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Solar drying of Ayaş tomato using a natural convection solar tunnel dryer

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Abstract

An experimental study was conducted to determine the thin layer drying characteristics of Ayaş tomato in a natural convection solar tunnel dryer. Open sun drying runs were also performed for comparison at the same time. The dryer was 20 m long and 5.4 m wide. This system can be used for drying various agricultural products. Also, it is simple in construction and can be constructed at a low cost with locally obtainable materials. Moisture content of tomato was reduced from 11.71 to 0.10 kg [H_2O]/kg [DM] in about 101 h for open sun drying, whereas the solar tunnel dryer took only about 86 h. Depending on weather conditions, the solar tunnel dryer was found to be more efficient than the open sun drying and resulted in saving to extent of about 17.4% of drying time. Samples dried in the solar tunnel dryer were completely protected from insects, rain and dusts and the dried samples were of high quality in terms of colour and hygienic. In falling rate period, moisture transfer from the test samples was described by applying the Fick's diffusion model and the effective diffusivity was calculated. The experimental drying data of tomato were used to fit the Page, Logarithmic, Approximation of diffusion, Two-term and Midilli *et al.* models, and drying rate constants and coefficients of models tested were determined by non-linear regression analysis. Among the various models tested to interpret the drying behaviour of tomato, the Midilli *et al.* model was in good agreement with the experimental data obtained.

Key words: Ayaş tomato, solar tunnel drying, open sun drying, mathematical model, moisture content, effective diffusivity.

Introduction

The drying technique is probably the oldest and the most important method of food preservation practiced by humans. The removal of moisture prevents the growth and reproduction of microorganisms which cause decay, and minimises many of the moisture-mediated deteriorative reactions. It brings about substantial reduction in weight and volume, minimizing packing, storage and transportation costs and enables storability of the product under ambient temperatures [1]. During drying many changes take place; structural and physicochemical modifications affect the final product quality and the quality aspects involved in dry conversation in relation to the quality of fresh products and applied drying techniques [2]. Currently hot air drying is the most widely used method in post-harvest technology of agricultural products. Using this method, a more uniform, hygienic and attractively coloured dried product can be produced rapidly[3]. However, it is an energy consuming operation and low-energy efficiency, so more emphasis is given on using solar energy sources due to the high prices and shortage of fossil fuels. Solar dryers are now being increasingly used since they are a better and more energy efficient option. The solar dryers could be an alternative to the hot air and open sun drying methods, especially in locations with good sunshine during the harvest season [4]. However, large-scale production limits the use of the open sun drying. Among these are lack of ability to control the drying process properly, weather uncertainties, high labour costs, large area requirement, insect infestation, mixing with dust and other foreign materials etc [5].

Solar drying is essential for preserving agricultural products. Using a solar dryer, the drying time can be shortened by about 65% compared to sun drying because, inside the dryer, it is warmer than outside; the quality of the dried products can be improved in terms of hygiene, cleanliness, safe moisture content, colour and taste; the product is also completely protected from rain, dust and insects; and its payback period ranges from 2 to 4 years depending on the rate of utilization. The most important feature of solar dryers is that the product does not include any kind of preservatives or other added chemical stuffs, which allows its use for people suffering from various allergic reactions from chemical preservatives and other added stuffs. Furthermore, the product is not exposed to any kind of harmful electromagnetic radiation or electromagnetic poles [6]. Although for agricultural products, solar dryers with solar air heater offer better control of required drying air conditions, solar tunnel dryers based on plastic tunnel greenhouses have a great potential and do not require any other energy during operation. Therefore, solar tunnel dryer may become a more convenient alternative for rural sector and other areas in which electricity is scarce and in irregular supply [4]. Also, it can reduce crop losses, improve the quality of dried product significantly and is economically beneficial compared to traditional drying methods.

Tomato is considered one of the most important vegetables. It is grown worldwide on variety of soils and climatic conditions. Over 120 million tonnes of tomato are produced in the world from about 4.6 million ha 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 2007 [7]. Although tomato production in Turkey is concentrated in Marmara, Mediterranean and Aegean Sea regions, tomato produced in Ayaş province, situated in Ankara, has a reputation for a good taste. However, Ayaş tomato is more prone to bruising than other type tomatoes. This problem of Ayaş tomatoes can be solved using solar tunnel drying technology. Moreover, Ayaş tomato harvesting goes from July to September, which is the high solar radiation period. These favourable conditions of temperature and relative humidity could justify the use of solar energy as extra source of energy for drying. Recently, a new natural convection solar tunnel dryer have been developed in Ankara University for drying fruits and vegetables. It is necessary for the newly solar dryer to determine the drying characteristics of agricultural products. To the knowledge of the authors, there is no literature specific to the drying behaviour of Ayaş tomato found. Therefore, the objective of current work is to study and compare the thin layer drying characteristics of Ayaş tomato in the newly developed solar tunnel dryer and under open sun.

Materials and Methods

The tomatoes used in this study were obtained from Ayaş Research and Experimental Farm, Faculty of Agriculture, Ankara University, Turkey, during the summer season of 2008. Ripe, well-coloured and sound tomatoes were harvested by hand and stored in a refrigerator at 4ºC until drying experiments. After 4 hour stabilization at an ambient temperature, homogenous samples were rinsed with tap water and cut into halves with a knife. The tomato halves were dipped in 10% salt solution for 10 min. The average weight of the sample used for the solar drying run was about 6 kg. The initial moisture content of the tomato sample was determined by using the vacuum oven method at 70°C for 24 h [8]. These experiments were replicated thrice to obtain a reasonable average. Average moisture content was found to be 11.71 kg [H_2O]/kg [DM].

A natural convection solar tunnel dryer was manufactured and installed at Ankara University. Dryer developed is used for large-scale drying of fruit and vegetables. A schematic view of the experimental solar tunnel is shown in Fig. 1. It consists of two conical type frames, each 10 m long. Inlet and outlet radius of solar tunnel frames are 2.7 and 1.7 m, respectively. Dryer was oriented in an east-west direction to make the solar radiation incident more efficient on the solar tunnel dryer. Tunnel was covered with a plastic film of semi-transparent polyethylene, 120 µm in thickness in order to incorporate UV and far infrared protection. To prevent insects and birds from entering the dryer, nylon mesh was fixed at the inlet and outlet side of the solar dryer. Two wire mesh trays, having dimensions of 3 m width by 10 m length, were used to accommodate tomato halves to be dried as thin layer solar drying. The temperature and relative humidity inside and outside of the tunnel were measured by using relative humidity and temperature probe. All data were taken from inlet, middle and outlet points of the solar tunnel and collected in a data logger unit at 1 hour intervals throughout runs by this probe.

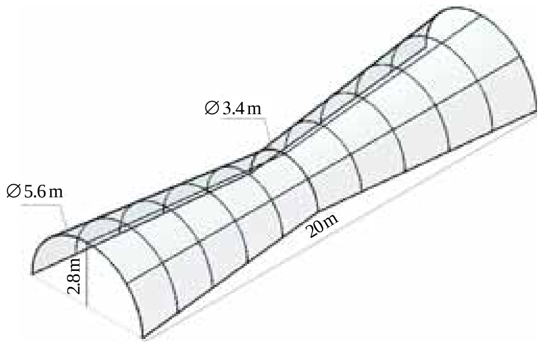

Figure 1. Experimental setup of the solar tunnel dryer.

Three sets of drying experiments were conducted during the periods of August to September 2008 under the climatic conditions of Ankara. Each experiment started at 8:00 a.m. and continued until 18:00 p.m. During the drying experiments, the weather was generally sunny and no rain appeared. For all drying experiments, tomato halves were distributed uniformly in a single layer in the sample tray inside the drying tunnel. To determine the moisture loss of drying tomatoes during experiments, tomato samples were taken from 3 points, namely inlet, middle and outlet of the solar tunnel dryer and weighed at various time intervals, ranging from 60 min at the beginning of the drying to 120 min during the last stage of the process. The moisture loss of samples was determined by means of a digital electronic balance having an accuracy of 0.01 g. No measurement was made during the night. The drying was continued until no further changes in their mass were observed. Also, to compare the performance of the solar tunnel dryer with that of open sun drying, control samples of tomatoes were distributed on a tray at the same loading density near the solar tunnel dryer. Both experimental and control samples were dried simultaneously under the same weather conditions.

The mechanisms of mass transfer in foods are complex. The dehydration of biological materials normally follows a falling-rate drying period. The moisture and/or vapour migration during this period is controlled by diffusion. Assuming that the resistance to moisture migration is uniformly distributed throughout the interior of the homogenous isotropic material, Fick's second law can be derived as follows:

$$\frac{\partial M_l}{\partial t} = \nabla(D_{eff} \nabla M_l) \tag{1}$$

where M_l is the local moisture content in kg [H_2O]/kg [DM]; t is the drying time in h and D_{eff} is the effective diffusivity in m^2 s^{-1}.

Assuming that the moisture is initially uniformly distributed throughout the sample, mass transfer is symmetric with respect to the centre, that the surface moisture content of the sample instantaneously reaches equilibrium with the conditions of surrounding air, and shrinkage is negligible or not taken into consideration, the solution of Eqn (1) for an infinite slab can be defined as follows [9, 10]:

$$M_R = \frac{M - M_e}{M_0 - M_e} = \frac{8}{\pi^2} \sum_{n=0}^{\infty} \frac{1}{(2n+1)^2} \exp\left(\frac{-(2n+1)^2 \pi^2 D_{eff} t}{4h^2} \right) \tag{2}$$

For long drying periods (M_R<0.6), a limiting form of Eqn (2) is obtained for slab geometries by considering only the first term in their series expansion. Also, the moisture ratio M_R was simplified to M/M_0 because M_e was relatively small compared to M and M_0. Then, Eqn (2) can be written in logarithmic form:

$$\ln\frac{M}{M_0}=\ln\frac{8}{\pi^2}-\left(\frac{\pi^2 D_{eff}\,t}{4h^2}\right) \qquad (3)$$

where M_R is the dimensionless moisture ratio; M is the moisture content at any time in kg [H_2O]/kg [DM]; M_e is the equilibrium moisture content in kg [H_2O]/kg [DM]; M_0 is the initial moisture content in kg [H_2O]/kg [DM]; h is the half-thickness of the slab in sample in m; and n is a positive integer.

The experimental drying data of tomatoes obtained were fitted to the five well-known semi-theoretical drying models (Table 1). The drying rate constants and coefficients of models were estimated using a non-linear regression procedure. The estimation method was quasi-Newton and the adequacy of models was evaluated and compared by means of the coefficient of determination r^2, mean relative percent deviation E_{MD}, root mean square error E_{RMS} and reduced mean square of the deviation χ^2. These comparison criteria methods can be calculated as follows:

$$E_{MD}=\frac{100}{N}\sum_{i=1}^{N}\frac{\left|M_{R,ex,i}-M_{R,pre,i}\right|}{M_{R,\exp,i}} \qquad (4)$$

$$E_{RMS}=\left[\frac{1}{N}\sum_{i=1}^{N}\left(M_{R,ex,i}-M_{R,pre,i}\right)^2\right]^{1/2} \qquad (5)$$

$$\chi^2=\frac{\sum_{i=1}^{N}(M_{R,ex,i}-M_{R,pre,i})^2}{N-z} \qquad (6)$$

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

The coefficient of determination r^2 was used as the primary comparison criteria for selecting the best model to fit the four models to the experimental data. Also, a model is considered better than another if it has lower values of the E_{MD}, E_{RMS} and χ^2.

Results and Discussion

Fig. 2 shows the variations of the ambient air temperature, relative humidity and solar radiation during the solar tunnel and open sun drying of Ayaş tomato for a typical day of August 2008 in Ankara. During the drying experiments, the weather was generally sunny and no rain appeared. During the solar drying experiments, the daily mean values of the ambient air temperature, relative humidity and solar radiation changed from 22 to 38ºC, from 24 to 49% and from 173.1 to 890 W m^{-2}, respectively. The drying air temperature and relative humidity in solar tunnel dryer varied continuously from morning to evening. The ambient air temperature and solar radiation reached the highest values between 12:00 and 15:00, whereas the relative humidity reached the lowest values during this time. The difference between the drying air temperature and ambient temperature was observed to be highest during this time. In other words, inside the solar dryer, it is warmer than outside. This clearly indicates that the drying rate in the solar tunnel drying would be higher than in open sun drying.

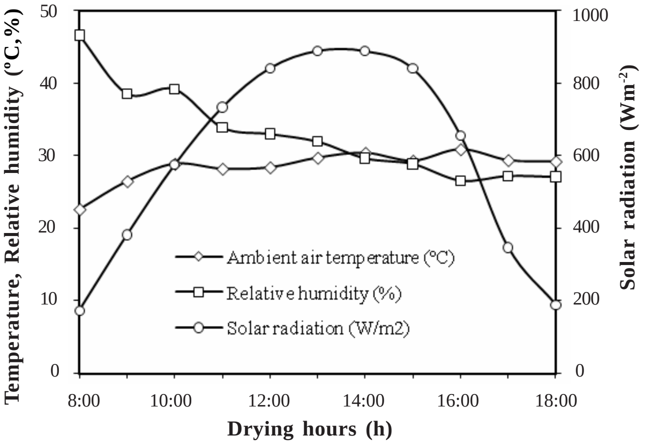

Figure 2. Changes in means of ambient air temperature, relative humidity and solar radiation with the drying hours for a typical day of August 2008.

Fig. 3 shows variations of means of drying temperature and relative humidity at inlet, middle and outlet of solar tunnel. The drying temperature and relative humidity at these points in solar tunnel dryer changed continuously from morning to evening. It was observed that the drying temperature in tunnel was higher than the ambient temperature, whereas the relative humidity in tunnel was lower than the ambient relative humidity. Also, there was a significant difference between the values of the temperature and relative humidity. This difference for the temperature and relative humidity was about 11.5ºC and 6.9% during the experiment time, respectively. This explicitly indicates that the drying rate in the solar tunnel drying will be higher than in open sun drying.

Fig. 4 suggests drying curves for Ayaş tomato dried by solar tunnel and open sun drying methods. The interruptions of the lines in this figure represent the night periods of the drying process. The tomato samples of average initial moisture content of around 11.71 kg [H_2O]/kg [DM] were reduced to the final moisture content which changed between 0.09 and 0.11 kg [H_2O]/kg [DM]. It is clear from Fig. 4 that the moisture content decreases continuously with the drying time. During the experiments, the time to reach the final moisture content of samples for solar tunnel were found to be between 80 and 92 h, while the drying time for the open sun drying changed between 96 and 106 h. Solar tunnel dryer had a shorter drying time than the open sun drying. In other words, drying time was reduced to about 17.4% by the solar tunnel dryer according to the open sun drying. Depending on weather conditions, the solar tunnel dryer developed shortened half day the drying time of tomato samples. The decrease in the

Table 1. Thin-layer drying models used for drying curves.

Model name	Model	References
Page	$M_R = \exp(-kt^n)$	Agrawal and Singh [11]
Logarithmic	$M_R = a\exp(-kt) + c$	Yagcioglu *et al.*[12]
Two-term	$M_R = a\exp(-kt) + b\exp(-k_0t)$	Henderson [13]
Approximation of diffusion	$M_R = a\exp(-kt) + (1 - a)\exp(-kbt)$	Yaldiz & Ertekin [14]
Midilli *et al.*	$MR = a\exp(-kt^n) + bt$	Midilli *et al*.[15]

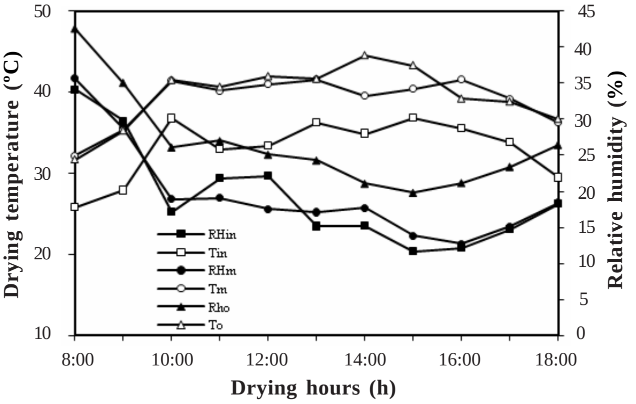

Figure 3. Variations of means of drying temperature and relative humidity at inlet, middle and outlet of solar tunnel.

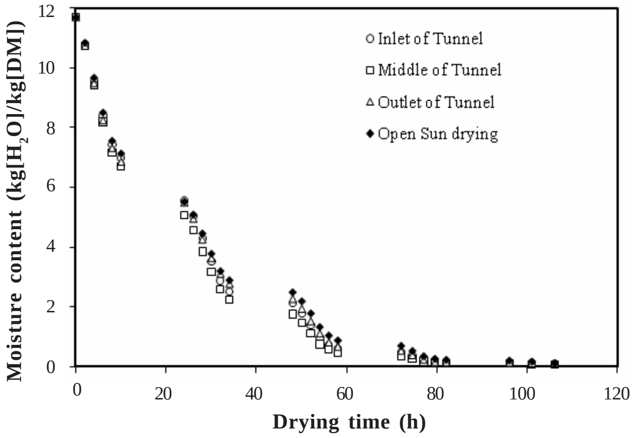

Figure 4. Drying curves for tomato dried by solar tunnel and open sun drying methods.

drying time could be attributed to the values of higher temperature and lower relative humidity obtained in dryer. Similar results have been reported for banana [16], fish [17], organic apple [18, 19] and organic tomato [20].

Fig. 5 presents the variation of drying rate with moisture content for tomatoes in the solar tunnel and open air sun drying process. Solar tunnel drying showed a faster drying rate than open sun drying. Also, there is no constant-rate drying period in these curves and all the drying processes occurred in the falling rate drying period in the drying of samples. During the falling rate drying period, the drying rate decreased continuously with decreasing moisture content and increasing drying time. These results were in agreement with the results for sultana grape [21, 22], currant, fig, apricot and plum [21] and prickly pear peel [23].

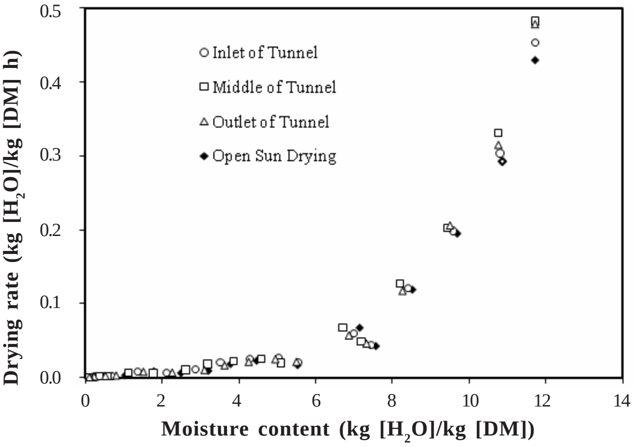

Figure 5. Variation of drying rate as a function of moisture content for tomato in solar tunnel and open sun drying process.

Table 2 presents the results of nonlinear regression analysis of fitting the five 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 solar tunnel drying of tomato samples. All the five models for solar tunnel drying gave a good fit to the experimental data with a value for r^2 of greater than 0.9843, indicating a good fit. Of all the models tested, the Midilli *et al.* model offered the highest value for r^2, followed by the Two-term, Approximation of diffusion, Logarithmic and Page models. However, the values of E_{MD} for the Midilli *et al.* model were less than 10% in all cases, which is in the acceptable range. Also, the values for E_{RMS} and χ^2 obtained from this model were less than those attained from other models. Hence, the Midilli *et al.* model was considered the best model in present study to represent the solar tunnel drying of Ayaş tomato within the experimental range of study.

Table 2. Parameter estimation and comparison criteria of the five drying models for solar tunnel drying.

Model	Estimated values		R^2	E_{MD}, (%)	E_{RMS}	χ^2
Page	k	0.0585	0.9843	21.59	0.04014	0.00177
	m	0.9208				
Logarithmic	a	0.9794	0.9853	15.96	0.03977	0.00174
	k	0.0394				
	c	-0.0273				
Two-term	a	0.1047	0.9863	13.40	0.03932	0.00171
	k	0.3745				
	b	0.9072				
	k_0	0.0407				
Approximation of dif.	a	0.0903	0.9862	13.31	0.03847	0.00163
	k	0.3623				
	b	0.1126				
Midilli *et al.*	a	1.0022	0.9874	9.37	0.03765	0.00157
	k	0.0711				
	b	-0.0006				
	m	0.8364				

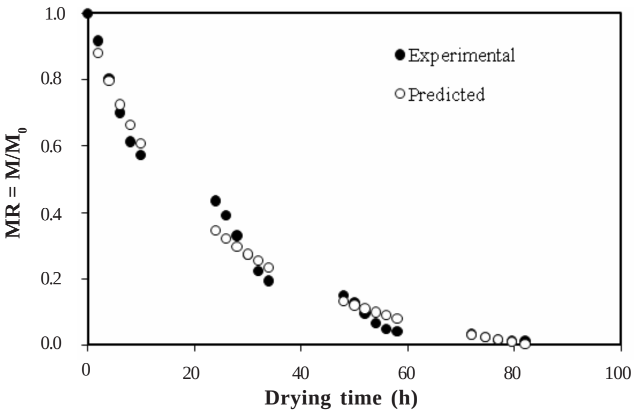

Figure 6. Comparison of the experimental and predicted moisture ratio obtained using the Midilli *et al.* model for solar tunnel drying.

Fig. 6 suggests the experimental moisture ratio fitted with the Midilli *et al.* model at various air temperatures for solar tunnel drying. It can be seen that there was a good conformity between experimental and predicted moisture ratios. This indicates the suitability of Midilli *et al.* model in describing the drying solar tunnel drying behaviour of Ayaş tomato.

During the falling rate drying period, the internal resistance governs the mass transfer. In this case, Fick's second law can be used to estimate the effective diffusivity. The effective diffusivity is typically calculated by plotting experimental dehydration data in terms of ln(M_R) versus drying time. From Eqn (3), a plot of ln(M_R) versus the drying time gives a straight line with a slope *s* of:

$$s = \frac{\pi^2 D_{eff}}{4h^2} \qquad (7)$$

The values of effective diffusivity for solar tunnel and open sun drying process are presented in Table 3. Middle of solar tunnel offered the highest values of D_{eff}, followed by the outlet, inlet of solar tunnel and open sun drying process. This is a clear indication of the fastest drying rate in middle of solar tunnel. In all the cases, the value of D_{eff} for the solar tunnel drying was higher than that for the open sun drying. The values of diffusivity in the range of 10^{-9}–10^{-11} m^2 s^{-1} are comparable with the reported values 2.26x10^{-9} to 9.14 x10^{-9} m^2 s^{-1} for hot air drying of tomato[24], 1.31x10^{-9} to 1.07x10^{-9} m^2 s^{-1} for solar tunnel drying of organic tomato [20], 3.91x10^{-10} to 6.65x10^{-10} m^2 s^{-1} for hot air drying of tomato[25] and 5.37x10^{-10} m^2 s^{-1} for solar tunnel drying of tomato [26]. However, D_{eff} values found in this study are within the general range 10^{-9}–10^{-11} m^2 s^{-1} for drying of food materials. The small differences among values could be due to the differences in varieties, drying equipment and other uncontrolled parameters.

Table 3. Values of effective diffusivity obtained from solar drying process.

Drying method	D_{eff} (m^2 s^{-1})
Inlet of solar tunnel	1.26x10^{-9}
Middle of solar tunnel	1.32x10^{-9}
Outlet of solar tunnel	1.29x10^{-9}
Open sun drying	1.13x10^{-9}

Conclusions

Based on the work described here, it is possible to make the following conclusions: 1) Average temperature in solar tunnel was about 11.5ºC above ambient temperature, whereas relative humidity in solar tunnel was about 6.9% below relative humidity. 2) In all the cases, the use of this dryer led to considerable reduction in drying time in comparison to that of open sun drying. 3) Tomatoes dried using the solar tunnel dryer were completely protected from insects, birds, rain and dusts and also of better quality as compared to their open sun dried. 4) The middle of solar tunnel had the fastest drying rate. 5) Of all the five models tested, the Midilli *et al.* model gave a good fit to the experimental data obtained with a value for r^2 of greater than 0.98 for solar tunnel drying process.

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Nomenclature

a, b, c	coefficients in models
D_{eff}	effective diffusivity (m^2 s^{-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	empirical constants in drying models
m	exponent in drying model
M	moisture content at any time (kg [H_2O]/kg [DM])
M_e	equilibrium moisture content (kg [H_2O]/kg [DM])
M_0	initial moisture content (kg [H_2O]/kg [DM])
M_l	local moisture content (kg [H_2O]/kg [DM])
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^2	coefficient of determination
RH_{in}	relative humidity at inlet of the solar tunnel (%)
RH_m	relative humidity in middle of the solar tunnel (%)
RH_o	relative humidity at outlet of the solar tunnel (%)
s	slope
t	drying time (h)
T	air temperature (°C)
T_{in}	air temperature at inlet of the solar tunnel (°C)
T_m	air temperature in middle of the solar tunnel (°C)
T_o	air temperature at outlet of the solar tunnel (°C)
z	number of constants
χ^2	reduced mean square of the deviation
∇	operator