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MATHEMATICAL MODEL OF SOLAR DRYING CHARACTERISTICS FOR PEPPER (CAPSICUM ANNUUM)

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Abstract: This experimental study was performed to determine drying characteristics of the *Capsicum Annuum* in a solar tunnel dryer with forced convection and in open sun drying process at the open field. Solar tunnel dryer consists of two solar air collectors connected in series, a greenhouse type tunnel dryer and an air circulation system. Heated air obtained from solar air collectors was forced towards the *Capsicum Annuum* by a blower during the drying process. During the period of drying, the moisture ratio of the *Capsicum Annuum* versus the drying time was measured in the presence of different data such as solar radiation, relative humidity and temperature of ambient air, inlet and outlet air temperature of the solar air collectors, inlet and outlet temperature and relative humidity of the tunnel dryer. Drying curve was formed for solar tunnel drying and open sun drying on the bases of the variation graph of moisture ratio and drying time of the *Capsicum Annuum*. Suitable mathematical model was examined by using non-linear regression method. To this end, ten different mathematical models were compared according to statistical parameters such as the chi-square error ($\chi2$), the root mean square error (RMSE), the mean bias error (MBE), the coefficient of determination (R^2). As a result, it was observed that the model which provides the best description of the solar drying behavior of the Capsicum Annuum is the two-term drying model. This model resulted in $\chi2$ = 0.0006, RMSE= 0.0061, MBE = 0.0190, R^2 = 0.9988 for forced solar drying, and $\chi2$ = 0.0004, RMSE = 0.0082, MBE = 0.0128, R^2 = 0.9940 for open sun drying.
Keywords: Drying kinetic, Drying, Mathematical model, Capsicum Annuum.

BİBER İÇİN GÜNEŞLİ KURUTMA KARAKTERİSTİKLERİNİN MATEMATİKSEL MODELLENMESİ

Özet: Bu deneysel çalışma, zorlanmış taşınımlı güneşli tünel kurutucusunda ve açık alanda açık güneş kurutma işleminde biberin kuruma karakteristiklerini belirlemek için gerçekleştirildi. Güneşli tünel kurutucusu, birbirine seri bağlı olan iki güneşli hava toplayıcısı, sera tipi tünel kurutucusu ve hava sirkülasyon sistemi içermektedir. Kurutma işlemi sırasında güneşli hava toplayıcısından elde edilen ısıtılmış hava fan aracılığıyla biberin üzerine gönderildi. Bu kuruma periyodunda, kuruma zamanına bağlı olarak biberin nem oranı, güneş radyasyonu, çevre havanın bağıl nem ve sıcaklığı, güneşli hava toplayıcısının giriş ve çıkışındaki hava sıcaklığı, tünel kurutucusunun giriş ve çıkışındaki sıcaklık ve bağıl nem değerleri gibi farklı datalara bağlı olarak hesaplandı. Kuruma eğrisi, güneşli tünel kurutma ve açık güneşli kurutma için biberin kuruma zamanına karşı nem oranı değişim grafiğinden elde edildi. Non-Lineer regrasyon yöntemi kullanılarak uygun matematiksel model geliştirildi. Bu amaç doğrultusunda, belirleme katsayısı (R^2), ortalama karesel hata (RMSE), ortalama sapma hata (MBE) ve azaltılmış Ki-kare ($\chi2$) gibi istatistiksel parametreler dikkate alınarak on farklı matematiksel model karşılaştırıldı. Sonuçlara göre, biberin güneşli kurutma davranışlarını en iyi tanımlayan modelin two term kurutma modeli olduğu görüldü. Two term kurutma modeline göre, güneşli tünel kurutucu için $\chi2$= 0.0006, RMSE= 0.0061, MBE = 0.0190, R^2 = 0.9988, açık güneş kurutma için $\chi2$ = 0.0004, RMSE = 0.0082, MBE = 0.0128, R^2 = 0.9940 sonuçları elde edildi.
Anahtar Kelimler: Kurutma kinetiği, Kurutma, Matematiksel model, Biber.

INTRODUCTION

Agricultural potential and climatic conditions of Turkey are suitable for the production of different type of agricultural product. While agricultural products are freshly consumed at various proportions, remainder products are subjected to the drying process for long shelf life. Drying process can be conducted either by traditional sun drying or by industrial applications of solar dryers. Various types of solar dryers to be used for different products have been investigated by researchers. For example, a solar dryer which consists of an air-heater solar collector and drying chamber was designed for drying food waste to be used as animal feed (Nijmeh et al ., 1998), a solar air heater with conical concentrator and drying cabinet was used for solar drying for apricots (Toğrul and Pehlivan, 2002), solar drying of pepper was carried out in naturally ventilated polyethylene greenhouse (Farhat et al., 2004), drying experiment of vegetables wastes in a wholesale market was performed by a convective cross flow pilot dryer (Lopez et al., 2000), an indirect forced convection solar dryer was used to determine the thin layer characteristics of long green pepper (Akpinar and Biçer, 2008), solar tunnel dryer was used for thin layer solar drying experiments of organic tomato (Sacılık et al, 2006; Gürlek et al, 2008), a forced convection greenhouse drier was used for sweet pepper and garlic (Condori and Savaria, 2003), an indirect forced convection solar dryer which consists of solar air heater and drying cabinet was used for sultana grapes (Yaldız and Ertekin, 2001; Yaldız et al., 2001).

Solar dryer systems are preferred in drying foods, for they are cheaper and more practical. Therefore, it is important to understand the parameters which influence the system. In this study, pepper (*Capsicum Annuum*) was used in order to solve the problems which occur in conventional drying of this product. In Turkey, *Capsicum Annuum* has been more widely produced in Aegean region because of the climatic conditions of the area.
Many researchers who study on mathematical modeling and experimental studies have conducted researches on thin layer drying processes of bell pepper (Tunde-Akintunde et al., 2005), sweet pepper (Vengaiah and Pandey, 2007; Condori et al., 2001), green pepper (Kaymak-Ertekin, 2002; Yaldız and Ertekin, 2001) and red pepper (Akpınar et al., 2003; Doymaz and Pala, 2002).

The main purpose of this study is to compare the thin layer drying characteristics of pepper (*Capsicum Annuum*) during solar drying with forced convection and open sun drying.

MATERIALS AND METHODS

Experimental Setup and Procedure

Drying of product was conducted in a 5 m long, 2.05 m wide and 2.28 m high solar tunnel dryer. As shown in Fig. 1, the tunnel dryer which is used in this experiment consists of two flat plate solar air collectors which were connected in a series, a greenhouse type tunnel dryer and an electrically driven radial fan to provide the required air-flow over the product for drying.

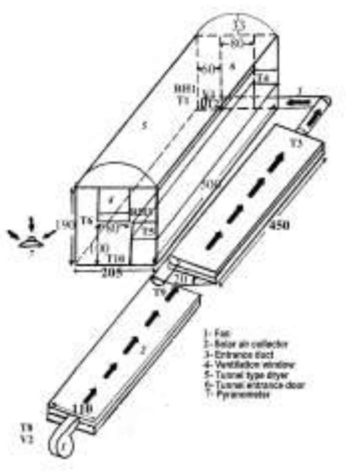

Figure 1. Schematic diagram of experimental setup showing the location of all measurement devices. (T1 and T4- Inlet shelves air temperature, T2- Inlet air temperature of tunnel dryer, T3- Outlet air temperature of second solar collector, T5 and T6- Outlet shelves air temperatures of tunnel dryer, T7- Ambient temperature, T8- Air temperature around the fan, T9- Outlet air temperature of first solar collector, T10- Temperature under the ventilation window, RH1- Relative Humidity of inlet air to the tunnel dryer, RH3- Relative Humidity of outlet air from the tunnel dryer, V1- Velocity of inlet air to the tunnel dryer, V2- Air velocity around the fan).

Four drying trays with 0.6 m x 5 m dimensions were used to place the product which will be dried. As can be seen in Fig. 2, two of these trays were on the left side and the other two on the right side and trays were placed one on the top of the other. Measurements were taken from heat- and moisture-sensitive equipments which were placed in greenhouse with the help of a data-logger. Ambient air was passed through two 4.5 m long, 1.1 m wide collectors which were connected to each other. Collectors were oriented towards south and located with a 20^o slope. Collectors and greenhouse were covered with polyethylene film. 5 cm thick polyurethane foam was placed under the collectors for insulation.

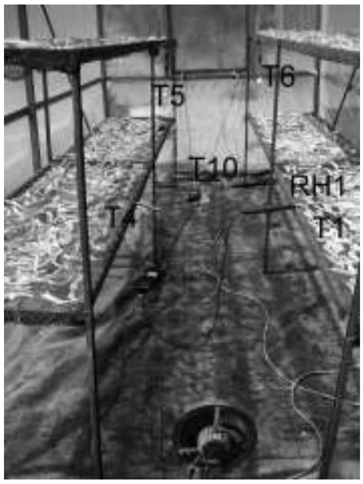

Figure 2. Arrangement of samples on the shelf in the solar tunnel dryer.

Drying experiment was conducted during the period of August in Gaziemir, Izmir, Turkey. Pepper (*Capsicum Annuum*) was used in this study as the experimental product. Homogenous sized pepper samples were washed and cut into half and seeds of pepper were taken out. In this experiment, 22 kg of pepper (*Capsicum Annuum*) were exposed to solar radiation for drying in the tunnel dryer.

Important parameters which affect the performance of the dryer, such as drying air temperature, relative humidity, air flow rates, solar radiations and mass loss of the product were measured. A schematic diagram of the experimental setup showing the location of all measurement devices are shown in Fig. 1. A pyranometer was used to measure the solar radiation on the horizontal surface. Table 1 illustrates the measurement ranges and accuracy of the temperature prob, moisture prob and velocity prob, while Table 2 shows the specifications of the pyranometer (Kipp and Zonen Instruction Manuel, 1993). The temperature and relative humidity inside and outside of the tunnel were measured with temperature and relative humidity probes. All data were collected in a data-logger. The velocity of air inlet to the tunnel dryer was measured with anemometer. Anemometer was placed in the inlet of the tunnel dryer in the cylindrical air duct. During the experiments, temperature of ambient air and velocity of wind were measured. The view of the inside of the tunnel dryer and the locations of the measurement devices were illustrated in Fig. 2.

To determine the mass loss of the product during the experiment, samples were taken from each shelve and weighed with electronic scale which is ±0.01 g. accurate. All data were continuously recorded at 1 hour intervals and the weather was sunny during the drying process. All the experiments were conducted simultaneously in the solar tunnel dryer and open field at atmospheric conditions. Different properties of products like drying time and variation of moisture ratio in open sun drying and forced solar drying were compared.

THEORETICAL APPROACH

Mathematical Modeling of Drying Curves

The thin layer drying model has been selected to analyze the drying behavior of *Capsicum Annuum*. In this study, ten widely used mathematical models were tested to select the best model for describing the drying curve equation of *Capsicum Annuum* (Table 3).

In these models, the moisture ratio MR was taken as a dimensionless value instead of MR = (M_t - M_e) / (M_o - M_e). In this equation, M_o, M_t, and M_e were used as an initial moisture content, moisture content at any time of drying and equilibrium moisture content, respectively. The moisture ratio MR was simplified to (M_t / M_o) instead of the (M_t - M_e) / (M_o - M_e) since M_e is relatively small as compared with M_o (Diamante and Munro, 1993; Ertekin and Yaldiz, 2004; Fang et al., 2009).

Drying rate of *Capsicum Annuum* was calculated by using equation below (Sobukola et al., 2008). In this equation, A stands for drying area.

$$Drying\ \ rate = \frac{M_{t+dt} - M_t}{dt\ \ A} \quad (1)$$

Table 1. Specification of all measurement devices.

Measurement Device Type	Measurement Range	Accuracy
Temperature Prob	-200…+400 ^oC	± 1,5 ^oC
Temperature Prob	-200…+600 ^oC	± 0,25 ^oC
Temperature Prob	-200…+1100 ^oC	± 1,5 ^oC
Temperature Prob	-200…+400 ^oC	± 0,25 ^oC
Temperature Prob	-100…+400 ^oC	± 0,55 ^oC
Temperature and Moisture Prob	-20…+120 ^oC	± 0,4 ^oC ± 2 %
Velocity Prob	-30…+140 ^oC +0,4…+60 m/s	± 0,2 m/s

Table 2. Pyranometer's specification (Kipp and Zonen, 1993).

Sensitivity	4-6 µV / Wm^{-2}
Non-linearity	± 0,6 %
Impedance	700-1500 ohm
Response Time	<5 s (1/e), 99% value after 24 s
Spectral Range	305-2800 nm. (50% transmission points)
Visual Angle	2 π sr
Radiation Measurement Range	0-1000 W/m^2

Table 3. Mathematical models given by various authors for drying curves.

Equation	Name	References
MR = exp(-kt)	Lewis (Newton)	(Tırıs et al., 1994; Babalis et al., 2006; Ghazanfari et al., 2003; Jain & Pathare, 2004)
MR = a exp(-kt)	Henderson and Pabis	(Yaldız & Ertekin, 2001; Diamante & Munro, 1993; Panchariya et al., 2002; Kashaninejad et al., 2007)
MR = a exp(-kt) + c	Logarithmic	(Toğrul & Pehlivan, 2002; Doymaz, 2004; Lahsasni et al., 2004; Diamante et al., 2010)
MR = a exp($-k_1$t) + b exp($-k_2$t)	Two-Term	(Akpinar & Biçer, 2008; Babalis et al., 2006; Panchariya et al., 2002; Vega-Gálvez et al., 2010; Özdemir & Devres, 1999)
MR = exp($-kt^n$)	Page	(Diamante & Munro, 1993, Karathanos et al., 1999; Dandamrongrak et al., 2002; Chen & Wu, 2001)
MR = exp($-(kt)^n$)	Modified Page	(Toğrul & Pehlivan, 2002; Vega-Gálvez et al., 2010; Ertekin & Yaldiz, 2004)
MR = a exp(-kt) + (1-a) exp(-kat)	Two-Term Exponential	(Akpinar & Biçer, 2008; Fang et al., 2009; Kaleta & Gornicki, 2010
MR = 1 + at + bt^2	Wang and Sing	(Babalis et al., 2006; Panchariya & Popovic, 2002; Lahsasni et al., 2004; Koua et al., 2009; Xanthopoulos et al., 2007)
MR = a exp(-kt)+ b exp(-gt)+ c exp(-ht)	Modified Henderson and Pabis	(Kaleta & Gornicki, 2010; Karathanos, 1999, Bal et al., 2010)
MR = a exp(-kt) + (1-a) exp(-gt)	Verma	(Chen & Wu, 2001; Fang et al., 2009; Kaleta & Gornicki, 2010; Bal et al., 2010; Toğrul & Pehlivan, 2004)

Calculation of Effective Diffusion Coefficient

It is generally accepted that drying process of biological materials takes place predominately in falling rate period which is controlled by liquid and/or vapor diffusion mechanism (Babalis et al., 2006; Panchariya et al., 2002). During the falling rate period, drying characteristics of biological materials are defined by using Fick’s second law of diffusion (Bal et al., 2010; Heldman and Lind, 1972; Wang et al., 2007). The diffusion is expressed as follows:

$$\frac{\partial M}{\partial t} = D_{eff}\frac{\partial^2 M}{\partial x^2} \qquad (2)$$

Here, m stands for the local moisture content on a dry basis, t for time, x for space coordinate, and D_{eff} for effective diffusion coefficient.

To solve Fick’s diffusion equation, following assumption were made: moisture is initially distributed uniformly throughout the mass of sample; mass transfer is symmetric to the centre; surface moisture content of the sample and the condition of surrounding air are always in equilibrium; resistance to the mass transfer at the surface is negligible compared to the internal resistance of the sample; mass transfer takes place by diffusion; diffusion coefficient is constant and shrinkage is negligible (Bal et al., 2010; Sharma and Prasad, 2004). In these circumstances, the solution of the Fick’s diffusion equation for slab geometry is as follows (Bal et al., 2010; Wang et al., 2007, Di Scala and Crapiste, 2008; Ramesh et al., 2001; Pezzutti and Crapiste, 1997):

$$\frac{M_t - M_e}{M_o - M_e} = \frac{8}{\pi^2}\sum_{n=0}^{\infty}\frac{1}{(2n+1)^2}\exp\left[-D_{eff}(2n+1)^2\pi^2 t/4L^2\right] \qquad (3)$$

Here, M_t stands for moisture content at a specific time, M_o for initial moisture content, M_e for equilibrium moisture content, D_{eff} for effective diffusion coefficient and L for the half thickness of slab. For long drying times, Eq (3) can be further simplified as follows:

$$\left(\frac{M_t - M_e}{M_0 - M_e}\right) = \frac{8}{\pi^2}\exp\left(\frac{-\pi^2 Fo}{4}\right) \qquad (4)$$

Eq (4) can be also written in a logarithmic form as follows:

$$\ln\left(\frac{M_t - M_e}{M_0 - M_e}\right) = \ln\left(\frac{8}{\pi^2}\right) - \frac{\pi^2 D_{eff}\, t}{4L^2} \qquad (5)$$

Effective diffusion coefficient is predicted by using slope method in which slope is calculated from a graph which illustrates drying time versus experimental values of logarithmic moisture ratio (ln (MR)). It can be seen that the plot is a straight line in the graph between drying time (t) and ln (MR) of Eq (5), and slope of this straight line is calculated by $\frac{\pi^2 D_{eff}}{4L^2}$ equation (Vega et al., 2007).

Effective diffusion coefficient usually depends on composition, moisture content, temperature and the type of the material. Effect of the temperature on effective diffusion coefficient is generally described by using Arrhenius type relationship since it enables the obtainment of a more consistent correspondence between the predicted curve and the experimental data.

Statistical Analysis

There are several statistical test methods which are used to compare experimental and predicted results. The root mean square error (RMSE), the mean bias error (MBE), and the reduced chi-square test ($\chi 2$) are the most widely used ones among these methods (Diamante et al., 2010; Kaleta and Gornicki, 2010; Bal et al., 2010; Bowen and Star, 1982; Freund and Simon, 1992; Iqbal, 1983; Singh and Bhatti, 1990; Rehman, 1999).

Mean bias error (MBE) gives the mean deviation of predicted (MR_{pre}) values from experimental (MR_{exp}) values and it must be equal to zero at ideal conditions. A positive value of MBE indicates an over-estimate while a negative value indicates an under-estimate by the model. This parameter can be calculated by an equation as follows:

$$MBE = \sum_{i=1}^{N} \frac{\left(MR_{pre} - MR_{\exp}\right)}{N} \qquad (6)$$

The root mean square error (RMSE) provides information on the short term performance of the correlations by allowing a term by term comparison of the actual deviation between predicted (MR_{pre}) and experimental (MR_{exp}) values. The RMSE is always positive, though a zero value is ideal. The lower the RMSE, the more accurate is the estimate. This parameter can be calculated by an equation as follows:

$$RMSE = \sqrt{\sum_{i=1}^{N} \frac{\left(MR_{pre} - MR_{\exp}\right)^2}{N}} \qquad (7)$$

Coefficient of determination (R^2) explains the relationship between the predicted (MR_{pre}) and the experimental (MR_{exp}) values and it is required to reach one for the best fit.

$$R^2 = \frac{\sum_{i=1}^{N}\left[(MR_{\exp})(MR_{pre})\right] - \frac{1}{N}\sum_{i=1}^{N}(MR_{\exp})\sum_{i=1}^{N}(MR_{pre})}{\sqrt{\left[(MR_{\exp})^2 - \frac{1}{N}\left(\sum_{i=1}^{N}(MR_{\exp})^2\right)\right]\left[(MR_{pre})^2 - \frac{1}{N}\left(\sum_{i=1}^{N}(MR_{pre})^2\right)\right]}} \qquad (8)$$

Reduced chi-square ($\chi 2$) is used to determine the goodness of the fit. The lower value of the $\chi 2$ gives the best fit.

$$\chi^2 = \frac{\sum_{i=1}^{N}\left(MR_{\exp} - MR_{pre}\right)^2}{N - n} \qquad (9)$$

where MR_{exp} is the experimental moisture ratio found in any measurement and MR_{pre} is predicted moisture ratio for this measurement. N stands for the number of observations and n stands for the number of constants.

Uncertainty analysis

Experimental studies are not free of errors and uncertainties originating from the observer, environmental effects and measuring equipments during the running of the system. Therefore, in order to indicate the quality of the measurement carried out, an uncertainty analysis was performed by following the method. In the experimental uncertainty analysis, the experimental result, r, is computed using a data-reduction equation and the value of the J basic measurements.

$$r = r(X_1, X_2, ..., X_J) \qquad (10)$$

The uncertainty in the result is computed to the first order using a root-sum-square of the product of the uncertainties in the measured variables and the sensitivities of the result to changes in that variable

$$U_r = \left[\left(\frac{\partial r}{\partial X_1}U_{X_1}\right)^2 + \left(\frac{\partial r}{\partial X_2}U_{X_{21}}\right)^2 + ... + \left(\frac{\partial r}{\partial X_J}U_{X_J}\right)^2\right]^{1/2} \qquad (11)$$

Here, the U_X value gives the uncertainty in each basic measurement and the partial derivatives are the sensitivity coefficients (Gürlek et al., 2008). The uncertainties in calculating the moisture content, velocity and temperature were calculated as ±2 %, ±0.2 m/s and ±2.25 ^{o}C, respectively.

RESULTS AND DISCUSSION

The constant and coefficient of the most suitable mathematical model for the drying process which involves the drying variables such as temperature, humidity and solar radiation was ascertained during the four days of experiment. Changes of the climate conditions during the drying period are given in Fig. 3. As shown in Fig. 3, in the course of drying experiments, the temperature of ambient air, the relative humidity of ambient air and solar radiation had ranged from 15 to 29.5 ^{o}C, from 26 % to 52 %, and from 200 to 862.75 W/m^2,respectively.

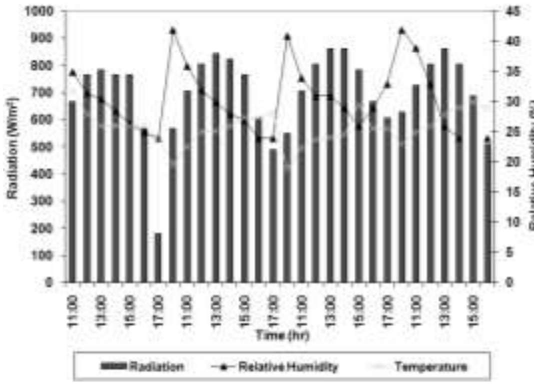

Figure 3. Change of the climate data of the ambient weather during four days

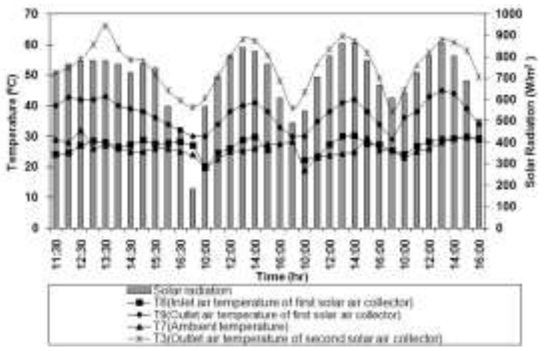

Figure 4. Working characteristics of collectors during four days

Temperatures in solar air collector, T8, T9, T3, T7 had ranged from 19 to 30 ^{o}C, from 29 to 45 ^{o}C, from 38 to 66 ^{o}C, and from 19 to 32 ^{o}C respectively as shown in Fig. 4. Working characteristics of the solar tunnel dryer is illustrated in Fig. 5. According to this, inlet temperature of solar tunnel dryer had changed between 33 and 60 ^{o}C; outlet temperature of solar tunnel dryer had changed between 34 and 55 ^{o}C; inlet relative humidity of tunnel dryer had changed between 4 % and 16.50 %; and outlet relative humidity of solar tunnel dryer had changed between 17 % and 47 %.

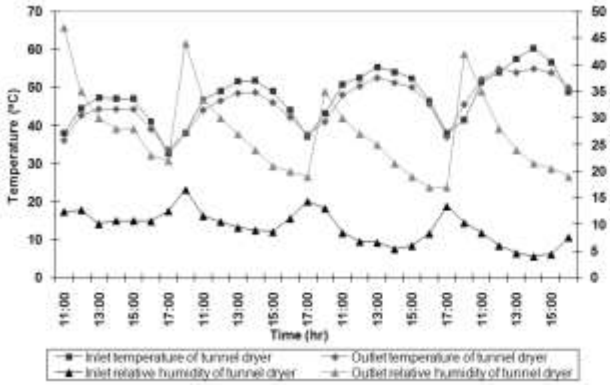

Figure 5. Working characteristics of the forced solar drying during four days

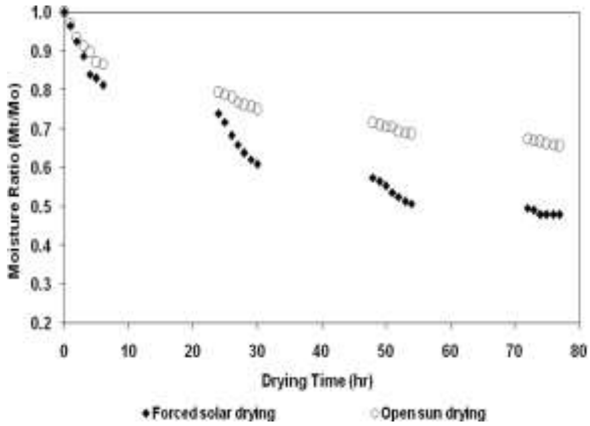

Figure 6. Moisture Ratio vs. drying time during four days for open sun drying and forced solar drying

Fig. 6 shows moisture ratio versus drying time for solar tunnel dryer and open sun drying. During drying process of pepper (*Capsicum Annuum*), initial moisture content of 15.67 kg water per kg dry matter was dried 7.60 kg water per kg dry matter until no further changes in their mass in solar tunnel dryer. Drying of peppers was started with an initial moisture content of 15.67 kg water per kg dry matter and was dried 10.27 kg water per kg dry matter in open sun. This drying process continued for 77 hours (four days) in solar tunnel dryer. In this experimental study, changes of moisture content and drying rate of pepper slices in time were investigated. Drying rate of pepper slices was calculated using equation 1 and variation of the drying rate versus time is given in Fig. 7. There was no constant drying rate period in the drying of pepper. The whole drying process occurred during the falling drying rate period. Falling rate period is also seen during drying process for many vegetables and fruits like okra (Doymaz, 2005), figs (Babalis and Belessiotis, 2004), tomato (Gürlek et al., 2008), red pepper (Akpınar et al., 2003), grape, peach, plum, fig (Toğrul and Pehlivan, 2004), red bell pepper (Vega et al., 2007), sweet pepper (Vengaiah and Pandey, 2007), long green pepper (Akpinar and Biçer, 2008), prickly pear fruit (Vega-Gálvez et al., 2010), apricot (Toğrul and Pehlivan, 2002), green and red peppers (Kaymak-Ertekin, 2002). Drying rate decreases continuously with drying time. The interruptions of the lines in Fig. 6 and 7 represent the night periods of the drying process (Toğrul and Pehlivan, 2002; Akpinar and Biçer, 2008). At night, without solar radiation, the drying curves show a slowdown in drying which is characterized by an internal slow diffusion of water within the product. It leads to a redistribution of water in product at night. This redistribution of the product water should contribute to the increase in the drying rates in the following sunrise (Dissa et al., 2009). The drying process continues after the sunset due to the thermal inertia of the drying system.

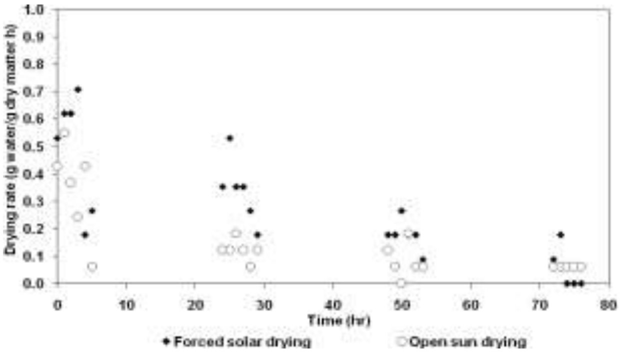

Figure 7. Drying Rate vs. drying time during four days for Forced solar drying and Open sun drying

Fig. 8 shows moisture content vs. drying time for forced solar drying and open sun drying. During drying process of pepper (Capsicum Annuum), initial moisture content of pepper in the solar tunnel dryer and under the sun drying is the same amount (15.67 kg water/kg dry matter). After 77 hours (four days), moisture content of pepper is 10.27 kg water/kg dry matter under the sun drying and 7.47 kg water/kg dry matter in the solar tunnel dryer.

Fig. 9 shows moisture content vs. drying rate for solar tunnel dryer. Initial moisture content of pepper in the solar tunnel dryer is 15.67 Kg water/kg dry matter. Equation of line gave the result of $y = 0.0028x^2 - 0.1628x + 2.7023$, $R^2 = 0.997$ for forced solar drying.

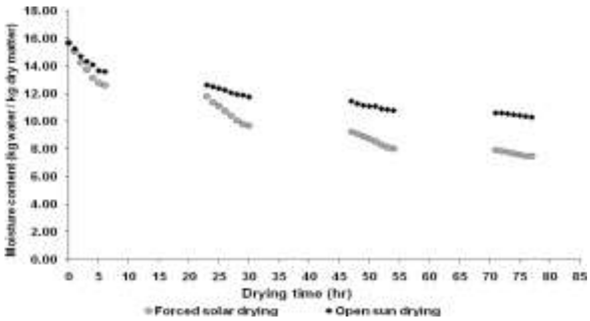

Figure 8. Moisture content vs. drying time for forced solar drying and open sun drying

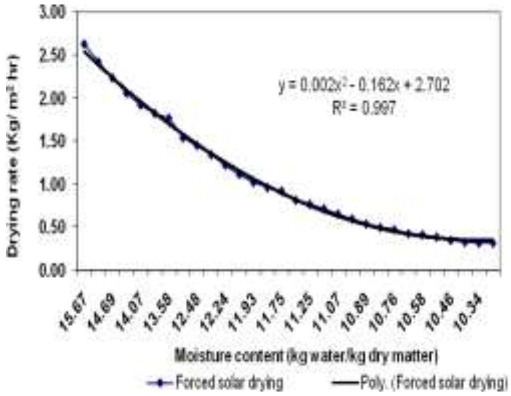

Figure 9. Moisture content vs. drying rate for solar tunnel dryer

Drying data were adjusted to different mathematical models by using regression analysis. Various statistical parameters such as; Mean Square Error (MSE), Mean Bias Error (MBE), coefficient of determination (R^2) and reduced chi-square test ($\chi 2$) were used.

Statistical parameters for different mathematical models are shown in Table 4 for solar drying and in Table 5 for open sun drying.

Table 4. Statistical parameters for different mathematical models for forced solar drying.

Model Name	Model coefficient	R^2	RMSE	MBE	χ^2
Lewis (Newton)	k=0.0299	0.9656	0.0301	0.0215	0.0015
Henderson and Pabis	k=0.0287; a=0.9802	0.9680	0.0295	0.0181	0.0013
Logarithmic	k=0.0748; a=0.6665; c=0.3930	0.9975	0.0085	0.0200	0.0007
Two-Term	**k_1=0.0456; k_2=-0.0499; a=0.9938; b=0.0503**	**0.9988**	**0.0061**	**0.0190**	**0.0006**
Page	k= 0.0449; n=0.8610	0.9784	0.0243	0.0159	0.0008
Modified Page	k=0.0299; n=0.9446	0.9706	0.0278	0.0113	0.0010
Two Term Exponential	a=0.2018; k=0.1035	0.9833	0.0209	0.0161	0.0007
Wang and Sing	a=-0.0341; b=0.0006	0.9943	0.0125	0.0281	0.0010
Modified Henderson and Pabis	a=-0.1478;b=0.2369;c=0.8162;k=10.52; h=0.0608;g= -0.0112;	0.9980	0.0080	0.0132	0.0009
Verma	a=0.9802; k=0.0287; g=20.6100	0.9680	0.0301	0.0187	0.013

Table 5. Statistical parameters for different mathematical models for open sun drying.

Model Name	Model coefficient	R^2	RMSE	MBE	χ^2
Lewis (Newton)	k=0.0172	0.8796	0.0374	0.0220	0.0017
Henderson and Pabis	k=0.0145; a=0.9513	0.9242	0.0280	0.0109	0.0009
Logarithmic	k=0.0895; a=0.4029; c=0.6323	0.9930	0.0082	0.0125	0.0003
Two-Term	**k_1=0.1125; k_2=0.0033; a=0.3281; b=0.7125**	**0.9940**	**0.0082**	**0.0128**	**0.0004**
Page	k=0.0425; n=0.6976	0.9646	0.0192	0.0105	0.0004
Modified Page	k=0.0110; n=0.7038	0.9645	0.0188	0.0103	0.0004
Two Term Exponential	a=0.0882; k=0.1148	0.9537	0.0219	0.0506	0.032
Wang and Sing	a=-0.0237; b=0.0006	0.9863	0.0119	0.0615	0.0059
Modified Henderson and Pabis	a= 0.3287; b=0.0781; c= 0.7126; g= 10.62; h= 0.0033;k= 0.1125;	0.9927	0.0853	0.0157	0.0009
Verma	a=0.3261; k=0.0453;g=-0.0134	0.9880	0.0113	0.0433	0.0023

Fig. 10 presents the variations of moisture ratio versus drying time during the experiment for solar drying and for open sun drying. Best results of regression analysis which were conducted by using the Matlab computer program for ten mathematical models for solar drying and for open sun drying were also shown in Fig. 10.

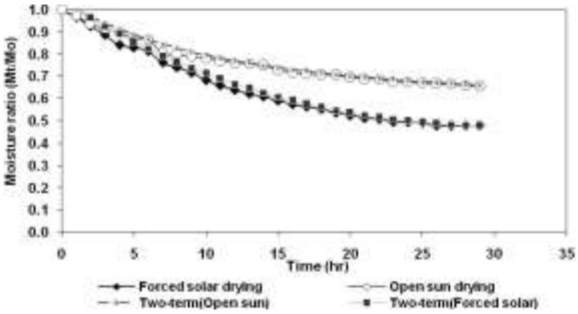

Figure 10. Forced solar drying and open sun drying and their best fitting models

The coefficient of determination (R^2) was one of the important criteria to select the equation which provides the best illustration of the solar drying curves of the dried sample of *Capsicum Annuum*. Besides, the various statistical such as; reduced Chi-square ($\chi2$), the Root Mean Square Error (RMSE) and Mean Bias Error (MBE), were used to determine the goodness of the fit. We need the lower value of $\chi2$, RMSE, MBE to reach zero and higher value of R^2 for the better goodness of the fit. As a result, Two-Term model gave the best result at Table 4 for forced solar drying and Table 5 for open sun drying as well when statistical parameters are compared. Statistical results were determined like $\chi2$ =0.0006, RMSE=0.0061, MBE=0.0190, R^2 =0.9988 forced solar drying, $\chi2$ =0.0004, RMSE=0.0082, MBE=0.0128, R^2 =0.9940 for open sun drying.

Fig. 11 and 12 presents the comparison between predicted moisture ratio of Two-Term model and experimental moisture ratio for forced solar drying and open sun drying. The Two-Term model provided satisfactorily a good conformity between experimental and predicted moisture ratios, and predicted data generally banded around the straight line, which showed the suitability of this model in describing solar drying behavior of *Capsicum Annuum*. Equation of line gave the result of y=1.0724x-0.028, R^2 = 0.998 for forced solar drying and y=1.0878x-0.0545, R^2 =0.993 for open sun drying.

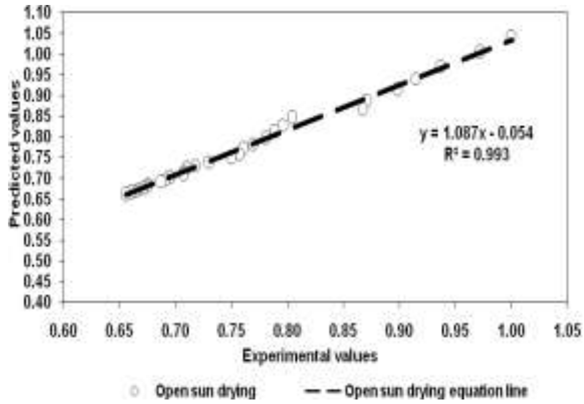

Figure 11. Comparison of the experimental and predicted moisture ratio for two-term model during open sun drying.

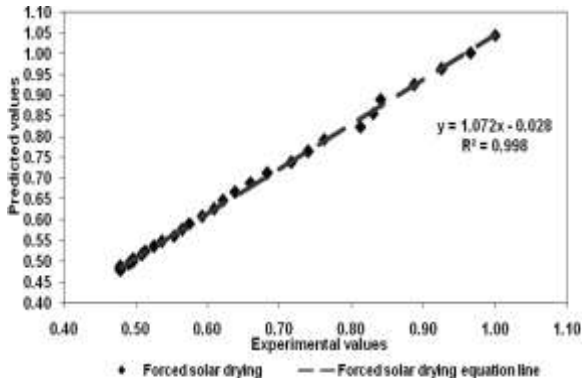

Figure 12. Comparison of the experimental and predicted moisture ratio for two-term model during forced solar

The effective diffusivity (m^2/s) is calculated by Eq. 4 for *Capsicum Annuum* is 2.9 10^{-9} m^2/s. This result was found by using the slope which was derived from the linear regression of ln (MR) versus time data shown in Fig. 13. The values of effective diffusivity in the range of 10^{-9} –10^{-11} m^2/s are comparable with the reported values between 5.01 x10^{-10} and 8.32x10^{-10} m^2/s for red pepper (Di Scala and Crapiste, 2008), 9.0 x10^{-10} and 8.0x10^{-9} m^2/s for green bell pepper (Faustino et al., 2007), 6.83x10^{-10} and 17.4x10^{-10} m^2/s for unblanched red pepper, 11.4x10^{-10} and 31.0x10^{-10} m^2/s for blanched red pepper (Turhan et al., 1997), 11.4 x10^{-10} and 31.0 x10^{-10} m^2/s for unblanched red pepper (Turhan et al., 1997), 4.38x10^{-11} m^2/s and 10.99x10^{-11} m^2/s for whole red peppers, 37.23x10^{-11} m^2/s and 99.61x10^{-11} m^2/s for shredded red peppers (Sanjuan et al., 2003), 3.2x10^{-9} and 11.2x10^{-9} for red bell pepper (Vega et al., 2007).

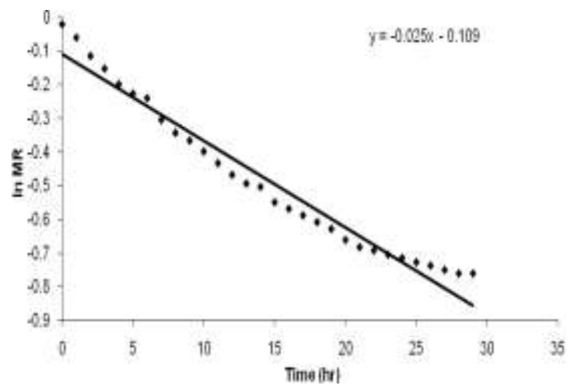

Figure 13. Experimental ln (MR) vs time

CONCLUSION

The study was conducted in order to determine the drying characteristics of pepper (*Capsicum Annuum*) in a solar dryer with forced convection and in open sun drying process at the open field and to develop the mathematical modeling of this process. In this study, a solar tunnel dryer with two connected collectors was used. This new design can be used for dehydration of *Capsicum Annuum* and various agricultural products. Water removal from *Capsicum Annuum* in the drying process occurs in the diminishing rate period. Besides, *Capsicum Annuum* samples of forced solar drying were completely protected from birds, insects, rain and dust. The comparison of ten different mathematical models in Table 4 and 5 according to statistical parameters has shown that Two-Term drying model adequately describes the solar drying behavior of *Capsicum Annuum* with $\chi 2$ =0.0006, RMSE=0.0061, MBE=0.0190, R^2 =0.9988 for forced solar drying and $\chi 2$ = 0.0004, RMSE=0.0082, MBE=0.0128, R^2 =0.9940 for open sun drying.

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