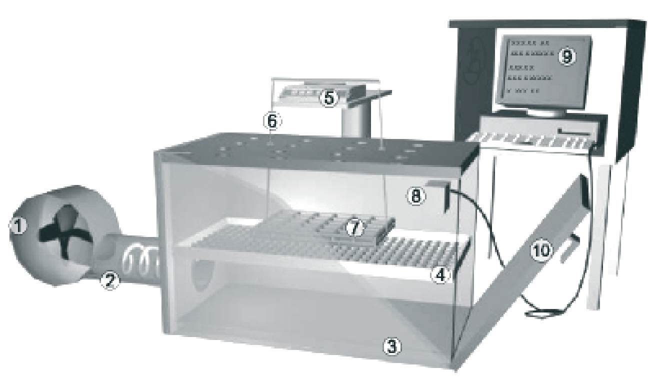

Figure 1.
Experimental setup of laboratory dryer: ①, centrifugal blower; ②, air heating duct; ③, drying chamber; ④, perforated floor; ⑤, electronic balance; ⑥, holding wire; ⑦, sample basket; ⑧, sensors; ⑨, Pc; ⑩; door

Table 1. Mathematical models given by various workers for drying curves

Model name	Model	References
Page	$M_R = \exp(-kt^m)$	Agrawal and Singh (1977), Diamante and Munro (1993)
Henderson and Pabis	$M_R = a\exp(-kt)$	Westerman *et al.* (1973) Chhinman (1984)
Logarithmic	$M_R = a\exp(-kt) + c$	Toğrul and Pehlivan (2003)
Two term	$M_R = a\exp(-kt) + b\exp(-k_0t)$	Henderson (1974), Madamba *et al.* (1996)

M_R, moisture ratio (dimensionless); k and k_0, drying rate constants in h^{-1}; a and b, coefficients (dimensionless); m, exponent; t, drying time in h

cylinder 110 mm in diameter and 400 mm in length. The temperature and relative humidity in the drying chamber was measured by SHT11 relative humidity and temperature sensor. The temperature was controlled to ±1°C using suitable controller and specially designed software. During the drying process, the temperature and relative humidity in drying chamber were continuously recorded at 1 min intervals throughout runs with the help of this software connected to a PC. The drying chamber, of 1000x500x500 mm^3, was made from a galvanised metal sheet of 1.5 mm thickness having a single door opening at the front for insertion and removal of sample. A perforated floor, having dimension of 1000 mm by 500 mm, was fitted inside the drying chamber for streamlining the airflow. The drying chamber as well as the air heating duct was covered with 30 mm rock wool and aluminium foil to prevent unnecessary heat losses to the surroundings during the test runs. The weighing system consisted of an electronic balance and sample basket having dimension of 50 mm in depth and 300 mm in diameter. The bottom of the basket had a perforated floor. The electronic balance, having an accuracy of 0.01 g, was placed outside the drying chamber. The sample basket, in which the tomato samples were evenly put as a single layer, was attached to the electronic balance by the sample holding wire.

Drying procedures

The drying experiments were conducted at 50, 60 and 70°C air temperatures and at a constant airflow velocity of 0.8 m s^{-1}. In each experiment, about 250 g of tomato samples were used. After the system was run for at least half an hour to reach steady conditions for the operation temperatures, the samples were uniformly put into the sample basket as a single layer and dried there. Moisture losses of samples were recorded at 30 min intervals for first hour and 1 h subsequently thereafter for determination of drying curves. Drying was continued until no further changes in their mass were observed (about 11% d.b.). The dried samples were allowed to cool down at an ambient temperature for 30 min and then packed in low-density polyethylene bags for determination of colour and rehydration ratio.

The colour characteristics and rehydration ratio were considered as the most important quality parameters for the dried tomato samples in this study. The colour is one of the most important properties of agricultural products. Colour evaluation of blanched and non-treated tomato samples was determined using a Hunterlab colour difference meter, which measures three parameters: lightness *L*, redness *+a* and yellowness *+b* together with the ratio *+a/+b*, which represents colour quality. In terms of desired tomato colour properties, higher *L* and higher *+a* and lower *+a/+b* are preferred. The colour of dried tomato surface was measured using a Minolta CR-300 Chromameter. It was calibrated each time with a standard white plate. Measurements were individually taken for five samples and the average of five readings was calculated.

The rehydration ratio was used to express the ability of the dried material to absorb water. A sample (~5 g) of the dried tomato was weighed (initial weight) into a 500 ml beaker containing 150 ml of distilled water and boiled for 5 min. After rehydration, the sample was weighed (final weight). The rehydration ratio was obtained by dividing the rehydrated weight by the initial weight (Prakash *et al.*, 2003).

Mathematical modelling

Mathematical modelling is essential to predict and simulate the drying behaviour. It is also an important tool in dryer's design, contributing to a better understanding of the drying mechanism. Experimental drying data was applied to four well-known drying models *i.e.* the Page, Henderson and Pabis, two term and logarithmic models (Table 1). The drying rate constants and coefficients of models were estimated using a non-linear least squares regression solved by a Quasi-Newton numerical method. Fit of these models was evaluated with the coefficient of determination R^2, mean relative percent deviation E_{MD}, root mean square error E_{RMS} and reduced chi-square χ^2. These comparison criteria methods can be calculated as follows:

$$E_{MD} = \frac{100}{N}\sum_{i=1}^{N}\frac{\left|M_{R,ex,i} - M_{R,pre,i}\right|}{M_{R,\exp,i}} \quad (1)$$

$$E_{RMS} = \left[\frac{1}{N}\sum_{i=1}^{N}\left(M_{R,ex,i} - M_{R,pre,i}\right)^2\right]^{1/2} \quad (2)$$

$$\chi^2 = \frac{\sum_{i=1}^{N}(M_{R,ex,i} - M_{R,pre,i})^2}{N - z} \quad (3)$$

where: $M_{R,ex,i}$ is the ith experimental dimensionless moisture ratio; $M_{R,pre,i}$ is the ith predicted dimensionless moisture ratio; N is the number of observations; and z is the number of constants.

R^2 was used as the primary comparison criteria for selecting the best model to fit the four models to the experimental data. Also, the lower values of the mean relative percent deviation E_{MD}, the root mean square error E_{RMS} and the reduced chi-square χ^2 were chosen as the comparison criteria for the evaluation of fit of the experimental data obtained.

Results and discussion

Drying curves

Tomato of average initial moisture content of around 14.02 kg [H_2O] kg^{-1} [dry matter] was dried to the final moisture content of about 0.11 kg [H_2O] kg^{-1} [dry matter] until no further changes in their mass were observed. Figures 2 and 3 present the variations in the moisture content as a function of drying time at various air temperatures for non-treated and blanched samples, respectively. As expected, the drying time decreased considerably with an increase in the air temperature. The times needed to reach the final moisture content for non-treated samples were 32, 26 and 20 h at air temperatures of 50, 60 and 70°C, respectively. Corresponding values for blanched samples were 22, 17 and 12 h at drying air temperatures of 50, 60 and 70°C, respectively. Blanched tomato samples were found to have a shorter drying time compared to non-treated ones. Boiling prior to drying showed that the drying time decreased by 44.4, 52.9 and 66.6% at air temperatures of 50, 60 and 70°C, respectively. Consequently, it can be concluded that boiling reduced the drying time. Similar results have been reported by Doymaz (2003) for white mulberry and Ertekin and Yaldiz (2004) for eggplant.

Calculation of effective diffusivity and activation energy

The effective diffusivity of the samples is estimated by using the simplified mathematical Fick's second diffusion model. The solution of Fick's second law in slab geometry, with the assumption that moisture migration was caused by diffusion, negligible shrinkage, constant diffusion coefficients and temperature was as follows (Crank, 1975):

$$M_R = \frac{M - M_e}{M_0 - M_e} = \frac{8}{\pi^2} \sum_{n=1}^{\infty} \frac{1}{(2n+1)^2} \exp\left(\frac{-(2n+1)^2 \pi^2 D_{eff} t}{4H^2} \right) \quad (4)$$

For long drying periods, Eqn (4) can be further simplified to only the first term of the series and the moisture ratio M_R was reduced to M/M_0 because M_e was relatively small compared to M and M_0. Then, Eqn (4) can be written in logarithmic form:

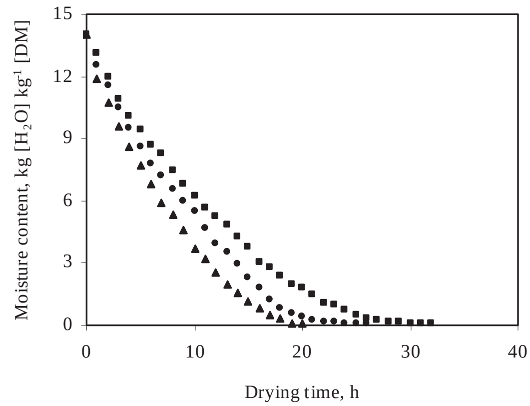

Figure 2.
Effect of air temperature on the moisture content of non-treated samples at an airflow velocity of 0.8 m s^{-1} and various air temperatures: ■, 50°C; ●, 60°C; ▲, 70°C

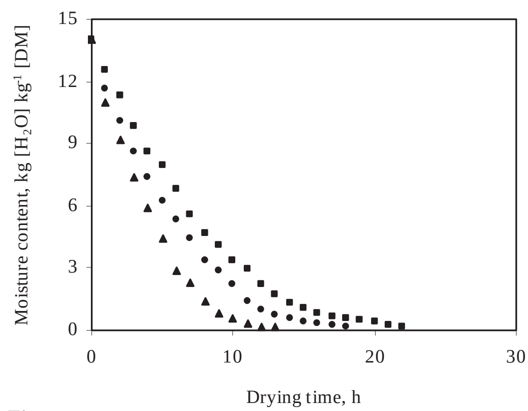

Figure 3.
Effect of air temperature on the moisture content of blanched samples at an airflow velocity of 0.8 m s^{-1} and various air temperatures: ■, 50°C; ●, 60°C; ▲, 70°C

$$\ln \frac{M}{M_0} = \ln \frac{8}{\pi^2} - \left(\frac{\pi^2 D_{eff} t}{4H^2} \right) \quad (5)$$

where: M_R is the dimensionless moisture ratio; M, M_e and M_o are the moisture content at any time, the equilibrium moisture content and the initial moisture content in kg [H_2O] kg^{-1} [dry matter], respectively; H is the half-thickness of the slab in sample in m; n is a positive integer; and D_{eff} is the effective diffusivity in m^2 s^{-1}.

The effective diffusivity is typically calculated by plotting experimental drying data in terms of $\ln(M_R)$ versus drying time. From Eqn (5), a plot of $\ln(M_R)$ versus the drying time gives a straight line with a slope of:

$$\text{Slope} = \frac{\pi^2 D_{eff}}{4H^2} \quad (6)$$

The values of D_{eff} for non-treated and blanched samples are presented in Table 2. From this, it can be seen that the air temperature and pre-treatment had effect on

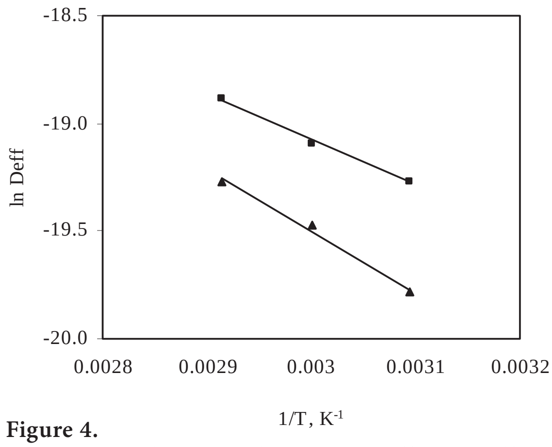

Figure 4.
Arrhenius-type relationship between the effective diffusivity and absolute temperature: ■, blanched samples; ▲, non-treated samples

Table 2. Values of effective diffusivity at various air temperatures for non-treated and blanched samples

	Air temperature, °C	Effective diffusivity (D_{eff}), $m^2\ s^{-1}$
Non-treated	50	2.56×10^{-9}
	60	3.48×10^{-9}
	70	4.28×10^{-9}
Blanched	50	4.29×10^{-9}
	60	5.11×10^{-9}
	70	6.28×10^{-9}

Table 3. Parameter estimation, R^2, E_{MD}, E_{RMS} and χ^2 of the four mathematical drying models fitted to the experimental drying data of non-treated tomato at an air temperature of 50°C

Model	Value of parameter		Coefficient of determination (R^2)
Page	k	0.0587	0.9957
	m	1.1504	
Henderson and Pabis	a	1.0368	0.9909
	k	0.0903	
Logarithmic	a	1.1173	0.9995
	k	0.0681	
	c	-0.1206	
Two term	a	0.4187	0.9901
	k	0.0903	
	b	0.6180	
	k_0	0.0903	

the effective diffusivity. These values are comparable with the reported values: $1.5 \times 10^{-9}\ m^2\ s^{-1}$ for raisin (Lomauro *et al.*, 1985), $2.02 \times 10^{-9}\ m^2\ s^{-1}$ for hot air drying of paprika at 60°C (Ramesh *et al.*, 2001) and $1.79\text{-}4.45 \times 10^{-9}\ m^2\ s^{-1}$ for apple slices at 60°C (Velic *et al.*, 2004). Giovanelli *et al.*, (2002) reported that the values of D_{eff} varied from 2.26 to $9.14 \times 10^{-9}\ m^2\ s^{-1}$ as a function of the structure of tomato products for hot air drying. These values are consistent with the present estimated D_{eff} values for tomatoes.

The temperature dependence of the effective diffusivity can be described by the Arrhenius-type relationship:

$$D_{eff} = D_0 \exp\left(-\frac{E_a}{RT}\right) \quad (7)$$

where: D_0 is the pre-exponential factor of the Arrhenius equation in $m^2\ s^{-1}$; E_a is the activation energy in kJ mol^{-1}; R is the universal gas constant in kJ $mol^{-1}\ K^{-1}$ and T is the absolute air temperature in K.

The activation energy was calculated by plotting the natural logarithm of D_{eff} versus reciprocal of the absolute temperature as presented in Figure 4. The plot was found to be a straight line in the range of air temperatures studied, indicating Arrhenius dependence. The activation energy for diffusion calculated from the slopes of straight lines of Figure 4 was determined to be 23.73 kJ mol^{-1} with a value for R^2 of 0.9911 for non-treated samples and 17.55 kJ mol^{-1} with a value for R^2 of 0.9958 for blanched ones. These values are within the range of 15-40 kJ mol^{-1} for various foods reported by Rizvi (1986).

Modelling of drying curves

The results of nonlinear regression analysis of fitting the four mathematical drying models to the experimental data and comparison criteria used to evaluate goodness of fit namely, R^2, E_{MD}, E_{RMS} and χ^2 for non-treated samples at 50°C air temperature are presented in Table 3. All models provided an adequate fit to the experimental data with a value for R^2 of greater than 0.99, indicating a good fit. However, the values for E_{MD} obtained from the Page and logarithmic models are less than 10% in all cases, which is in the acceptable range. Also, the logarithmic model gave a higher value of R^2 and lower values for the E_{MD}, E_{RMS} and χ^2 than the Page model. For this reason, the logarithmic model may be assumed to represent the thin-layer drying behaviour of tomato within the experimental study range. Figures 5 and 6 suggest the experimental moisture ratios fitted with the logarithmic model at various air temperatures for non-treated and blanched tomato samples, respectively. This shows there was a good conformity between experimental and predicted moisture ratios.

Evaluation of quality parameter

Colour evaluation of L, $+a$ and $+b$ together with the ratio $+a/+b$ of non-treated and blanched samples are presented in Table 4. From this, it can be seen that pre-treatment and air temperature have a significant effect on the colour of dried samples. L and $+a$ values for blanched samples at the examined air temperatures were lower than those for non-treated samples. L and $+a$ values for non-treated samples at all drying air temperatures ranged from 30.95 to 33.39 and 20.69 to 23.10, respectively. Corresponding values for blanched samples varied from 29.01 to 31.64 and 15.90 to 20.46, respectively. Colour quality values did not

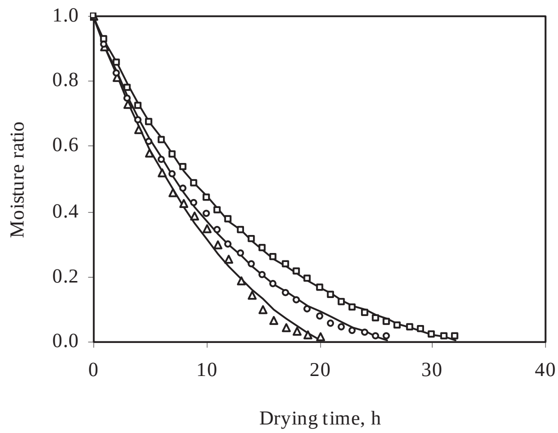

Figure 5.
Experimental moisture ratio versus drying time fitted with the logarithmic model for non-treated samples dried at various air temperatures: □, 50°C; ○, 60°C; Δ, 70°C; –––, logarithmic model

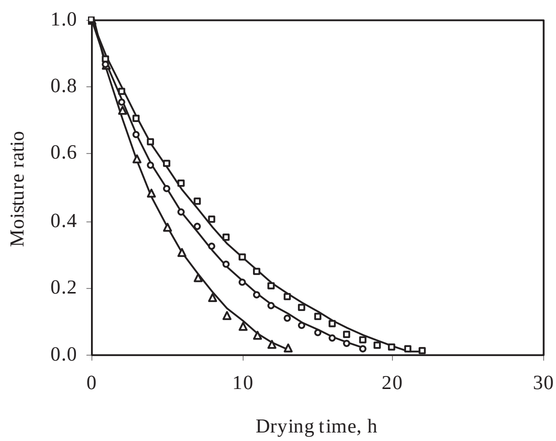

Figure 6.
Experimental moisture ratio versus drying time fitted with the logarithmic model for blanched samples dried at various air temperatures: □, 50°C; ○, 60°C; Δ, 70°C; –––, logarithmic model

change substantially but the lowest values for *+a/+b* were shown at 50°C air temperature. Non-treated samples had more red colour and were lighter than blanched ones. *L* and *+a* values decreased with increased air temperatures. As a result, the desired colour on dried tomato surface was better at lower temperatures. Similar results have been observed by Shi *et al.* (1999).

Table 5 shows the variation of rehydration ratio for non-treated and treated samples at 50, 60 and 70°C air temperatures. The rehydration ratio was affected by the pre-treatment and drying air temperature. The rehydration ratio obtained from all examined air temperatures for blanched samples were lower than those for non-treated ones. There was also an increase in rehydration ratio with an increase in air temperature. When drying air temperature changed from 50 to 70°C, rehydration ratio values for non-treated and treated samples increased by 8.37 and

Table 4. Colour analysis of dried tomato samples

	Air temp. °C	Hunter colour values			
		L	+a	+b	+a/+b
Non-treated	50	33.39	23.10	15.37	1.50
	60	31.96	21.77	13.89	1.57
	70	30.95	20.69	13.30	1.56
Blanched	50	31.64	20.46	13.63	1.50
	60	30.22	17.68	11.68	1.51
	70	29.01	15.90	10.61	1.50

Table 5. Rehydration ratio of dried tomato samples

	Air temperature, °C	Rehydration ratio
Non-treated	50	3.14
	60	3.25
	70	3.40
Treated	50	2.77
	60	2.84
	70	3.08

11.15%, respectively. Similar results have been reported by Krokida and Marinos-Kouris (2003) for tomato and Prakash *et al.* (2003) for carrot.

Conclusions

The following conclusions are drawn from this study.

Drying curves were affected by the air temperature and pre-treatment. Increase in the air temperature caused a decrease in the drying time. Blanched tomato samples had a shorter drying time as compared to non-treated ones.

The effective diffusivity increased with increasing the air temperature and D_{eff} values for blanched samples are higher than those for non-treated samples under the same air temperatures. The activation energy values for non-treated and blanched samples were 23.73 and 17.55 kJ mol^{-1}, respectively.

Of all the four models, the logarithmic model gave an excellent fit to experimental data obtained with a value for R^2 greater than 0.9995.

Pre-treatment and air temperature had a significant effect on the colour and rehydration ratio of dried samples.

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Notation

a, b	coefficients in models
$+a$	colour redness coordinate
$+b$	colour yellowness coordinate
D_{eff}	effective diffusivity, m^2 s^{-1}
D_0	pre-exponential factor, m^2 s^{-1}
E_a	activation energy, kJ mol^{-1}
E_{MD}	mean relative percent deviation, %
E_{RMS}	root mean square error
H	half-thickness of the slab in sample, m
k, k_0	drying rate constants in models, h^{-1}
L	colour lightness coordinate
m	exponent in drying model
M	moisture content at any time, kg [H_2O] kg^{-1} [dry matter]
M_e	equilibrium moisture content, kg [H_2O] kg^{-1} [dry matter]
M_0	initial moisture content, kg [H_2O] kg^{-1} [dry matter]
M_R	dimensionless moisture ratio
$M_{R,\,ex}$	experimental dimensionless moisture ratio
$M_{R,\,pre}$	predicted dimensionless moisture ratio
n	positive integer
N	number of observations
R	universal gas constant, kJ mol^{-1} K^{-1}
R^2	coefficient of determination
t	drying time, h
T	absolute temperature, K
z	number of constants
χ^2	reduced chi-square

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