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Mathematical modelling and experimental investigation on sun and solar drying of white mulberry

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Abstract

The drying kinetics of white mulberry was investigated in a solar dryer with forced convection and under open sun with natural convection. The constant rate period is absent from the drying curve. The drying process took place in the falling rate period. The drying data were fitted to the different mathematical models. The performance of these models was investigated by comparing the determination of coefficient (R), reduced chi-square (χ^2) and root mean square error ($RMSE$) between the observed and predicted moisture ratios. Among these models, the drying model developed by Logarithmic model showed good agreement with the data obtained from the experiments in the solar dryer with forced convection drying mode. The Verma et al. model has shown a better fit to the experimental mulberries data for open sun drying with natural convection mode than the other models.

The effective moisture diffusivity values were estimated from Fick's diffusional model. These values were $3.56\text{x}10^{-9}$ m^2/s for solar drying and $2.40\ \text{x}10^{-9}$ m^2/s for open sun drying.

Keywords: Solar drying; Natural sun drying; Forced drying; Thin layer drying models; White mulberry

1. Introduction

Drying is widely used in a variety of thermal energy applications ranging from food drying to wood drying [1]. It can either be done by traditional sun drying or industrially through the use of solar dryers or hot air drying [2]. 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 [3, 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 labor costs, large area requirement, insect infestation, mixing with dust and other foreign materials and so on [4].

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 it is warmer inside the dryer than outside; the quality of the dried products can be improved in terms of hygiene, cleanliness, safe moisture content, color and taste; the product is also completely protected from rain, dust, 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 [4, 5].

Simulation models are helpful in designing new or in improving existing drying systems or for the control of the drying operation. The drying kinetics of materials may be described completely by using their transport properties (thermal conductivity, thermal diffusivity, moisture diffusivity, and interface heat and mass transfer coefficients) together with those of

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the drying medium [6]. In the case of food drying, the drying constant K is used instead of transport properties. The drying constant combines all the transport properties and may be defined by the thin layer equation.

Thin layer equations describe the drying phenomena in a united way, regardless of the controlling mechanism. They have been used to estimate drying times of several products and to generalize drying curves. In the development of thin layer drying models for agricultural products, generally the moisture content of the material at any time after it has been subjected to a constant relative humidity and temperature conditions is measured and correlated to the drying parameters [6, 7]. Although there are many studies of solar and open sun on thin layer drying of fruits such as grapes [8], apricots, figs, grapes, plums [6], figs [9], apples [10], prickly pear peel [11], Stanley plums [12], no studies were found about the thin layer drying process in solar dryer with forced convection and under open sun with natural convection of mulberry in the literature.

The main objectives of this study are to:

(i) study and compare the thin-layer drying characteristics of mulberry by using the open sun and solar drying methods,

(ii) fit the experimental data obtained to semi-theoretical models widely used to describe thin-layer drying kinetics of mulberry, and

(iii) calculate the effective moisture diffusivity.

2. Mathematical modelling of drying curves

The moisture ratio was calculated from $MR = (M_t-M_e)/ (M_o-M_e)$, which some investigators simplified to M_t/M_o [8, 13-14] because of the continuous fluctuation of the relative humidity of the drying air during open sun and solar drying processes.

For mathematical modelling, the thin layer drying equations in Table 1 were tested to select the best model for describing the drying curve equation of mulberry during drying process by solar dryer and open sun [4, 6-10, 12-14]. The regression analysis was performed using Statistica computer program. The correlation coefficient (R) was primary criterion for selecting the best equation to describe the drying curve equation. In addition to R, the reduced χ^2 as the mean square of the deviations between the experimental and calculated values for the models and root mean square error analysis (*RMSE)* were used to determine the goodness of the fit. The higher the values of the R, and lowest values of the χ^2 and *RMSE*, the better the goodness of the fit [4, 6-10, 12-14]. These can be calculated as:

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

Table 1. Mathematical models widely used to describe the drying kinetics.

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

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

$$RMSE = \left[\frac{1}{N}\sum_{i=1}^{N}\left(MR_{pre,i} - MR_{\exp,i}\right)^2\right]^{1/2} \tag{3}$$

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.

3. Materials and procedure

3.1 Experimental set up

The experimental set up mainly consists of an indirect forced convection solar dryer with a solar air collector, a circulation fan and a drying cabinet as shown in Fig. 1. The solar air collector, which has dimensions of 1200x700 mm, is constructed from 0.5 mm thickness stainless steel sheets the outer surface of which is painted with black collector paint. The top part of the solar air heater was covered with copper sheet with thickness of 0.4 mm. The copper sheet was painted with black collector paint. In the solar air heater, fins were located in the flow area to increase the heat transfer coefficient and output temperature of air. The fins were designed in two different dimensions. Type I and II fins have 500x120 mm and 100x120 mm dimensions, respectively. The solar heater was divided to 5 using fins (Type I) with rectangular shape. The fins (Type I) were located with an interval of 200 mm on the solar heater. Moreover, as shown Fig. 1b, fins (Type II) were located with angle of 45^o as an equal interval to an arrangement on the solar heater. A glass was used as a transparent cover for the air heater to prevent the top heat losses. The solar heater was oriented southwards under the collector angle of 23.7^o (local latitude 38.4^o). This angle was fixed by foot. The frame was made of stainless steel sheet.

The drying cabinet was constructed from wood as a rectangular tunnel in 45x45x45 cm^3 dimensions. Bottom side of the cabinet was a circular tube contracted to the same diameter to connect the main collector tube. The connection to this tube was made with bendable spiral aluminium tube of the same diameter. Drying air existed from the circular tube at topside of the cabinet. One end of the cabinet was manufactured

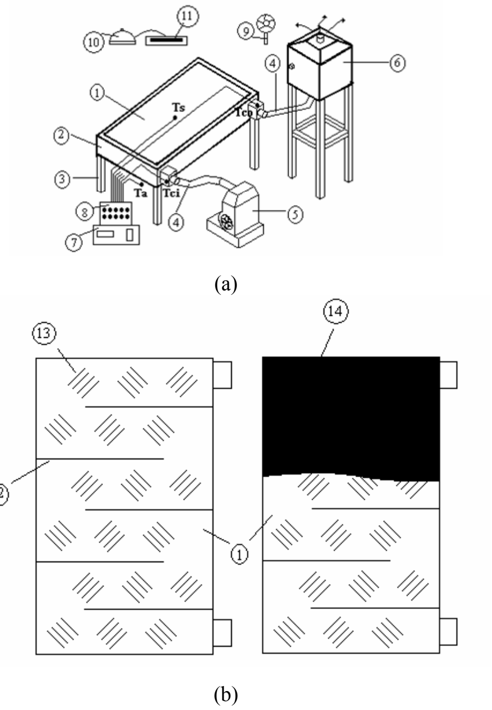

Fig. 1. Experimental set-up.
1-Solar collector; 2-Frame; 3-Foot; 4-Connection pipe; 5-Circulation fan; 6-Drying cabinet; 7-Channel selector; 8-Digitial thermometer 9-Anenometer; 10- Pyranometer; 11-Digital solar integrator; 12-Fin (Type I); 13- Fin (Type II); 14-Copper sheet

in a type of cover. This cover was used to load or unload the cabinet. One drying tray with 40x40 cm^2 dimensions was placed inside the drying cabinet and under open sun.

A centrifugal fan (0.0833 m^{3}s^{-1}, 0.25 kW, 220 V, 50 Hz, 1380 min^{-1}) connected to drying cabinet provided air velocity 0.4 ms^{-1}.

3.2 Experimental procedure

Fresh mulberries were obtained from Elazig, harvested by hand and kept refrigerated. Generally, samples of uniform size selected. The average radius of samples was 1.68 ± 0.02 cm. The initial weight of the white mulberries was approximately 300 g. Initial moisture content of the fresh mulberries found about 82 % (w.b.), and was determined by drying in an air convection oven at 105 ºC for 4 hr, performed in triplicate.

The solar drying experiments were carried out during the periods of July 2006 in Elazıg, Turkey. Each test started at 9:30 a.m. and continued till 17:30 p.m. Drying experiments were conducted for product grown in Elazig, Turkey. Elazig is located at 38°60'N and 39°28'E and above 950 m of sea level in the eastern part of Anatolia, Turkey.

In the experiments, weather temperature and relative humidity, inlet and outlet temperatures of air in the solar collector, the temperatures at the various points of drying cabinet, humidity, inlet and outlet temperatures of air in the cabinet, wind speeds, the amount of solar radiation, and mass loss of mulberries were measured at 30 min intervals.

In the measurements of temperatures, J type iron-constantan thermocouples were used with a manually controlled 20-channel automatic digital thermometer (ELIMKO, 6400, Turkey), with reading accuracy of ±0.1 °C. A thermo hygrometer (EXTECH, 444731, China) was used to measure relative humidity just above white mulberries. The wind speed was measured by a 0-15 m/s range anemometer (LUTRON, AM-4201, Taiwan). Moisture loss of mulberries was recorded during drying for determination of drying curves by digital balances (BEL, Mark 3100, Italy) in the measurement range of 0-3100 g and an accuracy of ±0.01 g. The solar radiation during the operation period of the drying system was measured with a Kipp and Zonen piranometer in ± 0.1 Wm^{-2} accuracy and its CC12 model digital solar integrator.

3.3 Experimental uncertainty

Errors and uncertainties in the experiments can arise from instrument selection, condition, calibration, environment, observation, reading and test planning. In drying experiments in solar dryer and open sun of the mulberries, the temperatures, velocity of drying air, relative humidity of drying air, the initial and final moisture content of mulberries, weight losses and solar radiation were measured with appropriate instruments. During the measurements of the parameters, the uncertainties that occurred are presented in Table 2. Considering the relative uncertainties in the individual factors denoted by x_n, uncertainty estimation was made by using the following equation [15]:

$$W = \left[(x_1)^2 + (x_2)^2 + ...(x_n)^2 \right]^{1/2} \tag{4}$$

4. Results and discussion

The weather conditions in the drying period are shown in Fig. 2. During the drying experiments, the temperature of ambient air ranged from 24.4 to 47.1 ºC, the temperature of drying air at the inlet of the drying cabinet from 42.3 to 62.6 ºC, and the temperature of drying air at the outlet of the drying cabinet from 33.8 to 57.6 ºC. The temperature of air entering the solar collector (T_{ci}) is different from the ambient temperature (T_a). At the beginning of experiment, in

Table 2. Uncertainties of the parameters during drying experiment of mulberries.

Parameter	Unit	Comment	
		Solar Dryer	Drying under open sun
Uncertainty in the temperature measurement			
Collector inlet temperature	°C	±0.380-±0.576	-
Collector outlet temperature	°C	±0.380-±0.576	-
Drying cabinet inlet temperature	°C	±0.380-±0.576	-
Drying cabinet outlet temperature	°C	±0.380-±0.576	-
Ambient air temperature	°C	±0.380	±0.380
Uncertainty in the time measurement			
Mass loss values	min	±0.1	±0.1
Temperature values	min	±0.1	±0.1
Uncertainty in the mass loss measurement	g	±0.5	±0.5
Uncertainty in the air velocity measurement	ms^{-1}	±0.14	±0.14
Uncertainty of the measurement of relative humidity of air	RH	±0.14	±0.14
Uncertainty in the measurement of moisture quantity	g	±0.001	±0.001
Uncertainty in the measurement of solar energy	$W.m^{-2}$	±0.1	±0.1
Uncertainty in reading values of table	%	±0.1-0.2	±0.1-0.2

the morning (9:30-11:30), T_{ci} is a little lower than T_a. The reasons of this situation may be explained as follows:

1- Fan hadn't been operated at 9:30 measurement. After 9:30 measurements, fan was operated.

2- There is heat loss in the duct at the collector inlet. This region hadn't been isolated. This region will be isolated at the other studies.

3-Diameter of the connection tube at the collector inlet is 50 mm. Geometry of the duct, which is connected collector with the connection tube, is square. The square duct has dimensions of 120x120 mm. Temperature of the air entering into the duct from the connection tube can decrease from geometry.

However, at period of 11:30-17:30, T_{ci} is a little higher than T_a. The temperature T_{ci} is a little higher than T_a since the fan draws in the air from the ambient.

Direct instantaneous solar radiation reached 952 Wm^{-2} (Fig. 3). The solar radiation energy was maximum in midday and minimum in the morning, and it was also zero in the night during the experiment. The values of the wind speeds measured with anemometer varied between 0 ms^{-1} and 2.3 ms^{-1} during days of the experimental work (Fig. 3). Moreover, the wind speed was determined as 1.2 ms^{-1} average by meteorological values.

4.1 Drying curves

The mulberries of 4.55 g water/g dry matter average initial moisture content were dried to 0.17 g water/g dry matter in the solar drying cabinet or spread out on the ground to apply open air sun drying. The final moisture contents represent moisture equilibrium between the sample and drying air under solar dryer conditions, beyond which any changes in the mass of sample could not occur.

The changes in the moisture content per amount of the dry matter of mulberries with time are shown in Fig. 4. The interruptions of the lines in this figure represent the night periods of the drying operation. The drying continued after the sunset due to the thermal inertia of the system. Final drying levels were realized in 104 hr in the solar dryer, while it took about 152 hr in the open-air sun drying. Fig. 4 clearly indicates that the drying rate in the solar dryer operating under forced convection could be much higher than the natural open-air sun drying. Depending on the increase in the drying rates, the present system practically shortens by two days the drying time of mulberries.

The drying rates versus drying time are shown in Fig. 5. It is apparent that drying rate decreases

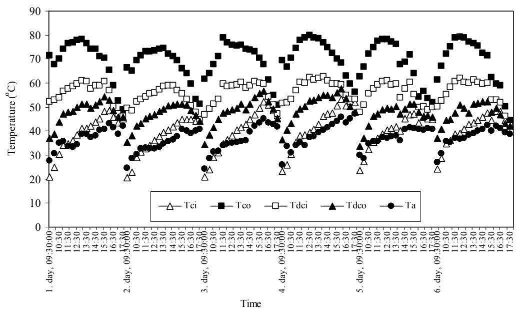

Fig. 2. The variation of temperatures in the solar dryer.

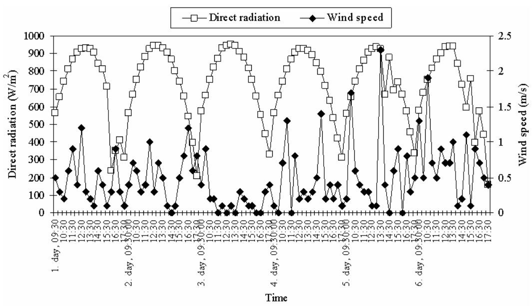

Fig. 3. The variation in the direct radiation and wind speed.

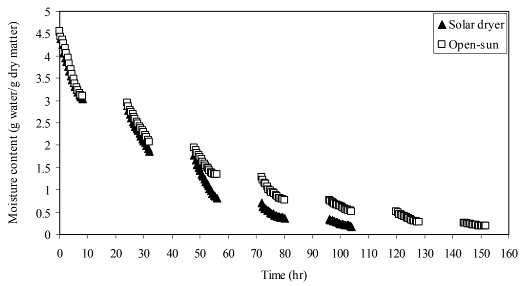

Fig. 4. Variation of moisture content with drying time of mulberries.

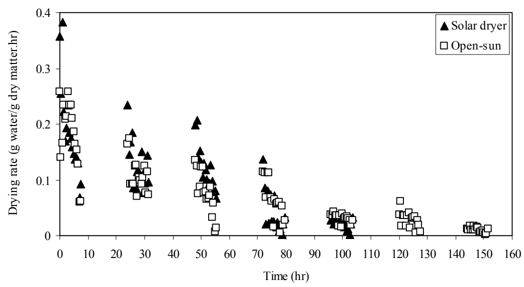

Fig. 5. Variation of drying rate with drying time of mulberries.

continuously with the decrease of moisture content or the increase with drying time. There is not any constant-rate drying period in these curves and all the drying operations seen to occur in the falling rate period. In the falling rate period the material surface is no longer saturated with water and the drying rate is controlled by diffusion of moisture from the interior of solid to the surface [16]. These results are in agreement with the observations of earlier researchers [6, 9, 11].

4.2 Mathematical modelling of solar and open-sun drying curves

In order to normalize the drying curves, the data involving dry basis moisture content versus time were transformed to a dimensionless parameter called moisture ratio versus time (Fig. 6). 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 13 drying models evaluated by the previous workers (Table 1). The results of statistical analyses undertaken on these models for the forced solar drying and the natural sun drying are given in Table 3 and Table 4, respectively. The models were evaluated based on R, χ^2 and $RMSE$. For the thin layer forced solar drying of mulberries, the Logarithmic model was the best descriptive model as shown in Table 3. From the Logarithmic model for mulberries, it was determined that ***R=0.98842, χ^2=0.001909399, RMSE=0.042918624***. For the thin

Table 3. Modeling of moisture ratio according to the drying time for the thin layer forced solar drying of mulberries.

Model no	Constant	Model constants	R	χ^2	$RMSE$
1	k	0.026858	0.97666	0.003732682	0.060735226
2	k	0.042307	0.97861	0.003465488	0.058171704
	n	0.882587			
3	k	0.027777	0.97861	0.003465488	0.058171704
	n	0.882585			
4	a	0.909440	0.98460	0.002502944	0.049437343
	k	0.024353			
5	**a**	**1.017934**	**0.98842**	**0.001909399**	**0.042918624**
	k	**0.017859**			
	c	-0.132876			
6	a	0.452870	0.98460	0.002564745	0.049437343
	ko	0.024353			
	b	0.456569			
	k1	0.024353			
7	a	0.074729	0.98279	0.002794048	0.052233185
	k	0.334293			
8	a	-0.020125	0.97201	0.004520653	0.066440087
	b	0.000108			
9	a	0.114060	0.98594	0.002314863	0.047256347
	k	0.918723			
	b	0.025835			
10	a	0.303151	0.98460	0.002629675	0.049437344
	k	0.024353			
	b	0.303151			
	g	0.024353			
	c	0.303151			
	h	0.024352			
11	a	0.114053	0.98594	0.002314863	0.047256346
	k	0.919240			
	g	0.023736			
12	a	0.896676	0.98824	0.001962531	0.043245537
	k	0.024565			
	n	0.942936			
	b	-0.000997			
13	a	-40.2592	0.98021	23.11242754	4.750642663
	b	-2.33241			

Table 4. Modelling of moisture ratio according to the drying time for the thin layer open sun drying of mulberries.

Model no	Constant	Model constants	*R*	χ^2	*RMSE*
1	k	0.021051	0.98364	0.002319584	0.047959276
2	k	0.043648	0.98938	0.001523171	0.038698463
	n	0.822565			
3	k	0.022212	0.98938	0.001523171	0.038698463
	n	0.822573			
4	a	0.901055	0.99225	0.001112949	0.033079353
	k	0.018865			
5	a	0.911954	0.99238	0.001104156	0.032807325
	k	0.017999			
	c	-0.015917			
6	a	0.450512	0.99225	0.001132304	0.033079353
	ko	0.018865			
	b	0.450543			
	k1	0.018865			
7	a	0.094683	0.99071	0.001332548	0.036196027
	k	0.202275			
8	a	-0.015389	0.96649	0.004748687	0.068329182
	b	0.000062			
9	a	0.139829	0.99299	0.00102408	0.031458818
	k	0.508311			
	b	0.035453			
10	a	0.300360	0.99225	0.001152345	0.033079356
	k	0.018863			
	b	0.300360			
	g	0.018864			
	c	0.300359			
	h	0.018872			
11	**a**	**0.139814**	**0.99446**	**0.000802732**	**0.027973112**
	k	**0.508510**			
	g	**0.018022**			
12	a	0.946968	0.99299	0.00102408	0.031458818
	k	0.041626			
	n	0.790531			
	b	-0.000487			
13	a	-49.4428	0.98451	25.74261185	5.030900805
	b	-.271164			

layer natural sun drying of mulberry, the Verma et al. model was the best descriptive model as shown in Table 4. From the Verma et al. model for mulberries, it was determined that ***R=0.99446, χ^2=0.000802732, RMSE=0.027973112.***

Validation of the established model was made by comparing the computed moisture content with the measured moisture content in any particular drying run under certain conditions. The performance of the model for the thin layer forced solar drying and the natural sun drying is illustrated in Fig. 7. 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 behaviour of mulberries.

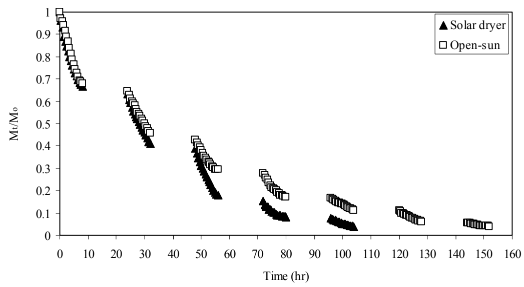

Fig. 6. Variation of moisture ratio with drying time of mulberries.

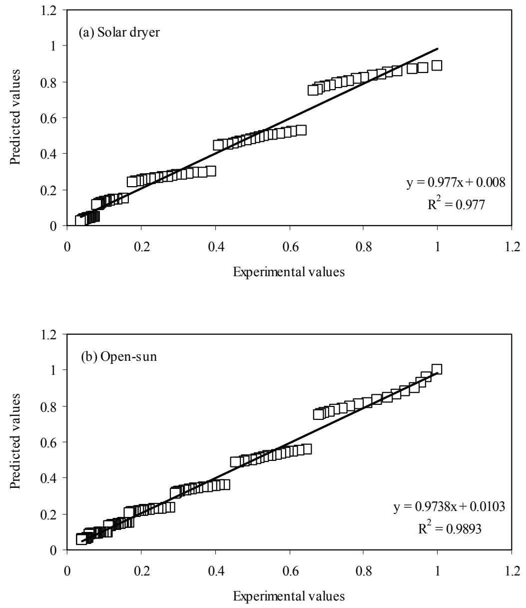

Fig. 7. The comparison of experimental and predicted dimensionless moisture content by the resulting model.

4.3 Determination of the effective diffusivity coefficients

The mechanisms of mass transfer in foods are complex. Frequently, the modelling of the drying curves during the falling rate period is carried out by assuming that the main mechanism is of diffusional nature. Therefore, the diffusion coefficient estimated from experimental results is an effective parameter that includes the effects of the known hypotheses together with the unknown phenomena [17].

The experimental drying data for the determination of diffusivity coefficients were interpreted by using Fick's second diffusion model.

$$\frac{dM}{dt} = D\frac{d^2M}{dr^2} \tag{5}$$

To solve Eq. (5), the assumption of moisture migration being by diffusion, constant temperature and diffusion coefficients, negligible shrinkage and for sphere is [18]:

$$MR = \frac{M_t - M_e}{M_o - M_e} = \frac{6}{\pi^2}\sum_{n=1}^{\infty}\frac{1}{n^2}\exp\left[-n^2\pi^2\frac{D_{eff}t}{R^2}\right] \tag{6}$$

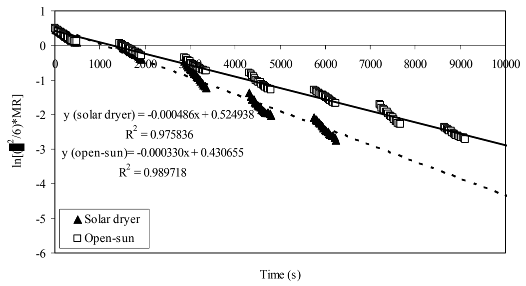

Fig. 8. Variation of $\ln[(\pi^2/6)*MR]$ with drying time of mulberries.

For long drying periods, Eq. (6) can be further simplified to only first term of the series [19]:

$$\ln(MR) = \ln(\frac{6}{\pi^2}) - \left(\pi^2\frac{D_{eff}t}{R^2}\right) \tag{7}$$

The effective moisture diffusivity was calculated by the method of slopes. Diffusion coefficients are typically determined by plotting experimental drying data in terms of ln (MR) versus time (as given in Eq. (7)) as shown Fig. 8 [20]. From Eq. (7), a plot of ln (MR) versus time gives a straight line with a slope of:

$$Slope = \left(\pi^2\frac{D_{eff}t}{R^2}\right) \tag{8}$$

The D_{eff} value of white mulberry was found as $3.56\text{x}10^{-9}$ m^2/s for solar drying and 2.40 $\text{x}10^{-9}$ m^2/s for open sun drying. Maskan and Gogus [21] found that D_{eff} was $2.32\text{x}10^{-10}$ to 2.76 $\text{x}10^{-9}$ m^2/s in mulberry hot air-drying at 60–80 °C. These values are consistent with the present estimated D_{eff} values for mulberries.

5. Conclusions

In this study, the drying behavior of white mulberries was investigated in a convective type with forced convection mode and under open sun with natural convection mode. Drying of white mulberries at each of mode occurred in the falling rate period; no constant-rate period of drying was observed. In order to explain the drying behavior and to develop the mathematical modelling of mulberries, thirteen models in the literature were applied to thin layer forced solar drying and open sun drying processes. The results showed that the Logarithmic model was the most suitable for describing the drying curve of the thin layer forced solar drying process of mulberries with ***R of 0.98842, χ^2 of 0.001909399, RMSE of 0.042918624.*** However, the Verma et al. model satisfactorily described the drying curve of mulberries with a ***R of 0.99446, χ^2 of 0.000802732, RMSE of 0.027973112*** for open sun mode. The effective moisture diffusivity values were estimated from Fick's diffusional model. These values were 3.56x10^{-9} m^2/s for solar drying and 2.40 x10^{-9} m^2/s for open sun drying.

Acknowledgment

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Nomenclature

a, b, c, g, h, n : Empirical constants in the drying models
D_{eff} : Effective moisture diffusivity, m^2/s
k, k_o, k_1 : Empirical coefficients in the drying models (hr^{-1})
n : Number constants, positive integer
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
MR_{exp} : Experimental moisture ratio
MR_{pre} : Predicted moisture ratio
r : Diffusion path (m)
R : Regression coefficient, radius in the berry cross-section (m)
R^2 : Coefficient of determination
$RMSE$: Root mean square error
W : Total uncertainty in the measurement
t : Time (s, hr, min)
T_a : Ambient temperature (°C)
T_{ci} : Temperature of the air entering into the collector (°C)
T_{co} : Temperature of the air leaving the collector (°C)
T_{dci} : Temperature of the air entering into the drying cabinet (°C)
T_{dco} : Temperature of the air outlet the drying cabinet (°C)
T_s : Temperature of the collector surface (°C)
$x_1, x_2,..x_n$: The uncertainties in the independent variables
χ^2 : Chi-square

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