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Experimental Study on Eggplant Drying by an Indirect Solar Dryer and Open Sun Drying

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Abstract: In this article, an indirect forced convection solar dryer is used to study the kinetic drying of eggplant. The effective moisture diffusivity calculated by slop method follows the solar intensity with the maximum value of 1.68 E-09 at 15 PM. Performance of solar dryer is determined by defining the efficiency of collector and an effectiveness factor as the ratio of the drying rate in the indirect solar dryer to the drying rate in the open sun. The collector efficiency and the effectiveness factor vary with the drying time inversely. Results show that the drying rate in the solar dryer is 3.5 g H_2O. g ds^{-1}. Hr^{-1} and is 2 g H_2O. g ds^{-1}. Hr^{-1} for the open sun drying method in the beginning of the process. Several well-known mathematical models are applied in order to select the best model to present the eggplant drying behavior. Midilli and Kucuck model refers to drying process of product with correlation coefficients (R^2) which are 0.9998 for solar dryer and 0.9996 for open sun.

Key words: Renewable energy · Indirect solar dryer · Collector efficiency · Effectiveness factor

INTRODUCTION

Energy is a parameter for development and improvement, and plays an important role in our livelihood. Now, fossil energy resources are utilized in industry worldwide. Utilizing these resources is not without problems like polluting the environment, global warming and high transportation cost [1]. In recent decades all efforts are directed towards substituting of the fossil energy with renewable energies such as wind energy, wave energy, biomass, geothermal, nuclear energy and solar energy in order to reduce the problems caused by fossil resources. Among the renewable energy resources, solar energy is a bless of God on this green planet due to its accessibility, abundance, purity and none polluting is known as one of the most suitable renewable resources. Applying solar energy systems due to its advantages such as energy saving, generation of new jobs and diminishing the environmental pollution are remarkable in many countries of the world [2]. Nowadays innovation in designing and manufacturing solar systems is on an increase.

Solar dryers due to eliminate of the open sun drying problems such as wind, debris, rain, insect infestation, rodents, birds, etc. [3] can be the suitable alternative for dryers with fossil resources. Installing the solar dryers in the agricultural farm can reduce the harvest losses that is more than 30% [4] and costs of the transportation. Solar dryers are designed and manufactured as direct, indirect and mixed modes [5]. Several researchers have applied these dryers for drying of fig [6], cabbage [7], chili [8], seedless grape [9], coffee [10], pupae of the silkworm [11], apricot [12], Dill and Spearmint [13] and leafy green product [14]. In order to assess the solar dryer performance, it is necessary to survey the drying kinetics and attaining the drying time. Thin layer models were applied in calculating the drying time of mackerel, pistachio, green pepper and onion by [15-18] in different solar drying methods, respectively.

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Fig. 1a: Schematic view of an indirect forced convection solar dryer

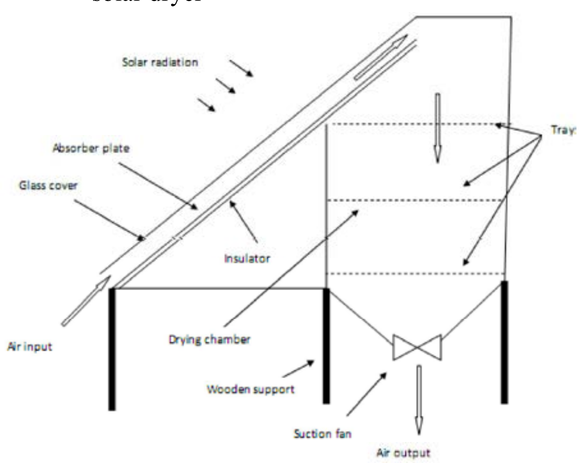


Fig. 1b: Photo of an indirect forced convection solar dryer

In this study, the performance of an indirect forced convection solar dryer for drying eggplant is investigated. Eggplant is very low in saturated fat and cholesterol. It is also a good source of vitamin K, thiamin, vitamin B6, potassium, manganese and a very god source of dietary fiber. In order to survey the greenhouse effect in the collector ratio of the drying rate in the solar dryer to the drying rate in the open sun is defined as the effectiveness factor. The relation between effectiveness factor and collector efficiency is determined here. Finally, the nine thin layer models are applied for mathematical modeling regarding the drying behavior of product and the best model is presented according to the statistical criteria.

Experimental Study

Experimental Setup: Fig. 1a and Fig. 1b show the photo and a schematic view of the experimental setup, respectively. The set up consists of a solar collector, drying chamber and measurement devices. The solar collector is a flat plate collector and was installed on the drying chamber. Absorber plate is separated from drying chamber by 4 cm thick glass wool. In order to decrease heat lose, wooden walls of drying chamber are insulated. Two uniform trays of $1m^2$ area are made of wood and mesh stainless steel wire and used for keeping the products in the drying chamber. In order to provide hot air evacuation from collector inside the drying chamber a suction fan with duct diameter of 0.15 m, speed of 1000 rpm and maximum flow rate of 250 $m^3.Hr^{-1}$ was installed under the trays at the bottom of chamber. A home-made temperature measuring system showed the dry bulb temperature of drying and ambient air as online by installing several temperature sensors at different of the solar collector and drying chamber inside-out. In order to allow for the maximum incident solar energy absorption the apparatus was manually rotated toward the sun on the installed wheels. Therefore, the azimuth angle was varying during the experimental data collection and the tilt angle was fixed to 33 degrees.

Procedure: Experimental study was performed in early October, in the city of Isfahan (32°N latitude, 51°E longitude). The eggplants were purchased from a local market and cut to slab shape with 2 cm thick and 3 cm diameter. Specific content of product with initial moisture of 0.9 (w.b) was spread on the trays in the indirect solar dryer and under the open sun. The dryer ran without load for 120 min for stabilizing the drying conditions. Experiments started at 9:00 AM for 8 hours drying time. The temperature and sample weight loss were recorded at 60 min intervals between 9:00 AM and 17 PM. After conducting the experiments the drying data were presented as dimensionless moisture content and the drying rates versus drying time. The pictures of fresh and dried eggplant are shown in Fig. 2a and Fig. 2b, respectively.

Effective Moisture Diffusivity: According to the results reported by [19] the general range of effective moisture diffusivity of agriculture products is between

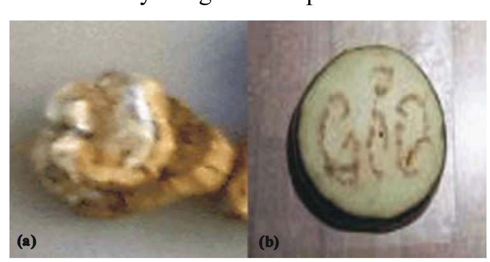


Fig. 2: The pictures of eggplant. a) Fresh product. b) Dried product

0^{-9} and 10^{-11}. Accordingly, the Fick's first law can be used to describe moisture transfer by using equation:

$$j_m = -D_{eff} A \frac{\partial C_m}{\partial x} \quad (20)$$

The relationship between the effective moisture diffusivity and temperature can be expressed by an Arrhenius equation [21] and [22] in the bellow form:

$$D_{eff} = D_0 \exp(-\frac{E}{RT}) \quad (21), (22)$$

Based on the above equation, an increase in the product temperature leads to an increase in moisture diffusivity. The analytical solution of Fick's second law equation with the assumption of a constant moisture diffusivity, the infinite slab geometry and the uniform initial moisture distribution is introduced as below equation [23]:

$$MR = \frac{8}{\pi^2} \sum_{n=1}^{\infty} \frac{1}{(2n+1)^2} \exp(-(2n+1)^2 \frac{\pi^2 D_{eff} t}{4L^2}) \quad (23)$$

For long time drying periods, the above equation can be simplified in a logarithmic form as follows:

$$Ln(MR) = Ln(\frac{8}{\pi^2}) - (\frac{\pi^2 D_{eff} t}{4L^2}) \quad (23)$$

The effective moisture diffusivity can be calculated by plotting the drying data in terms of $Ln(MR)$ versus drying time [22] and [24] as given in the following equation:

$$Slope = \frac{\pi^2 D_{eff}}{4L^2} \quad ([22], [24])$$

Mathematical Modeling of the Drying Curves: Dimensionless moisture content and drying rate of samples during experiment were expressed by following equations:

$$MR = \frac{M_t - M_e}{M_0 - M_e} \quad (19)$$

$$DR = \frac{M_{t+dt} - M_t}{dt} \quad (11)$$

As M_e value is very small with respect to M_0 and M_t values, the M_e value can be neglected and the moisture ratio can be expressed as $\frac{M_t}{M_0}$ [25]. In order to select the best model for describing eggplant drying behavior, drying data were fitted with nine thin layer models shown in Table 1. For evaluating the models some statistical parameters such as correlation coefficient (R^2) in Eq.(8) and root mean square error (RMSE) in Eq.(9) were selected [26, 27]. The higher value of R^2 and lower the value of RMSE indicate better of fitting [26, 28].

$$R^2 = \frac{\sum_{i=1}^{n} (MR_{pre,i} - \overline{MR}_{pre,i})^2}{\sum_{i=1}^{n} (MR_{\exp,i} - \overline{MR}_{\exp,i})^2} \quad (26)$$

$$RMSE = \left[\frac{1}{n} \sum_{i=1}^{n} (MR_{\exp,i} - MR_{pre,i})^2 \right]^{\frac{1}{2}} \quad (27)$$

Collector Efficiency: In order to assess the collector performance, the collector efficiency is defined as the ratio of the increased air enthalpy to the solar radiation intensity in the same intervals through the following equation [29]:

Table 1: Different mathematical models for the drying curves

Name and Equation No.		Equation	References
1.	Newton	$MR = \exp(-kt)$	[15]
2.	Page	$MR = \exp(-kt^n)$	[30]
3.	Henderson and Pabis	$MR = a \exp(-kt)$	[16]
4.	Two term	$MR = a \exp(-k_0 t) + b \exp(-k_1 t)$	[25]
5.	Approximation of diffusion	$MR = a \exp(-kt) + (1 - a) \exp(-kbt)$	[26]
6.	Logarithmic	$MR = a \exp(-kt) + c$	[16]
7.	Midilli and kucuk	$MR = a \exp(-kt^n) + bt$	[17]
8.	Verma *et al.*	$MR = a \exp(-kt) + (1 - a) \exp(-gt)$	[25]
9.	Wang and Singh	$MR = 1 + at + bt^2$	[17]

$$\eta_c = \frac{\dot{m}_a C_a \sum_{i=1}^{n} \left(T_{c,out} - T_{c,in}\right)\Delta t}{A \sum_{i=1}^{n} I_t \Delta t} \qquad (29)$$

Effectiveness Factor: In order to survey the greenhouse effect on the product drying rate in the solar dryer with respect to the open sun drying, an effectiveness factor is defined as the ratio of the drying rate in the indirect solar dryer to the drying rate in the open sun as below:

Effectiveness Factor (EF) =
(drying rate in the solar dryer)/(drying rate in open sundrying)

RESULTS AND DISCUSSIONS

Fig. 3 shows the variation of the ambient air, the mean drying air and the collector outlet temperatures with local time for a typical day in October. This figure illustrates that the each three curves followed the solar intensity trend that is parabolic. The overall trend of variation of temperature with respect to local time is in a fairly good agreement with the recorded results by Hanif Khalil *et al*. (2012). The maximum temperature of ambient air, drying air and collector outlet is 29.1, 52.8 and 79.3°C, respectively and take place between 12 and 13 PM. Due to the short wave length radiation penetration through the glass cover and lack of the long wave length radiation penetration via the absorber plate the greenhouse effect occurs in the collector that leads to energy accumulation and a rise in temperature. It is also considered that due to the heat leakage in the drying chamber, the mean drying air temperature is less than the collector outlet temperature. Literature review shows that this range of the drying air temperature is suitable for drying of the product in good quality of color, aroma and taste.

The variation of the effective moisture diffusivity versus the drying time in the indirect solar dryer is illustrated in Fig. 4. As shown in this figure, the maximum value of effective moisture is 1.68E-09 and takes place at 15 pm. Here, trend of the effective moisture diffusivity follows the solar intensity trend. The increase of solar intensity during the day causes an enhancement in air drying temperature thereupon the increase of samples temperature. As formerly mentioned an increase in drying air temperature leads to increase of effective moisture diffusivity. At the end of the day, decrease of temperature beside the gradient concentration reduction causes to decrease of diffusivity.

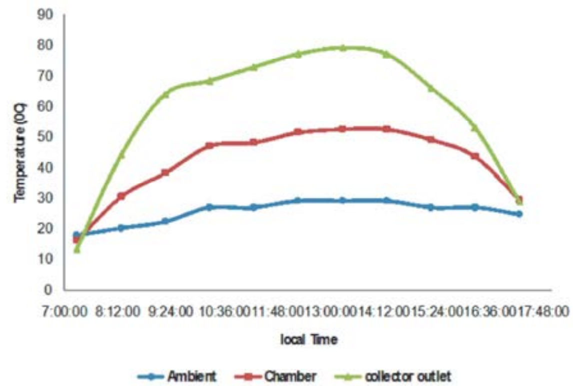


Fig. 3: The variation of ambient temperature, chamber air temperature and collector outlet temperature versus local time

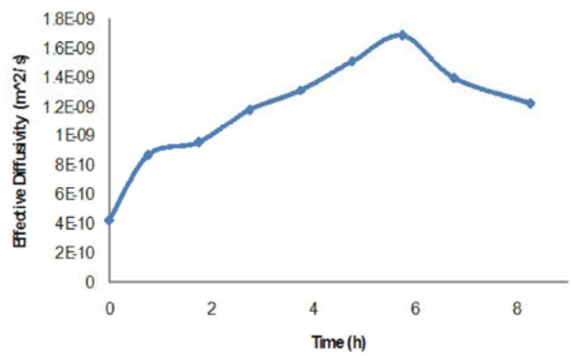


Fig. 4: The variation of effective moisture diffusivity versus drying time in the indirect solar dryer

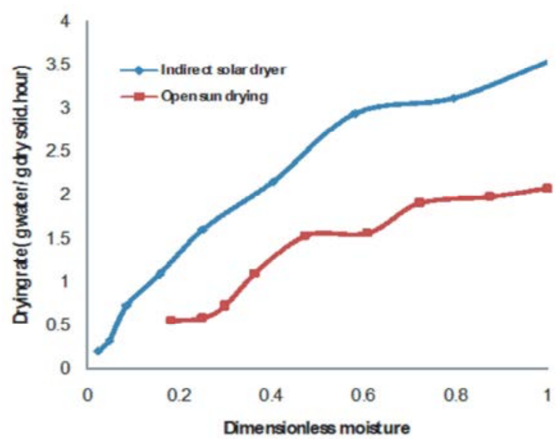


Fig. 5: The variation of drying rate sample versus the dimensionless moisture in the indirect solar dryer and open sun drying

The variation of the drying rate samples versus the dimensionless moisture for solar dryer and open sun drying are shown in Fig.5. This figure reveals that the final dimensionless moisture at the end of the experiment day

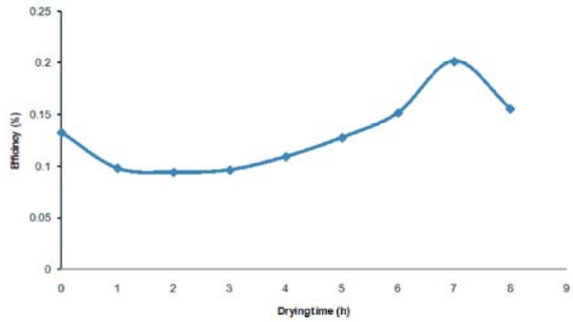


Fig. 6.a: The variation of the collector efficiency with the drying time

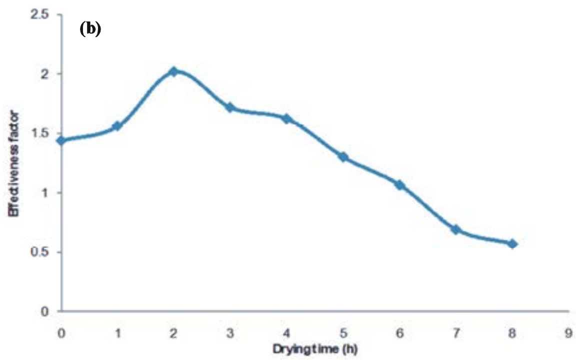
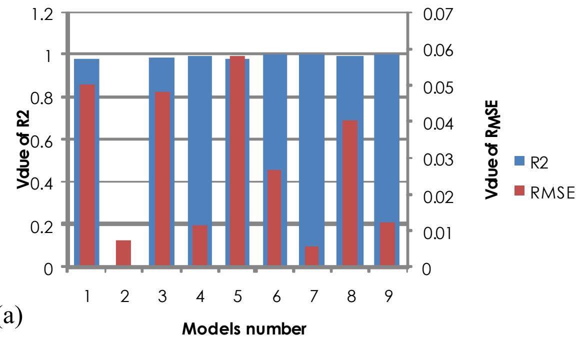
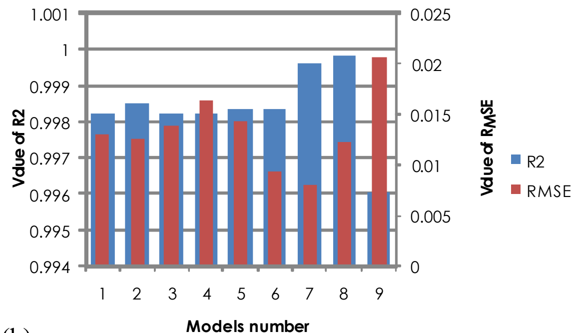


Fig. 6.b: The variation of the effectiveness factor with the drying time



(a)



(b)

Fig. 7: The value of R^2 and RMSE for applied models. a) in the solar dryer, b) in the open sun drying

is 0.025 and 0.183 for indirect solar dryer and open sun drying respectively. In both methods the drying rate decreases with decrease of the dimensionless moisture that its reason is reduction of the mass transfer driving force. Here, the drying rate of samples in the solar dryer is higher than that of the open sun drying. The results depicted in figures 3 and 4 can be discussed the reason of this difference. It is also observed that the main part of the drying process occurs in the falling drying rate period. These results are consistent with performed experimental data for apricot in the dish type solar air heater [12].

Evaluation of the Solar Dryer Performance: Figs. 6a and 6b show the variation of the collector efficiency and effectiveness factor versus drying time, respectively. Here, the maximum efficiency occurs at 4 PM, after 7 hours drying time. The low mass flow rate causes the efficiency does not increase from 0.2. The conducted study by Sami *et al*. (2011) on the indirect solar dryer indicate that the increase of mass flow rate lead to increase in efficiency more than 0.8. It can be seen in Fig. 5a that between 12 and 13 PM when solar intensity value is at its maximum, the efficiency value is at its minimum. This means that the solar collector could not increase the air temperature to considerable values while in the initial and final drying time for lower value of solar intensity, the efficiency is more. In Fig. 5b, it is observed that the effectiveness factor is more than 1:00except for the last period of drying time. This indicates the high ability of the solar dryer for product drying as compared to that of the open sun drying method. In the initial times, the product in the solar dryer loses more moisture with respect to the open sun drying method which causes the effectiveness factor be less than 1:00at the last drying moments. In during the drying time, it is also considered that high value of the collector efficiency implicates the low value of effectiveness factor. The reason can relate to the influence of solar radiation intensity magnitude on the air enthalpy enhancement. High values of solar intensity lead to the high enhancement of air enthalpy, thereupon increasing the drying rate while the collector efficiency values decreases.

Evaluation of the Models: The dimensionless moisture content as a function of drying time was fitted with the presented models in Table. 1. Figs. 7a and 7b indicate the values of R^2 and RMSE of the drying models for indirect solar dryer and open sun drying, respectively. As shown in these figures, the Midilli and Kucuck model could describe the eggplant drying behavior with higher values

Table 2: Evaluated constants of models in the indirect forced convection solar dryer and open sun drying

Name of equation	Indirect solar dryer	Open sun drying
	Constants	
Newton	k=0.3291	k=0.2596
Page	k=0.2132	k=0.2469
	n=1.345	n=1.045
Henderson and pabis	a=1.0503	a=1.002
	k=0.3454	k=0.2602
Two term	a=11.27	a=1.056
	b=-10.27	b=-0.05402
	k_0=0.6008	k_0=0.2604
	k_1=0.6482	k_1=0.2637
Approximation of diffusion	a=1.049	a=-0.07338
	b=0.8701	b=0.694
	k=0.3269	k=0.3836
Logarithmic	a=1.194	a=1.005
	c=-0.1683	c=-0.06285
	k=0.2466	k=0.2283
Midilli and Kucuck	a=0.9978	a=0.9983
	b=-0.0020	b=-0.00937
	k=0.2149	k=0.2506
	n=1.313	n=0.9303
Verma *et al*.	a=15.17	a=1.599
	k=0.2099	k=0.3032
	g=0.2031	g=0.4019
Wang and singh	a= -0.2439	a= -0.2125
	b=0.01527	b=0.01288

of R^2 and lower values of RMSE with respect to other models in both the indirect solar dryer and open sun. The constants of models are obtained by Matlab software and are presented in Tables 2. The best models are shown in bold print in this table. It is observed the independence of the drying behavior from the drying method in this study. The same results have been recorded by [31] for drying of eggplant in a laboratory dryer.

CONCLUSIONS

In order to assess an indirect solar dryer performance, a kinetics study was performed on drying behavior of eggplant. The drying curves showed that the main part of drying process took place in the falling drying rate period. The collector raises the ambient temperature more than 45°C in the peak of the solar intensity at noon. Evaluation of the effectiveness factor and collector efficiency illustrated an inverse relationship between them in most of the drying process. According to performed mathematical modeling on the drying curves, the Midilli and Kucuck model could present drying behavior of product for both indirect solar drying and open sun drying methods. The effective moisture diffusivity of product calculated by slop method ranged between 4.26E-10 and 1.68E-09. The analysis of diffusivity indicates the following of it from solar intensity.

Nomenclature:

A	Surface area of the collector	m^2
C_a	Heat capacity of the air	$j.kg^{-1}.\ K^{-1}$
E	Activation energy	$j.mol^{-1}$
D_{eff}	Diffusivity	$m^2.s^{-1}$
DR	Drying rate	$g\ \ H_2o.g\ \ ds^{-1}.\ Hr^{-1}$
I_t	Solar radiation intensity	$W.m^{2-1}$
i	Numerator	
jm	Rate of mass transfer	$mol.s^{-1}$
L	Characteristic length	m
$\dot{m}_a$	Air mass flow rate	$kg.s^{-1}$
M_0	Initial moisture content	$g\ H_2o.g\ ds^{-1}$
M_e	Equilibrium moisture content	$g\ H_2o.g\ ds^{-1}$
MR	Dimensionless moisture content	
$\overline{MR}$	Mean dimensionless moisture content	
MR_{exp}	Experimentally observed dimensionless moisture content	
MR_{pre}	Predicted dimensionless moisture content	
M_t	Moisture content at t	$g\ H_2o.g\ ds^{-1}$
n	Number of Fourier series solution terms	
R	Gas constants	$j.mol^{-1}.K^{-1}$
RMSE	Root mean square error	
R^2	Coefficient of correlation	
$T_{c,in}$	Collector inlet temperature	K
$T_{c,out}$	Collector outlet temperature	K
t	Time	Hr
x	Direction coordinate	
Δt	Time interval (hour)	
η_e	Collector efficiency	%

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