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SOLAR TUNNEL DRYING CHARACTERISTICS AND MATHEMATICAL MODELLING OF TOMATO

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Abstract: Solar drying experiments of tomato were conducted in Izmir, Turkey. In this purpose, new type tunnel solar dryer was designed and manufactured. Solar dryer consist of an air collector, drying chamber and an air circulation system. Heated air in solar air collector was forced through the tomatoes by a blower. Rio Grande type tomato was used for drying experiments. During the drying period, drying air temperature, relative humudity, air flow rates, solar radiation, and lose of mass were measured continuously in different part of the dryer. Drying time was examined with mass ratio as exponantial and polynomial correlations. Twelve different mathematical models available in literature were compared using their coefficient of determination of estimate solar drying curves. According to statistical analysis results, the two-term drying model has shown a better fit to the experimental drying data of tomato with a coefficient of determination R^2 of 0.9967 as compared to other models.
Keywords: Tunnel dryer, Solar drying, Mathematical modeling, Moisture Ratio,Tomato

DOMATESİN TÜNEL TİPİ GÜNEŞLİ KURUTUCUDAKİ KURUTMA KARAKTERİSTİKLERİ VE MATEMATİKSEL MODELLEMESİ

Özet: Domates kurutma denemeleri İzmir, Türkiye'de gerçekleştirilmiştir. Bu amaçla yeni geliştirilen tünel tipi güneşli kurutucu tasarlanmış ve imal edilmiştir. İmal edilen güneşli kurutucu, havalı toplayıcı, kurutma odası ve hava sirkülasyon sisteminden oluşmaktadır. Havalı toplayıcıdan elde edilen ısıtılmış hava, fan aracılığıyla domateslerin üzerinden geçirilmiştir. Kurutma denemelerinde Rio Grande tip domates kullanılmıştır. Kurutma periyodu süresince, kurutma hava sıcaklığı, bağıl nem, hava debisi, güneş ışınım değeri ve kurutucunun farklı noktalarından alınan numunelerdeki kütle kayıpları düzenli olarak takip edilmiştir. Kurutma zamanının kütle kaybıyla ilişkisi bağıntılarla takip edilmiştir. Kurutma eğrileri dikkate alınarak oniki farklı matematiksel model karşılaştırılmıştır. Istatistiksel analiz sonuçlarına göre deneysel kurutma verilerine en iyi uyum sağlayanın R^2 değerinin 0.9967 olduğu two-term matematiksel model olduğu görülmüştür.
Anahtar Kelimeler: Tünel kurutucu, Güneşli kurutma, Matematiksel modelleme, Nem oranı, Domates

Nomenclature

a,b,c,n	empirical coefficients in drying models
D_{eff}	effective moisture transfer diffusion coefficient (m^2/s)
EF	modelling efficiency
H	half-thickness of the slab in sample
J	value of the basic measurements
k, k_1, k_2	empirical constants in drying models
M_t	sample mass in time t (kg moisture / kg dry matter)
M_e	equilibrium moisture content (kg moisture / kg dry matter)
M_o	sample mass at the beginning (kg moisture / kg dry matter)
MBE	mean bias error
MR	moisture ratio
MR_{exp}	experimental moisture ratio
MR_{pre}	predicted moisture ratio
n	number of constants in the model
N	number of observations
r	experimental result
RMSE	root mean square error
R^2	coefficient of determination
t	drying time (t)
χ^2	reduced chi-square

INTRODUCTION

Many different types of vegetables and fruits have been produced in Turkey because of its suitable climate. Turkey has a high potential solar enegy and mean annual bright sunshine hours. According to experimental data, annual mean sunshine hours is 2640 hours/year (7.2 hours/day), annual mean solar energy is 1311 kWh/m^{2}year (3.6 kWh/m^{2}day) for Turkey. Table 1 shows annual sunshine hours and annual solar energy datas for seven different regions of Turkey (EIE 2006).

Table1. Annual sunshine hours and annual solar energy datas for seven different regions of Turkey (EIE 2006).

Region	Solar Enegy (kWh/m^{2}year)	Sunshine Hour (hours/year)
South Eastern	1460	2993
Mediterranean	1390	2956
Eastern	1365	2664
Central	1314	2628
Aegean	1304	2738
Marmara	1168	2409
Black Sea	1120	1971

Drying has always been of great importance for conserving agricultural products in agricultural countries like Turkey. Drying process is the most common form of food preservation and extends the food self-life. It is a simultaneous heat and mass transfer operation in which moisture is removed from food material and carried away by hot air. Open sun drying is a well-known food preservation technique that is still the most common method used to preserve agricultural product in most tropical and subtropical countries.

In Turkey, drying is achieved natural method by spreading out the material on the ground. In this way, there are many disadvantages like low quality and hygienic problems. Being unprotected from windborne dirt and dust, rain, infestation by insects, rodents and other animals, the quality of food is seriously degraded. The resulting loss of food quality in the dried products may have effect negatively trade potential and economical worth. For preventing the deterioration of the materials different types of drying methods have been developed. On the other hand, the conventional dryers are not economic due to high energy cost. For that reason, direct or indirect sun dryers have good opportunity for about quality and efficiency improvement.

In this purpose, there have been many studies on the drying behaviour of vegetables and fruits such as sweet pepper and garlic (Condori et al., 2001), tomato seed (Sogi et al., 2003), grape (Tiris et al., 1994; Gungor and Ozbalta, 2003), pineapple (Bala et al., 2003), tomato (Yilmaz et al., 1999), figs and onion (Gallali et al., 2000), red pepper (Tiris et al., 1994; Doymaz and Pala, 2002).

Properly designed solar drying systems must take into account drying requirements of specific crops. Simulation models are needed in the design, construction and operation of drying systems. Several mathematical model equations available in the literature for explaning drying behaviour of agricultural products have been used by Togrul and Pehlivan (2002) for apricot, Sacilik, Keskin and Elicin (2005) for organic tomato, Yaldiz, Ertekin and Uzun (2001) for sultana grapes, Midilli and Kucuk (2003) for pistachio, El-Sebaii, Aboul-Enein, Ramadan and El-Gohary (2002) for grapes, figs, apple, peas, onion and tomato, Ertekin and Yaldiz (2004) for eggplant, Sharma, Verma and Pathare (2005) for onion, Menges and Ertekin (2006) for apples.

This study was undertaken to investigate drying characteristics of tomato in a new designed solar tunnel dryer in Izmir, and to fit the experimental data to mathematical models available in literature.

MATERIALS AND METHODS

Solar Tunnel Dryer

In this experimental study, solar tunnel dryer, which has 10 m^2 base area and 2.23 m height is used for large scale drying of tomato. This tunnel dryer consists of a flat plate solar air collector, a greenhouse type tunnel drying unit and an electrically driven radial fan to provide the required air flow over the product to be dried as shown in Fig. 1. The dryer was oriented in an east-west direction to make the incident solar radiation more efficient on the solar tunnel dryer. Tunnel was covered with polyethylene plastic film material.

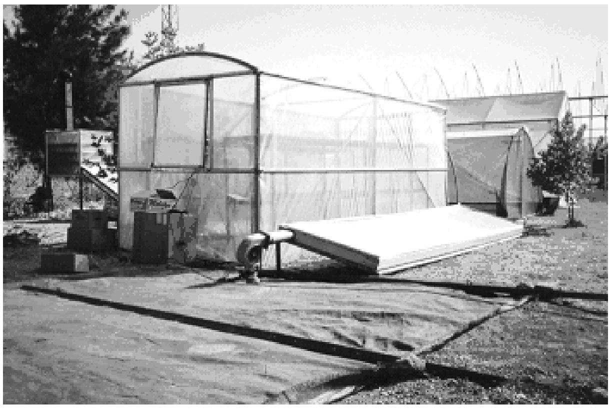

Figure 1. View of new designed solar tunnel dryer.

Four drying trays, having dimensions of 0.6 m x 5 m, were placed in the tunnel dryer. Two of them were placed left side of tunnel and the other two trays were placed right side of tunnel. These trays were used to accommodate tomato halves to be dried. The solar air collector dimensions were 1.2 m wide by 4.5 m long and 0.1 m high. A corrugated galvanized iron sheet pointed black was used as an absorber plate for absorbing the solar radiation. It was oriented to the south under the collector angle of 20^o for maximum solar energy. Polyethylene plastic film materials was used as a transparent cover for the air collector to prevent the heat losses. Styrofoam is used as insulation material to prevent heat losses from the sides and bottom of solar collector. The air at the required flow rate is provided by an electrically driven radial fan. Ambient air is forced by fan through the collector. Heat is transferred from the absorber surface to the air in the collector and heated air while passing over the product absorbs moisture.

Experimental Procedure

Drying experiments were conducted during the periods of August in Izmir. The tomato was used in this study as experimental product. Experimental solar drying run was conducted on Rio Grande type tomato. Homogeneous size tomato samples were washed and cut into halves.

After that tomatoes were pre-treated before drying with calcium chloride solutions for 5 minutes. Tomato halves were placed on shelves as shown in Fig. 2. 80 kg of tomato were used for drying experiment.

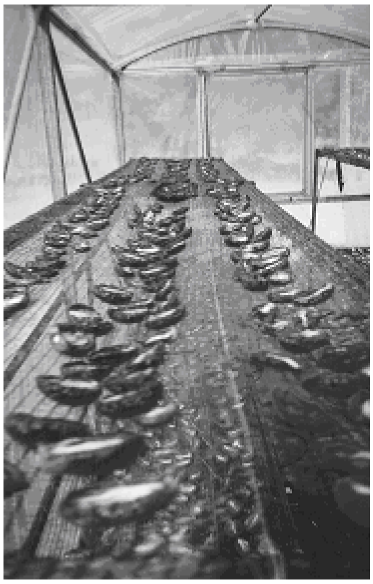

Figure 2. View of tomatoes halves on shelf.

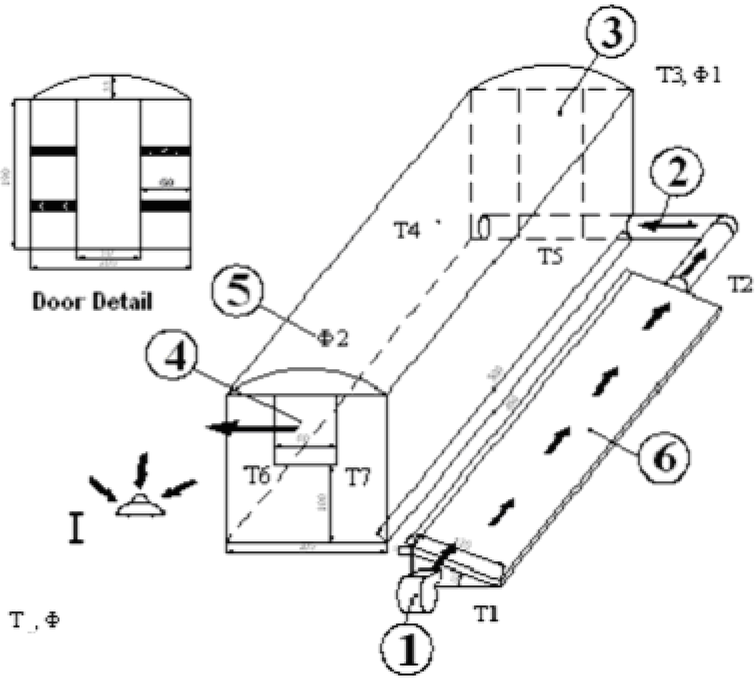

Figure 3. A schematic diagram of the experimental setup showing the locations of all measurement devices (1-Fan, 2-Entrance duct, 3-Tunnel entrance door, 0,8m x 1,9m, 4-Ventilation window, 0,8m x 0,9m, 5-Tunnel type dryer, 10 m^2, 6-Solar air collector, 5,4 m^2, T1-Inlet air temperature of solar air collector, T2-Outlet air temperature of solar air collector, T3-Inlet air temperature of tunnel dryer, T4 and T5-Inlet shelves air temperature of tunnel dryer, T6 and T7-Outlet shelves air temperature of tunnel dryer, I-Solar meter, Φ1-Inlet air moisture of tunnel dryer, Φ2-Outlet air moisture of tunnel dryer, Φ-Ambient moisture, T- Ambient temperature.)

The important parameters as drying air temperature, relative humudity, air flow rates, solar radiation, and lose of mass affecting the performance of the dryer were measured. A schematic diagram of the experimental setup showing the locations of all measurement devices are shown in Fig 3. A pyranometer was used to measured the solar radiation on the horizontal surface. Table 2 and Table 3 show all measurement devices and pyranometer's specifications. The temperature and relative humidity inside and outside of the tunnel were measured with a temperature and relative humidity probes. These probes were installed in inlet, middle and outlet points of the tunnel dryer and all datas were collected in a data logger unit. The velocity of drying air was measured with an anemometer at the inlet of the dryer.

Table 2. Specifications of all measurement devices

Measuremen Device Type	**Measurement Range**	**Accuracy**
Temperature Prob	-200...+400 °C	±1.5 °C
Temperature Prob	-200...+600 °C	±0.25 °C
Temperature Prob	-200...+1100 °C	±1.5 °C
Temperature Prob	-200...+400 °C	±0.25 °C
Temperature Prob	-100...+400 °C	±0.55 °C
Temperature and Moisture Prob	-20...+120 °C	±0.4 °C ±2%
Velocity Prob	-30...+140 °C +0,4...+60m/s	±0.2 m/s

Table 3. Pyranometer specifications

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 Mesurement Range	0-1000 W/m^2

To determine the mass loss of the product during experiment, tomato samples were taken from one point for each shelve and weighed with an electric balance having an accuracy of 0.01 g. During the drying process, all these data were continuously recorded at 1 hour intervals by data logger unit. During the drying experiment, the weather was generally sunny and no rain appeared.

Mathematical Modeling of Solar Drying Curves

The most widely investigated theoretical model in the drying of different foods is given by the solution of Fick's second law (Doymaz and Pala, 2002; Sacilik et al., 2005; Diamante and Munro, 1993; Liu and Bakker-Arkema, 1997). Fick's law is often used to describe a moisture diffusion process,

$$\frac{\partial m}{\partial t} = D_{eff} \frac{\partial^2 m}{\partial x^2} \tag{1}$$

where m is the local moisture content on a dry basis, t the time, x the spatial coordinate and D_{eff} is the effective diffusivity in m^2/s. To apply Fick's law, the food product is usually assumed to be undimentional, to have a uniform initial moisture content, and to have internal moisture movement as its main resistance to moisture transfer. The solution of Fick's law for a slab is as follows (Okos et al., 1992);

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

where M_t, M_e, M_o are the moisture content at time t, the equilibrium content and the initial moisture content, respectively, H is the half-thickness of the slab in tomato sample. For long drying times (setting n=1), Eq. (2) can be further simplified to a straight line equation as;

$$\ln\left(\frac{M_t - M_e}{M_0 - M_e} \right) = \ln\left(\frac{8}{\pi^2} \right) - \left(\frac{\pi^2 D_{eff} t}{4H^2} \right) \tag{3}$$

Thus, the moisture ratio (MR) was simplified to M_t/M_o as written in the following form:

$$MR = \frac{M_t - M_e}{M_0 - M_e} \tag{4}$$

Table 4. Mathematical models given by various authors for the solar drying curves

Model No.	Model equation	Model name	References
1	$(M_t / M_o) = \exp(-kt)$	Newton	[15, 19, 22, 25, 26]
2	$(M_t / M_o) = \exp(-kt^n)$	Page	[16, 18 , 24, 26,29]
3	$(M_t / M_o) = a \exp(-kt)$	Henderson and Pabis	[15, 23, 26, 29, 32]
4	$(M_t / M_o) = a \exp(-kt) + c$	Logarithmic	[10, 13, 26]
5	$(M_t / M_o) = a \exp(-k_1t) + b \exp(-k_2t)$	Two-Term	[15, 12, 26, 33]
6	$(M_t / M_o) = 1 + at + bt^2$	Wang and Singh	[15, 21, 26]
7	$(M_t /M_o) = a \exp(-kt) + (1-a) \exp(-kat)$	Two-Term Exponential	[10, 12, 34]
8	$(M_t / M_o) = \exp(-(kt)^n)$	Modified Page	[15]
9	$(M_t / M_o) = a \exp(-kt) + (1-a) \exp(-gt)$	Verma et al.	[10, 15, 26]
10	$(M_t / M_o) = a \exp(-kt) + (1-a) \exp(-kbt)$	Diffusion approximation	[10, 15, 26]
11	$(M_t / M_o) = \exp(-k(t/l^2)^n)$	Modified Page Equation	[10, 18]
12	$(M_t / M_o) = at^3+bt^2+ct+1$	Authors approximation	

where; M_o is sample mass at the beginning, M_e is equilibrium moisture content and M_t is sample mass in time t. The effective diffusion coefficients are typically determined by plotting experimental drying data in terms of $\ln(M_t/M_0)$ versus time (Ozdemir and Devres, 1999; Ayensu, 1997; Doymaz, 2004; Karathanos and Belessiotis, 1999). The values of effective diffusivity in the range of $10^{-9} - 10^{-11}$ m^2/s can be found in literature.

The drying curves obtained were fitted with twelve different moisture ratio equations by several authors (Table 4).

Data Analysis

The moisture content was expressed as a percent wet basis and the converted to kg water per kg dry matter. The experimental drying data for tomato were fitted to drying models in Table 4 by using regression analysis. Regression analysis were done by using the Matlab statistical computer program. The coefficient of determination (R^2) was one of the important criteria to select the best equation in the solar drying curves of the dried samples as tomato. In addition to R^2, the various statistical parameters such as; reduced Chi-square (χ^2) [25], mean bias error (MBE), the root mean square error (RMSE) and the modelling efficiency (EF) were used to determine the quality of the fit. χ^2 is used to determine the goodness of the fit. The lower the values of the χ^2, the better the goodness of the fit. The RMSE gives the deviation between the predicted and experimental values and it is required to reach zero. The EF also gives the ability of the model and its highest value is 1 (Aktas and Polat, 2007). These parameters can be calculated as;

$$\chi^2 = \frac{\sum_{i-1}^{N}\left(MR_{\exp,i} - MR_{pre,i}\right)^2}{N-n} \quad (5)$$

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

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

$$EF = \frac{\sum_{i=1}^{N}\left(MR_{\exp,i} - MR_{i,\exp mean}\right)^2 - \sum_{i=1}^{N}\left(MR_{pre,i} - MR_{\exp,i}\right)^2}{\sum_{i=1}^{N}\left(MR_{\exp,i} - MR_{i,\exp mean}\right)^2} \quad (8)$$

where $MR_{exp,i}$ is the experimental moisture ratio found in any measurement and $MR_{pre,i}$ is predicted moisture ratio for this measurement. N the number of observations, n the number of constants and $MR_{expmean}$ is the mean value of the experimental MR (Demir et al., 2004; Akpinar et al., 2003; Doymaz). The best model describing the drying behaviour of tomato was chosen as the one with the highest coefficient of determination and the modelling efficiency and the least reduced Chi-square, mean bias error and root mean square error.

Uncertainty Analysis

Experimental studies are not free of errors and uncertainties originating from measuring instruments, observer, environmental effect 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 (Kaya et al., 2007). In the nomenclature of experimental uncertainty analysis, the experimental result, r, is computed using a data-reduction equation and the value of the J basic measurements.

$$r = r\left(X_1, X_2, ..., X_J\right) \quad (9)$$

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

$$U_r = \left[\left(\frac{\partial r}{\partial X_1}U_{X_1}\right)^2 + \left(\frac{\partial r}{\partial X_2}U_{X_{21}}\right)^2 + ... + \left(\frac{\partial r}{\partial X_J}U_{X_J}\right)^2\right]^{1/2} \quad (10)$$

where the U_X's are the uncertainty in each basic measurement and the partial derivatives are the sensitivity coefficients (Hodge and Taylor, 1999). The uncertainties in calculating the moisture content, velocity and temperature were obtained to be ±2%, ±0.2 m/s and ±2.25 ^oC, respectively.

RESULST AND DISCUSSION

In this study, the constant and coefficients of the best fitting mathematical model involving the drying variables such as temperature, humidity of the drying air were determined. During the drying experiments, the temperature of ambient air ranged from 22 to 36 ^oC, the relative humidity of ambient air from 30 % to 40 %, the temperature of drying air from 32 to 59 ^oC, the relative humidity of drying air from 10 % to 20 % and the solar radiation from 400 to 950 W/m^2 for collector surface.

The changes in the moisture ratio of tomato with drying time are shown in Fig 4. The experimental data obtained for air at temperature ranging from 32 to 59 ^oC. During the experiments, the time to reach final moisture content of 5% for solar tunnel were found to be 96 hour. The interruptions of the lines in this figure represent the night periods of the drying operation. The drying continues after the sunset due to the thermal inertia of the system. There is not any constant-rate drying period in this curve and all the drying operations are seen to occur in the falling rate period.

During the falling rate drying period, the drying rate decreases continuously with decreasing moisture content and increasing drying time. Similar results have been reported in the literature for various fruits and vegetables such as Sacilik et al. (2005) for organic tomato, Yaldiz et al. (2001) for sultana grapes, Doymaz (2007) for tomato, Sharma et al. (2005) for onion slices, Kashaninejad et al. (2007) for pistachio nuts.

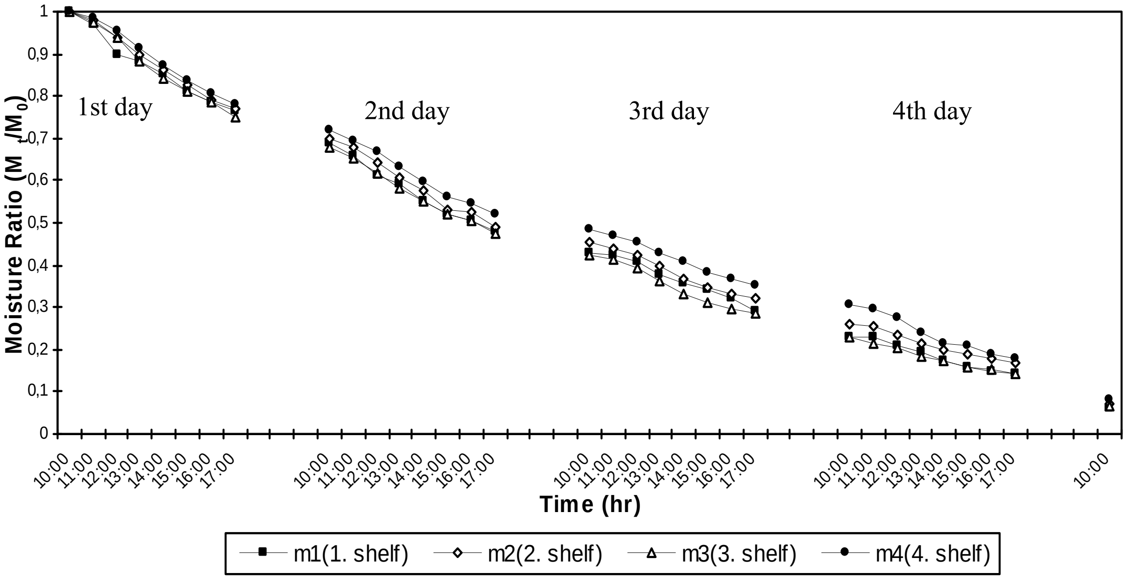

Figure 4. The changes in moisture ratio of tomato with time.

The effect of these variables on the constant and coefficient of drying expression were also investigated by regression analyses. The drying data as the moisture ratio (MR) versus drying time were fitted to the twelve drying models. Fig 5 presents results of regression analyses were done by using the Matlab computer program and the variations of moisture ratio versus drying time for twelve mathematical model. Table 5 shows drying model coefficients and the comparison criteria used to evaluate goodness of fit, namely the coefficient of determination (R^2), the reduced Chi-square (χ^2), mean bias error (MBE), the root mean square error (RMSE) and the modelling efficiency (EF) for solar tunnel drying. The values of R^2, χ^2, MBE, RMSE, and EF for models range from 0.9652 to 0.9973, 0.000225 to 0.010364, -0.14368 to 0.09384, 0.0142 to 0.0512 and 0.6616 to 0.99671, respectively. According to Table 5, the two-term model showed good agreement with the experimental data and gave the best result for tomato samples.

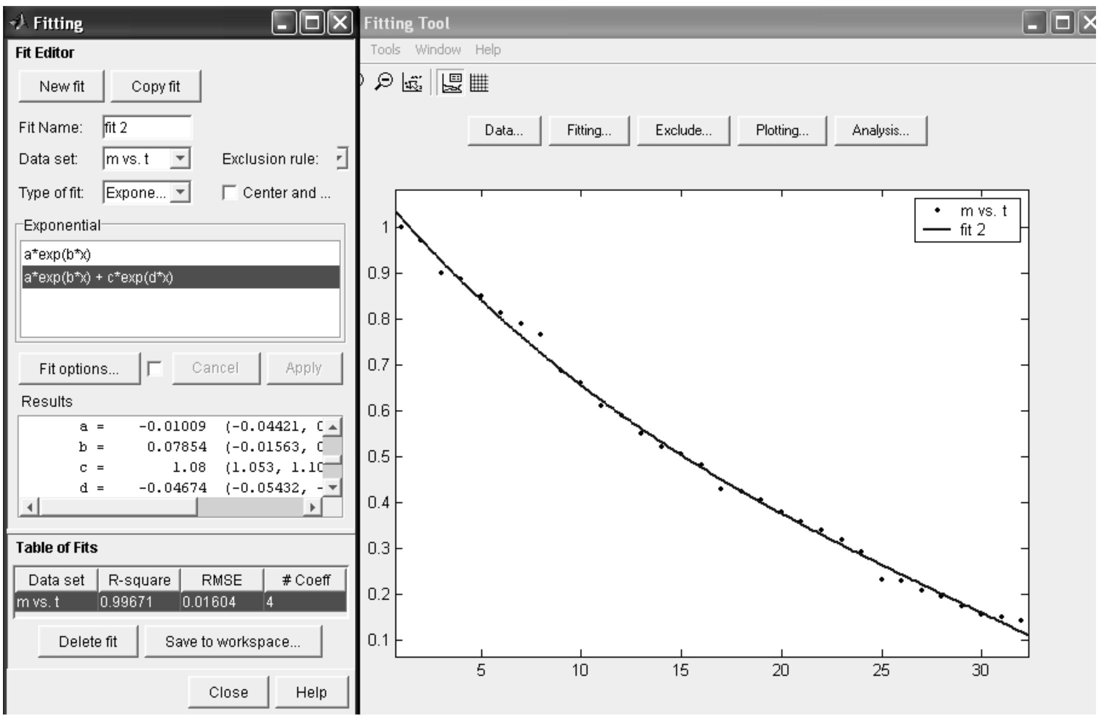

Figure 5. Result of regression analyses for two-term mathematical model.

Table 5. Results of analyses on the modelling of moisture contents and drying time

Model No.	Model name	Coefficients	R^2	RMSE	MBE	χ^2	EF
1	Newton	k=0.04909	0.9652	0.0496	-0.00806	0.002383	0.96523
2	Page	k= 0.01864; n= 1.335	0.9965	0.0159	0.000286	0.000237	0.99652
3	Henderson and Pabis	k= 0.0562; a=1.115	0.9868	0.0310	0.002893	0.000901	0.98684
4	Logarithmic	k=0.03105; a= 1.473; c=-0.4194	0.9973	0.0142	0.093848	0.010364	0.94880
5	**Two-Term**	**k_1=-0.07854; k_2=0.04674; a=-0.01009; b=1.08**	**0.9967**	**0.0160**	**-0.00014**	**0.000225**	**0.99671**
6	Wang and Singh	a= -0.03695; b=0.00029	0.9944	0.0201	-0.00606	0.000386	0.99436
7	Two-Term Exponential	k=0.07617; a=1.879	0.996	0.0171	0.009387	0.002734	0.96011
8	Modified Page	k=0.05065; n=1.335	0.9965	0.0159	0.000179	0.000238	0.99652
9	Verma et al.	k=0.09291;a=10.09;g=0.1008	0.9961	0.0171	0.000829	0.000265	0.99613
10	Diffusion approximation	a=-6.082;b=0.8854;k=0.1046	0.9962	0.0169	-0.00013	0.000259	0.99621
11	Modified Page Equation	k=0.7335;l=3.082;n=1.201	0.9652	0.05128	-0.14368	0.023193	0.66166
12	Authors approximation	a=0.00001096;b=-0.00018 c=-0.03233	0.9957	0.01791	-0.00237	0.000291	0.9957

The constants and coefficients of the accepted model for the solar tunnel drying of tomato were as below:

$$(M_t / M_o) = a \exp(-k_1 t) + b \exp(-k_2 t)$$

where k_1=-0.07854, k_2=0.04674, a=-0.01009 and b=1.08 for tomato.

The effective diffusivity (m^2/s) is calculated by Eq. 3 for solar tunnel dryer is 5.37×10^{-10} . According to this result, using slope derived from the linear regression of ln (MR) vs time data shown in Fig 6.

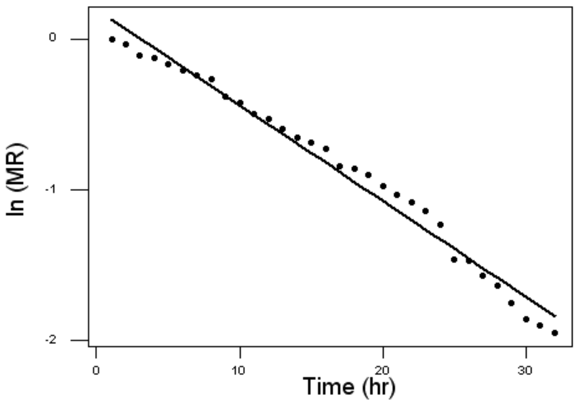

Figure 6. Experimental ln (MR) vs time

The values of effective diffusivity in the range of 10^{-9} – 10^{-11} m^2/s are comparable with the reported values 1.31×10^{-9} to 1.07×10^{-9} m^2/s for organic tomato (Sacilik et al., 2005), 1.383×10^{-9} to 4.145×10^{-9} m^2/s for pumpkin (Kaya et al., 2007), 5.42×10^{-11} to 9.29×10^{-10} m^2/s for pistachio nuts (Kashaninejad et al., 2007). Doymaz (2007) reported that the effective diffusivity values changes from 5.65×10^{-10} to 7.53×10^{-10} m^2/s for different temperatures.

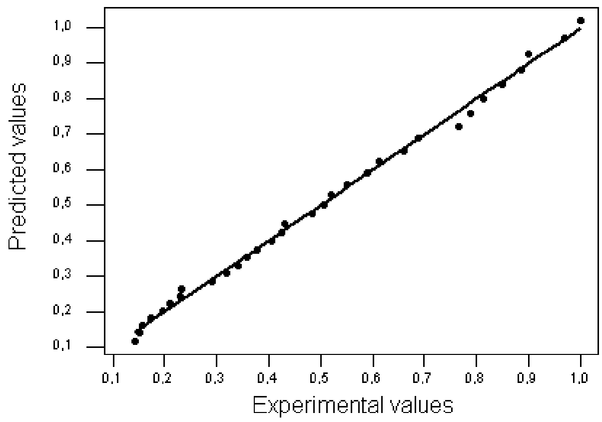

Figure 7. Comparison of experimental and predicted moisture ratios by two-term model for solar tunnel drying

Fig. 7 indicated the comparison of the predicted and the experimental moisture ratio values by two-term model for solar tunnel drying (Sharma et al., 2005; Doymaz, 2004). 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 behaviour of tomato.

CONCLUSIONS

In this study, the new designed solar tunnel dryer can be used for drying of various agricultural products as well as Rio Grande type tomato under the climatic conditions of Izmir. The moisture content was reduced in four days. All drying processes occured in the falling rate period. In adddition, the tomato samples of solar tunnel dryer were completely protected from birds, insects, rain and dusts.

In order to explain the drying behaviour of tomato, twelve different mathematical models were compared according to their coefficient of determination values. According to the results, the two-term model could adequately describe the solar drying behaviour of tomato in a new designed solar tunnel dryer.

It is expected that this system will help growers reduce the cost of drying and obtain more quality dried products. The results of the predicted models showed that used for tunnel dryers design for different capacity. Further studies are ongoing.

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