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Mathematical Model of Grapes Solar Drying

Gamea, G.R. and Taha, A.T.

Agricultural Engineering Department, Faculty of Agriculture, Minoufiya Universiyy, Egypt

ABSTRACT

A computer mathematical model based on mass and energy balance has been developed which incorporate arrange of solar flat plate air collector geometrics and a drying model base on the thin layer drying principles. This model will be useful in understanding the extreme complexity of the drying process which influenced by many design parameters. Thin layer solar drying experiments for grapes by indirect solar dryer. Air heated by solar collector was forced throw the product by an electric fan. The best fit of the thin layer solar drying of grapes was obtained by Modified Henderson and Pabis Model which fitted very well experimental data. The required drying time was about 18 hour. The model is capable to asses the performance of the solar dryer and predict the solar radiation intensity, temperature, relative humidity and moisture ratio of the product.

Key words: *Solar drying, Mathematical modeling, Moisture Ratio, Grapes*

Introduction

Drying has always been of great importance for conserving agricultural products in agricultural countries like Egypt. 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. The high energy consumption of the drying operation and the importance of environmental protection have directed interest towards the application of solar energy to agricultural and industrial processes. In addition, the quality of the dried end-products has also recently become more& more important for processing of agricultural products. These are the motivations for a multi-objective optimization problem of the drying along with the constraint of processing time.

Egypt is one of the countries that have solar energy in abundance. The solar energy incident on Egyptian land has a magnitude of 12-30 MJ/m^2/day, and the sunshine duration is between 3500 and 4500 h per year. Egypt has abundant solar energy. Solar energy can solve a part of energy demand problem. However the use of solar energy in Egypt could play a useful role in satisfying energy requirements of most urban areas in appropriate circumstances (Tadros, 2000; Chedid and Chaaban, 2003; El-Metwally, 2005).

Nomenclature

A	:surface area	[m^2]
AH	:Absolute humidity of air	[kg kg^{-1}]
Ch	Drying chamber	
$Coll$	collector	
C_p	:specific heat	[Wh.kg^{-1}.K^{-1}]
h_{conv}	:coefficient of convective thermal transmission	[Wm^{-2}K^{-1}]
I_{sc}	:Solar constant =1353	[Wm^{-2}]
k	:thermal conductivity for insulation.	[W m^{-1}K^{-1}]
m	:Mass flow rate of fluid	[kgs^{-1}]
MBE	: mean bias error	
M_e	:equilibrium moisture content	(kg moisture / kg dry matter)
MR	:moisture ratio	
MR_{exp}	: experimental moisture ratio	
MR_{pre}	: predicted moisture ratio	
M_i	:initial moisture content	(kg moisture / kg dry matter)
M_t	:moisture content at time (t)	(kg moisture / kg dry matter)
m_w	:Mass of wet sample	[kg]
m_{water}	:Mass of water	[kg]
N	: The number of observation.	---
n	: number of constants in the model	[h]
Q_{cond}	:heat flux due to conduction .	[W]
Q_{conv}	:heat flux due to convection	[W]
Q_b	: beam radiation	[Wm^{-2}]

Corresponding Author: Gamea, G.R., Agricultural Engineering Department, Faculty of Agriculture, Minoufiya Universiyy, Egypt
E-mail: gamea_gamalrashad@yahoo.com; Tel: 00201270390272, 009660501722535;
Fax: 009665801778

Q_{bt}	:direct or beam solar radiation absorbed at collector surface	$[Wm^{-2}]$
Q_d	:diffuse radiation	$[Wm^{-2}]$
Q_{dt}	:diffuse solar radiation absorbed at collector surface.	$[Wm^{-2}]$
Q_G	:The total solar radiation	$[Wm^{-2}]$
Q_{Gt}	:solar radiation absorbed at collector tiled surface	$[Wm^{-2}]$
Q_{rd}	:heat transfer by radiation	[W]
Q_{rt}	:reflected radiation from the surroundings .	$[Wm^{-2}]$
Q_{sup}	:heat supplied to the solar dryer element .	$[Wm^{-2}]$
Q_{los}	:heat loss from the solar dryer element.	$[Wm^{-2}]$
r	: experimental result	
R^2	:coefficient of determination	
RH	:Relative humidity	[%]
Rad.H	Radiation on horizontal	
R_b, R_d, R_r	The geometric factors, and R_b, Ratio of beam radiation on the tilted surface to that on a horizontal surface at any time, leading in northern hemisphere, for $\gamma = 0°$,	
T	:temperature.	[K]
T_{amb}	:Surrounding temperature	[K]
T_{sky}	:temperature of the sky	[K]
x	:thick ness of the element .	[m]
X	:thickness for insulation.	[m]
	Greek letters	
ε	:surface emissivity is < 1	[-]
γ	:surface–solar azimuth angle	[°]
β	:tilt angle of the collector surface is 30°.	[°]
ρ	:density of the air	$[kg.m^{-3}]$
ρ_g	:The albedo of the ground.	
σ	:Stefan-Boltzmann constant, $= 5.67\times 10^{-8}$	$[Wm^{-2}K^{-4}]$
ε_{sky}	:the emissivity of the sky , = 1.0	[-]
τ	:simulation time.	[h]
ΔT	:temperature difference	[K]
θ	:incidence angle	[°]
α	:Solar altitude angle	[°]
χ^2	reduced chi-square	

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 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 tunnel 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 (Condori *et al*., 2001), grape (Tiris *et al*., 1994; Gungor and Ozbalta, 2003, Yilmaz *et al*., 1999), pineapple (Bala *et al*., 2003), figs and onion (Gallali *et al*., 2000). 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 grapes, Yaldiz, Ertekin and Uzun (2001) for sultana grapes, Midilli and Kucuk (2003) for pistachio, Ertekin and Yaldiz (2004) for eggplant, Sharma *et al*., (2005) for onion, Menges and Ertekin (2006) for apples. This study was undertaken to investigate drying characteristics of grapes in a new designed solar dryer in Shibin El-kom, Egypt, and to fit the experimental data to mathematical models available in literature.

Materials and Methods

2.1 Solar Dryer:

An indirect solar dryer was designed and manufactured in the Faculty of Agricultural., Minofiya University, Shibin El-Kom, Egypt, and installed on the roof of Agricultural Engineering Department at (latitude 30.54° N, longitude 31.3° E, and altitude 16.2 meters from mean sea level). The dryer essentially consists of absorber plate air heating collector, drying chamber and small fan to provide the required air flow over the product to be dried. These are connected in series as shown in Fig.1.

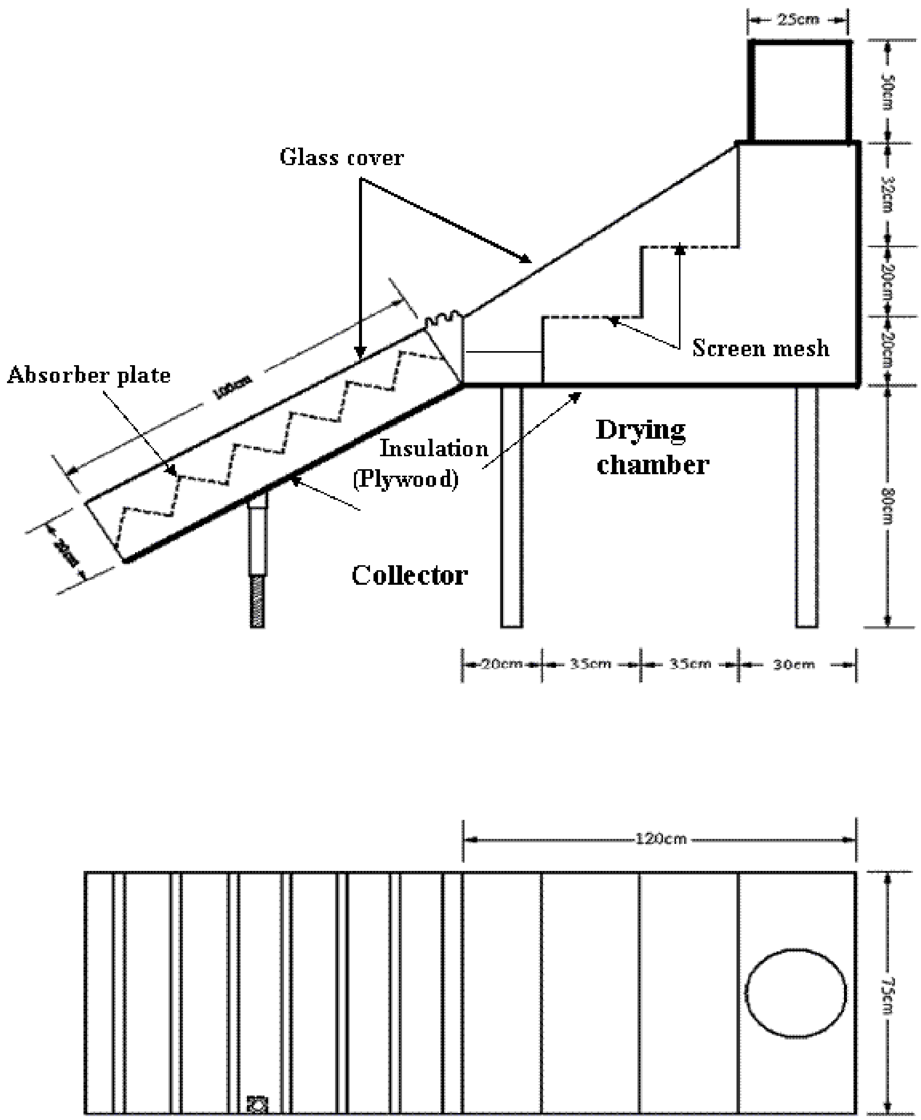

Fig. 1: View of designed solar dryer.

Both the solar collector and the drying chamber are covered with glass sheets. Black paint corrugated metal sheet is used as an absorber in the collector. The products to be dried are placed in a single layer on a wire mesh in the solar dryer. Glass wool is used as insulation materials to reduce the heat loss from the bottom of the dryer. The whole system is placed horizontally on a raised platform. The air at required flow rate is provided by Ac fan operated.

Measurements:

A Appley Radio Meter was used to measure the solar radiation on the horizontal surface. The velocity of drying air was measured with a Dwyer Thermal Anemometer 470 at the inlet of the dryer. The temperature was measured using thermocouple wires placed in the required measuring points. 15 thermocouples were used, five thermocouples were placed at the inlet, the absorber flat plate temperature, glass cover, airflow and exit port in the solar collector. Five thermocouples inside the drying chamber to measure the air inlet the drying chamber, air trays, glass cover, and outlet temperatures, Four thermocouples to measure wet and dry temperatures inside and outside solar dryer. One thermocouple to measure ambient temperature. The LM35 series are precision integrated-circuit temperature sensors, whose output voltage is linearly proportional to the Celsius (Centigrade) temperature. LM35 calibrated directly in °Celsius (Centigrade) ,linear + 10.0 mV/°C scale factor ,0.5°C accuracy guarantee able (at +25°C); rated for full −55° to +150°C range , nonlinearity only ±1⁄4°C typical, was used for temperature measurements. Temperature reading at a certain time intervals [x100 ms] ≈ (600×100 ms = 1 min) were recorded using a ProfiLab-Expert 4.0 computer program. The relative humidity of air at required points were measured by Digital thermo hygrometer Model 37200.

The moisture content of initial products was determined according to El-Awady *et al*., (1993), by drying the products in an electrical oven at 70˚C for 24 hours. The quantity of moisture present in a material can be expressed on either the wet basis or dry basis and expressed either as decimal or percentage.

2.3 Software tools used:

The system has three input parameters as ambient temperature, solar irradiation and the required mass flow of the loaded airflow. These parameters have been simulated based on the information about modelling the ambient temperature and the solar irradiation found in the relevant literature (Farkas *et al*., 1999). The simulation models of solar drying were designed by using Simulink (Graf *et al*., 2005; Yang *et al*., 2005) which is a program that runs in combination with MATLAB. Simulink is an interactive tool for modeling, simulating, and analyzing dynamic systems. It supports linear and nonlinear systems, modeled in continuous time, sampled time, or a mix of the two. Simulink enables the building of graphical block diagrams, evaluating system performance and refining the designs. MATLAB is both a computer programming language and a software environment for using that language effectively (Shen *et al*., 2008), Simulink program is represented in Fig. 2.

2.4 Experimental procedure:

Drying experiments were conducted during the periods of July 2010 in Shibin El-Kom, Egypt. Seedless grapes (cv. Thompson seedless) were obtained from a private farm. Homogeneous size grapes samples were washed with fresh ground water to remove undesired materials, e.g. dust and foreign materials and the clusters cut to ones, then treated by 1.0 % sodium bi hydroxide at 90˚C for 10 seconds and then rinsed well with water to remove any traces of alkaline. The samples after that were sulfured with 1.0 % sodium meta-bisulphate for 5 minutes at room temperature according to Radwan, (2002), and spread on the mesh trays of the drying chambers with load of 5 kg.m^{-2}. The initial moisture content of the grapes 3.37 kg water per kg dry matter. The working procedure may be summarized as follows:

1. Solar dryer orientation was set with its solar collector facing south. The direction was confirmed by a simple magnetic needle (Tilt angle =30.5°)
2. Pre- treated sample (grapes) was loaded in two trays in the drying chamber (2 kg each) so that steady-state temperatures were obtained after 1 h.
3. After checking all dryer parts, glass cover was cleaned and the door of the drying chamber was closed.
4. Readings were taken at intervals of 1 h (from 7am to 7pm) in the following sequence (solar radiation, drying air properties, and moisture content of samples).
5. The above readings were noted in a specially prepared datasheet.
6. The final readings were taken at 7pm. The product was then removed from the drying chamber, taken in plastic bags and their weight was noted.
7. The drying tests were termined when the decrease in the weight of the samples had almost ceased. The-dried samples were weighed and their values were used to determine the final moisture content.

Mathematical models:

The total radiation received on the horizontal is the sum of the direct and diffuse radiation (Parker, 1991 and Taha, 2010).

$$Q_G = Q_b + Q_d \qquad [\mathrm{Wm^{-2}}] \qquad (1)$$

An improvement on this model, the isotropic diffuse model, was derived by Liu and Jordan, 1963; Parker, 1991; Duffie and Beckman, 2006).

The radiation on the tilted surface was considered to include three components: beam, isotropic diffuse and solar radiation diffusely reflected from the surroundings.

$$Q_{Gt} = Q_b R_b + Q_d R_d + Q_G \rho_g R_r \qquad [\mathrm{Wm^{-2}}] \qquad (2)$$

Radiation:

Long-wave radiation is an important mode of heat transfer between surfaces inside the solar dryer and the environment. Inside, the elements of the solar dryer (cover material, airflow, absorber plate and product in drying chamber, heat is transferred directly to each element by radiation, and some heat is radiantly exchanged with the air. It is possible to calculate the radiant energy exchanges of the solar dryer. The surface of any part of the solar dryer at a given temperature T emits electromagnetic radiation, the flux measured in W, is subjected to the Stefan-Boltzmann law seen below:

$$Q_{rad} = \varepsilon . \sigma . A . T^{4} \qquad [W] \tag{3}$$

Convection:

The design and analysis of all solar thermal systems requires familiarity with the fundamentals of heat transfer. In discussion of modeling in the present study, it has been assumed that, the various heat transfer coefficients involved have different values. For example, the coefficients (h_{ins}), (h_{out}) and (k) all unincorporated knowledge about the magnitude of convection and radiation coefficients used to represent the heat transfer between the interior and exterior surfaces of the collector and the environment. Heat exchange by convection occurs at three different locations of any collector: on the inward and outward sides of the glass cover, on airflow, and on heating flat plate. The convective heat flux between couples of inward sides, called (Q_{conv}), is proportional to the temperature difference ΔT, between the inward side and the medium. Consequently, the (Q_{conv}) is given by the following equation:

$$Q_{conv} = h_{conv} . A . \Delta T \qquad [W] \tag{4}$$

Conduction:

The flux of conductive heat (Q_{cond}) through an element of a wood measured in W depends upon the cross – sectional area of the element, the temperature gradient and thermal conductivity of the wood. This can be expressed as follows:

$$Q_{cond} = \frac{k . \Delta T}{X} \qquad [Wm^{-2}] \tag{5}$$

Differential equation:

To calculate the temperature of the solar dryer elements (glass cover, airflow, absorber plate, insulation, product) the following differential equation was used (Taha, 2003):

$$T = \frac{1}{\rho . C_{p} . X} \int_{\tau=0}^{\tau=n} (Q_{sup} - Q_{los}) \, d\tau \qquad [°K] \tag{6}$$

Mathematical Modeling of Solar Drying Curves:

The solar drying curves were fitted with eleven different moisture ratio equations given by several researchers as listed in table 1. To calculate the coefficients of each model and to select the best model for describing the drying curves, the nonlinear optimization method was applied, using the computer programs Datafit 9.0.

Tripathy, and Kumar, 2008 and Yaldiz *et al*., (2001), simplified the moisture ratio (MR) to M_t/M_i instead of $(M_t\text{-}Me)/(M_i\text{-}Me)$ because the relative humidity of the drying air continuously fluctuated in solar drying

Where: *MR*, is moisture ratio, M_i is initial moisture content, *Me* is equilibrium moisture content, M_t is moisture content at time t. Since the values of Me are relatively small compared to M_t or M_i.

The regression analysis was performed using the statistical computer program. Datafit 9.0 the goodness of fit of the tested mathematical models to the experimental data was evaluated from the coefficient of determination R^2 and the reduced chi-square χ^2 between the predicted and experimental values. The higher the R^2 values and the lower the χ^2 values, the better is the goodness of fit (Ertekin and Yaldiz, 2004).The reduced chi-square can be calculated as follow:-

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$$\chi^2 = \frac{\sum_{i=1}^{N} (MR_{\exp,i} - MR_{pre,i})^2}{N - n} \tag{7}$$

$$MBE = \frac{1}{N} \sum_{i=1}^{N} (MR_{pre,i} - MR_{\exp,i}) \tag{8}$$

Table 1: Mathematical models applied to the drying curves, (Idlimam *et al*., 2007).

Model number	Model name	Model expression
1	Newton	$MR = \exp(-k.t) = e^{-k.t}$
2	Page	$MR = \exp(-k.t^n) = e^{-k.tn}$
3	Henderson and Pabis	$MR = a.\exp(-k.t) = a.e^{-k.t}$
4	Logarithmic	$MR = a.\exp(-k.t)+c = a.e^{-k.t+c}$
5	Two term	$MR = a.\exp(-k_0.t) + b\exp(-k_1 t) = a.e^{-k0.t} + b\, e^{-k1\,t}$
6	Two term exponential	$MR = a.\exp(-k.t) + (1-a)\exp(-k.a.t) = a.e^{-k.t} + (1-a)\, e^{-k.a.t}$
7	Wang and Singh	$MR = 1+ a.t+bt^2 =1+ a.t+bt^2$
8	Approximation of diffusion	$MR = a\exp(-k.t) + (1-a)\exp(-k.b.t) = a\, e^{-k.t}+ (1-a)\, e^{-k.b.t}$
9	Modified Henderson and Pabis	$MR = a\exp(-k.t)+b.\exp(-g.t)+c.\exp(-h.t) = a\, e^{-k.t}+b.e^{-g.t}+c.e^{-h.t}$
10	Verma *et al.*	$MR = a\exp(-k.t) + (1-a)\exp(-g.t) = a\, e^{-k.t} + (1-a)\, e^{-g.t}$
11	Midilli–Kucuk	$MR = a\exp(-k.t^n) +b.t = a\, e^{-k.tn} +b.t$

Results And Discussions

4.1 Ambient conditions (temperature and relative humidity):

During the days of experiments, the variations of the ambient air temperature, relative humidity and solar radiation are shown in Fig. 3. or a typical day of July 2010 in Shibin El-kom Minofiya Egypt. During the drying experiment, the daily mean values of ambient air temperature, relative humidity and solar radiation ranged from 24.4 to 38.69 °C, 37–87%, 100.3–945.4 W/m^2, respectively. The ambient air temperature and solar radiation were reached the highest values between 12:00 and 15:00, whereas the relative humidity was reached the lowest values during this time. The relative humidity decreases with the increase of ambient air temperature. The temperature was always relatively low at the beginning and the end of the day while it reaches its maximum value at afternoon and then started to decrease again.

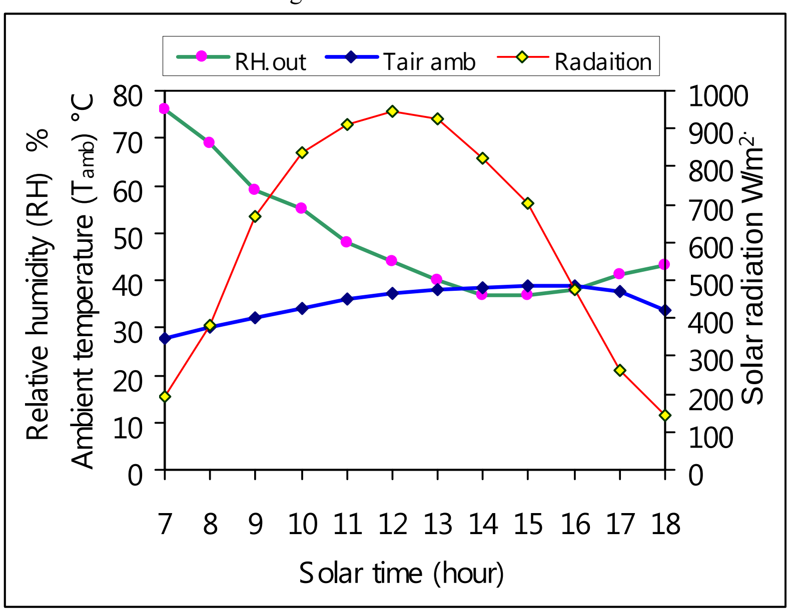

Fig. 3: Variations of the ambient air temperature, relative humidity and solar radiation , with the solar time (hour) typical day of July 2010

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The relative humidity has a reverse trend to that of temperature. Linear regression analyses between both ambient and drying air temperatures and solar insolation are illustrated in Fig. 4 where the ambient air temperature and dryer air temperature increased with increase in solar insolation and the two variables appeared to be linearly related.

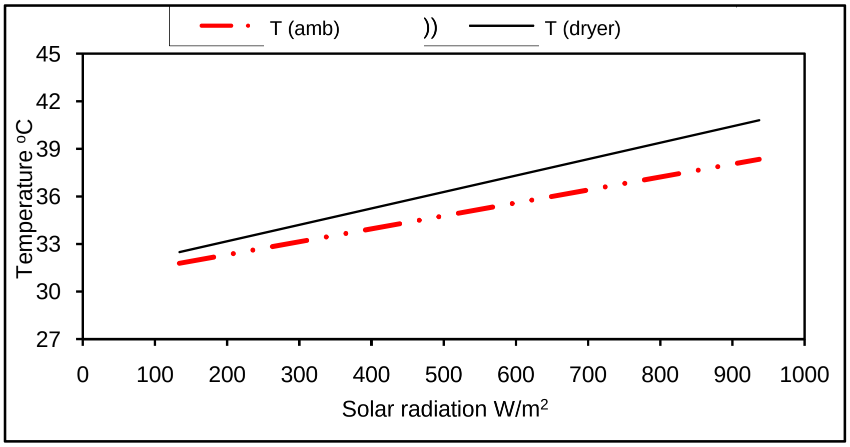


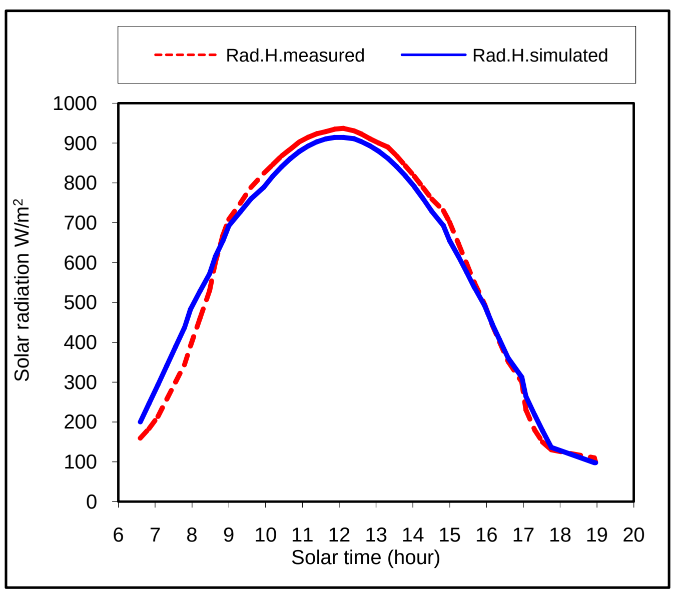
Fig. 4: Relation between the solar radiation (horizontal) and air temperatures (ambient and inside the dryer).

4.2 Validation of the simulation model:

Solar radiation on horizontal surface:

Fig. 5 shows the results of total solar radiation on horizontal surface measured and predicted during daylight hours ranging between 7:00 and 19:00. where solar radiation changes in the range of 103–945 Wm^{-2} and the values used in the typical configurations and operating conditions. It can be seen that a good agreement had been found between the simulated and the experimental result.

Fig. 5 shows correlation coefficient between the total solar radiation for the horizontal surface with measured and predicted data that resulting of model which, gave an R^2 of (0.9941).



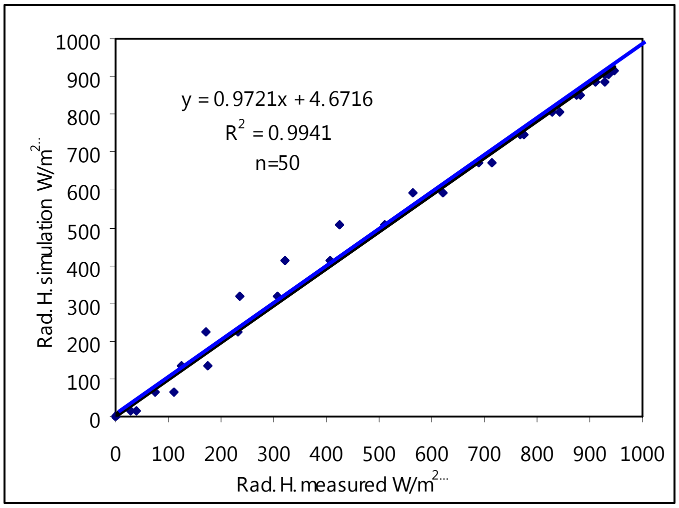


Fig. 5: Measured and calculated of solar radiation for the horizontal surface at 19th July 2010.

Collector air temperature:

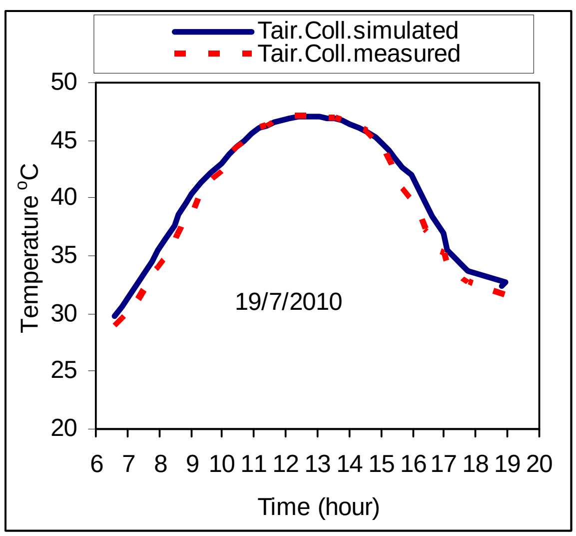
Fig. 6 shows the comparison between predicted and measured values of collector outlet airflow temperature, during one day of changeable climatic conditions. It can be seen that a good agreement had been found between the simulated and the experimental result.

Fig. 6 shows the correlation coefficient between calculated and measured values of the collector outlet air temperature that, resulting from model gave an R^2 of (0.9777).

Collector absorber plate temperature:

Fig. 7 shows the comparison between predicted and measured values of the solar collector absorber plate temperature, during one day of changeable climatic conditions. It can be seen that a good agreement had been found between the simulated and the experimental result

Fig. 7 shows the correlation coefficient between Predicted and measured values of the solar collector absorber plate temperature that, resulting from the model, which, gave an R^2 of (0.9662).



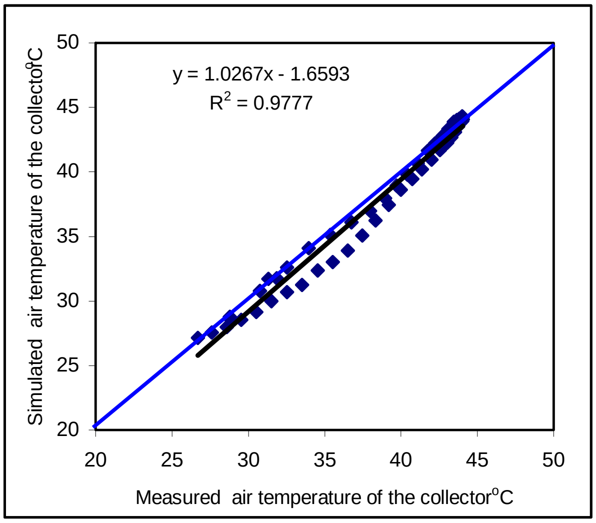


Fig. 6: Comparison between predicted and measured values of the collector outlet airflow temperature at at 19th July 2010

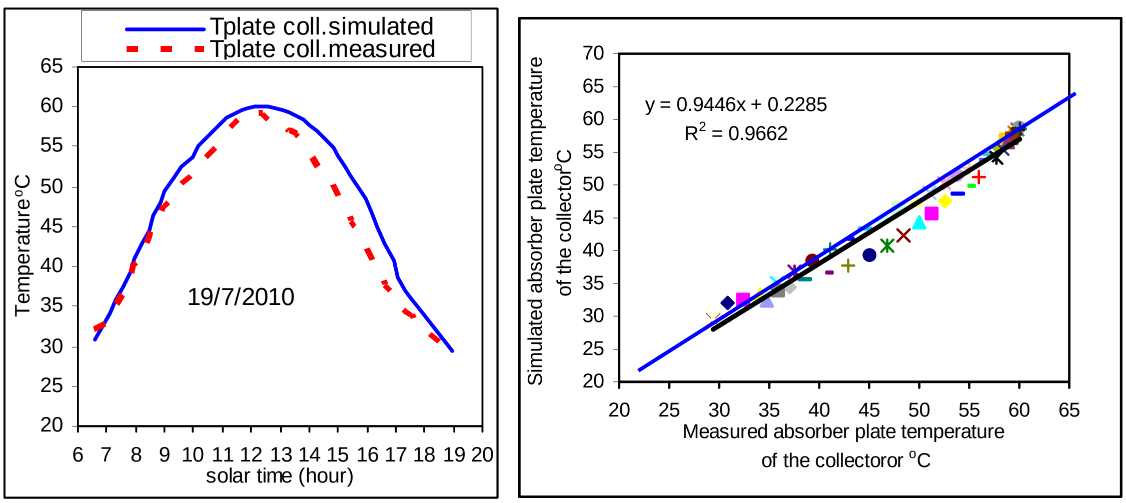
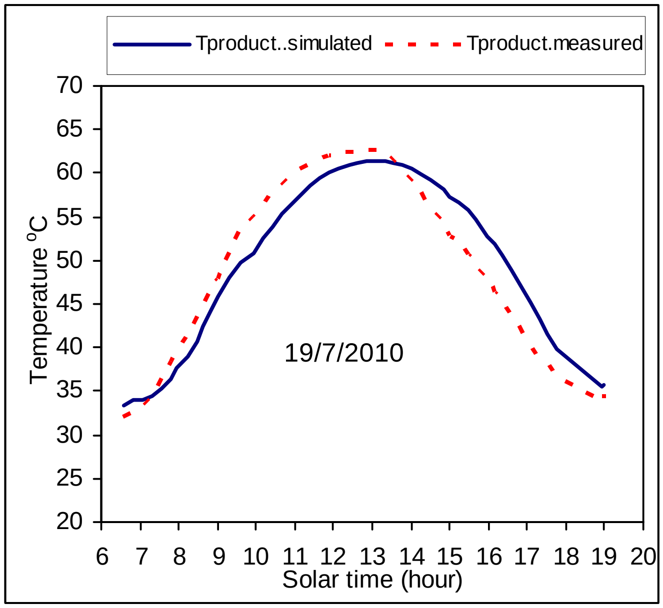


Fig. 7: Calculated and measured values of the collector absorber plate temperature at 19th July 2010

The temperature of the agricultural product:

Fig. 8 shows the comparison between predicted and measured values of the drying chamber product temperature, during one day of changeable climatic conditions. It can be seen that, a good agreement had been found between the simulated and the experimental result.

Fig. 8 shows the correlation coefficient between Predicted and measured values of the drying chamber product temperature that resulting from the model which, gave an R^2 of (0.902).



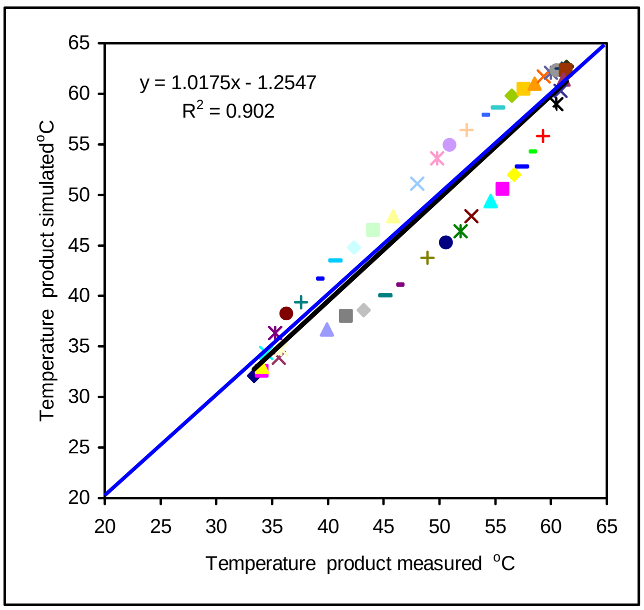


Fig. 8: Calculated and measured values of the product temperature at 19th July 2010

Collector glass cover temperature:

Temperature of the glass cover is an essential parameter needed for any analysis of energy transfer in the solar dryer. Measuring the correct value of temperature of the glass cover is difficult due to the transparency of the covering materials and the effects of solar and thermal radiation and air movement on the cover surface. Therefore, temperature of the glass cover, in most cases, has been estimated theoretically by applying an energy balance to the solar dryer. This result is in agreement with the result of Abdel-Ghany *et al*, (2006).

Drying chamber air temperature on trays:

Fig. 9 shows the comparison between predicted and measured values of the drying chamber airflow temperature, during one day of changeable climatic conditions. It can be seen that, a good agreement had been found between the simulated and the experimental result

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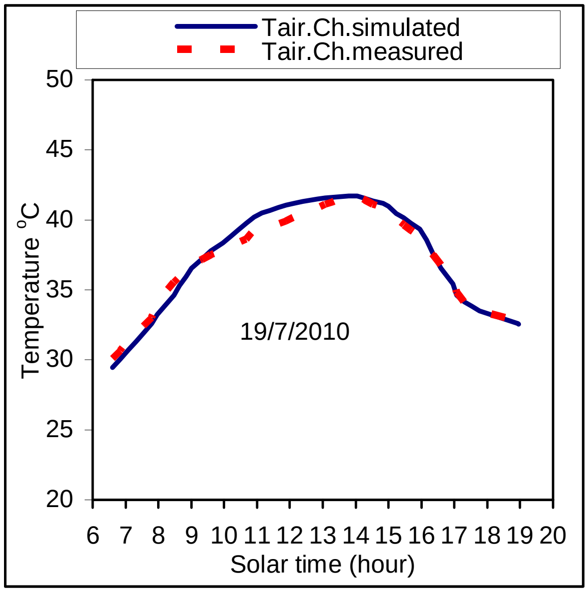
Fig. 9 shows the correlation coefficient between Predicted and measured values of the drying chamber product temperature that, resulting from the model, which, gave an R^2 of (0.9874).



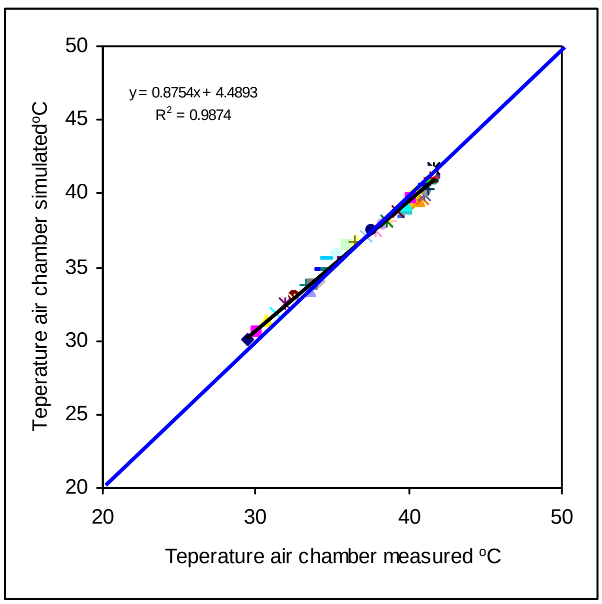


Fig. 9: Calculated and measured values of the drying chamber temperature at 19th July 2010

Relative humidity of the solar drying chamber:

The predicted and measured values of relative humidity (RH) for one typical period of four consecutive days chosen from the measuring period were compared and shown to be in good agreement. However, there was a slight difference between the predicted and measured RH values due to the fact that RH-value depends on both T_{ins} and AH_{ins} (water content) for product, and also due to the fact that the relative error of RH depends on the relative errors of the simulated T_{ins} and AH_{ins}. At the mid-day, the predicted RH was lower than the measured one, since the predicted temperature was higher than the measured one.

Fig. 10 shows the comparison between predicted and measured values of relative humidity inside the drying chamber, during one day of changeable climatic conditions. It can be seen that a good agreement had been found between the simulated and the experimental result. These results are in agreement with the results of Elsheikh, (2001) and Taha, (2009).

Fig. 10 shows the correlation coefficient between Predicted and measured values of the drying chamber product temperature that, resulting from the model which, gave an R^2 of (0.9725).

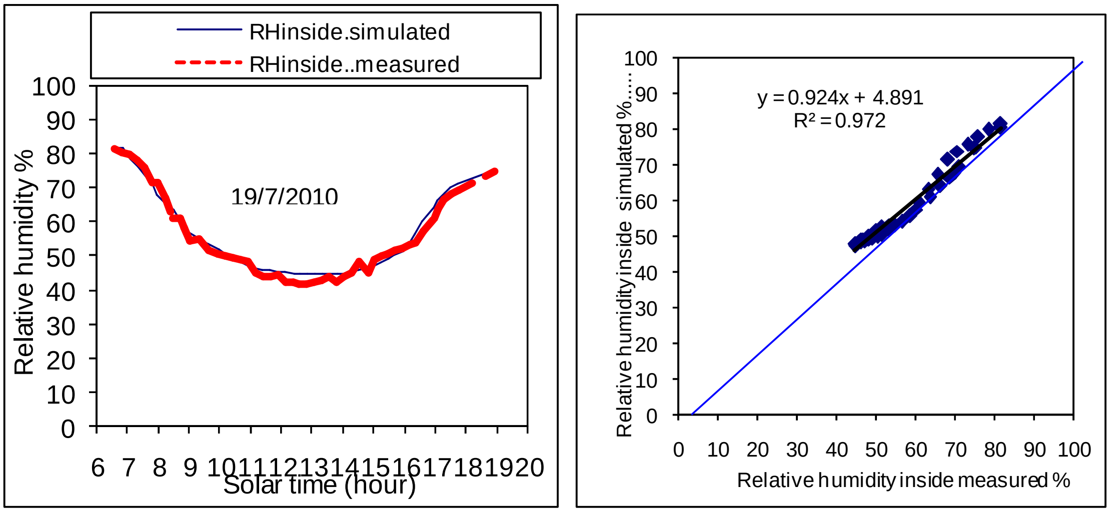


Fig. 10: Calculated and measured values of relative humidity inside drying chamber at 19 th July 2010

Drying curves:

The moisture content dry basis (d.b) versus drying time for two drying trays are shown in Fig. 11. In these figures, the constant drying rate period is absent in solar drying of grape. The drying process took place in the falling rate period. Drying rate decreases continuously with moisture content or drying time. These results are in agreement with the observations of earlier researchers (Yaldız *et al*., 2001) for sultana grape and (Lahsasni *et al*., 2004) for prickly pear peel.

The grapes were dried from an initial moisture content of 337 g water/g dry matter. The mean final moisture content that could be obtained was 116 g water/g dry matter in both trays. The reduction in moisture content of product in tray 1 was a little faster at the beginning of drying due to the higher product temperature. However, the final moisture content of the product in both trays were the same (0.16 g water/g dry matter). The hourly variation in drying rate is shown in Fig. 11 There was linear reduction in drying rate from first to the 18th hour and thereafter the drying rate was steady for the rest of the drying time. The effect of moisture content on the rate of drying is presented in Fig. 13 The linear reduction in drying rate can be observed with reduction in moisture content of the grapes product. These results also concur with the work presented by Jain, (2005).

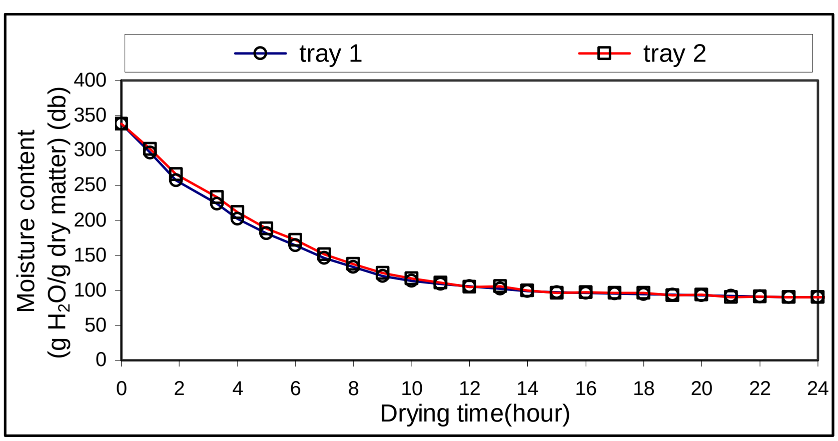


Fig. 11: Variation of moisture content in air with drying time

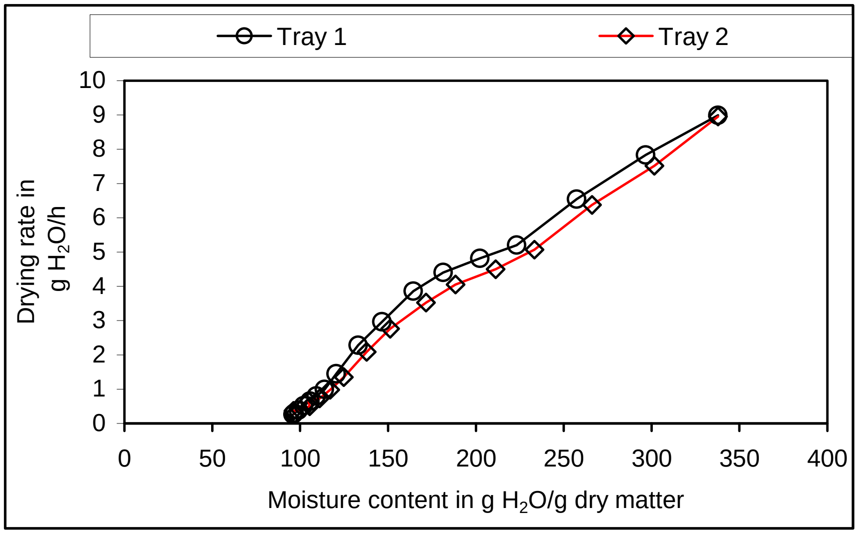


Fig. 13: Variation of drying rate with change in moisture content

Simulation of the solar drying process:

Drying curves were simulated using empirical models of reduced moisture content. These empirical models coming from the fundamental diffusion models are generally suitable for fruits.

As shown in table 2, the Modified Henderson and Pabis model gave good agreement with the experimental data and considered to be the best result for grapes samples.

Fig. 14 presents drying curve of the predicted data and the experimental data obtained by the selected model (Modified Henderson and Pabis)

Fig. 14 Indicates the comparison of the predicted and the experimental moisture ratio values by Modified Henderson and Pabis model for solar drying. The Modified Henderson and Pabis model provided satisfactorily a good conformity between experimental and predicted moisture ratios, and predicted data generall which showed the suitability of this model in describing solar drying behaviour of grapes. As previously mentioned, the drying of grapes occurred in the falling rate drying period only and liquid diffusion controls process. Accordingly, Fick's second law can be used to describe the drying behaviour.

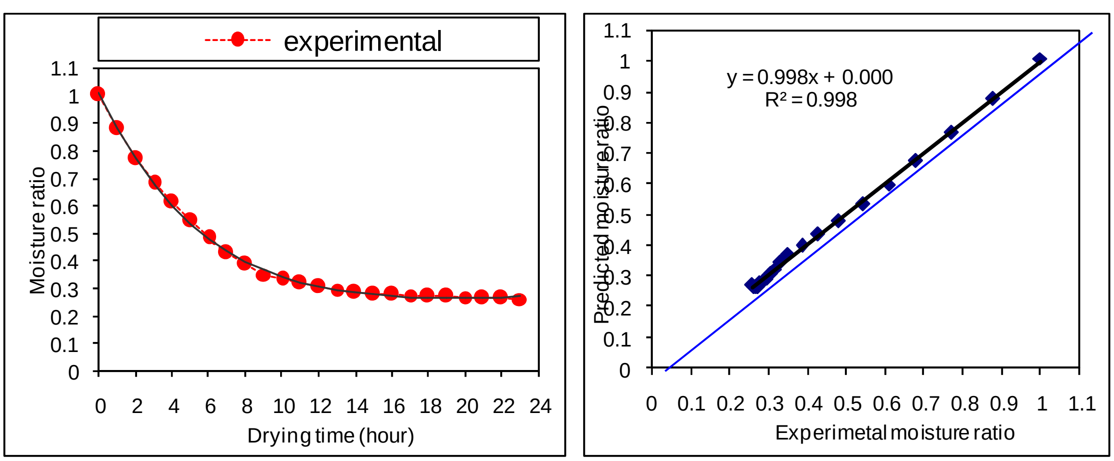


Fig. 14: Comparison between experimental and predicted moisture ratios by Modified Henderson and Pabis model for solar drying

This simulation model will be used for the optimization of the dryer components and drying process. Good agreement was found between the experimental and simulated moisture contents. This findings agreement with, (Hossain *et al*., 2007). 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, Kashaninejad *et al*., (2007) for pistachio nuts. The effect of these variables on the constant and coefficient of drying expression were also investigated by regression analyses.

Conclusions:

The indirect solar dryer was successfully tested under weather condition of El-Menoufiya, Egypt, where high quality dried grapes was obtained.

The performance of the solar collector to head the drying air is assumed satisfactory, it could varies the ambient temperature to around 48 C at peak conditions which is considered adequate for grape drying.

The proposed model is capable to predict the solar radiation intensity incident on the horizontal and tilted surfaces, temperature, relative humidity, and moisture ratio of the agricultural product.

The drying mathematical model provides information about the influence of various important parameters on the drying phenomenon.

Modified Henderson& Pabis model was the best model fitted very well the experimental data and could adequately describe the thin layer solar drying of grapes

Temperature was found to be the most important factor of the drying rate for grape.

Table 2: Modelling of moisture ratio according to drying time for grapes.

No	Model	Coefficients	R^2	χ^2	MBE
1	Newton	K=0.092752	0.85574874	1.3727E-05	-0.0007403
2	Page	k = 0.217815 n = 0.540889	0.9527030558	3.8728E-04	-0.0038450
3	Henderson and Pabis	a = 0.875219 k = 0.077541	0.89770181	1.5285E-03	-0.0078870
4	Logarithmic	a = 0.772277 k = 0.201058 c = 0.245054	0.9972552593	7.5190E-21	-1.5555558E-11
5	Two term	a = 0.1400409 k_0=-0.025550 b = 0.858008 k_1= 0.1584290	0.99859809	1.4301E-09	7.0455208E-05
5	Two term exponential	a =0.225773 k =0.315213	0.92830751	2.7537E-05	-0.0010274
7	Wang and Singh	a =-0.094481 b = 0.002858	0.9555188308	2.5117E-03	0.0099877
8	Approximation of diffusion	a = 0.74543 b = 0.24725 k = 0.20588	0.998501142	7.5320E-05	-0.00052749
9	Modified Henderson and Pabis	a = 0.075558 k =-0.025550 b = 0.075558 g = -0.025550 c =0.858008 h = 0.158429	0.99859809	1.5890E-09	7.0455458E-05
10	Verma *et al*	a = 0.859148 k = 0.153871 g = -0.028384	0.998501142	7.5320E-05	0.0007225
11	Midilli–Kucuk	a = 1.00709 k = 0.18584 n = 0.89202 b = 0.00135	0.9985425215	2.3357E-07	-0.00009007

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