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Thermal Performance Analysis For Three Different Geometric Shapes Of Greenhouse Type Solar Dryer

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ABSTRACT

An analytical study was carried out for evaluating and analyzing the thermal performance of three different geometrical shapes of green-house type solar dryers which can be used for date drying. The different shapes are, Quonset shape (SD1), gable-even-span (SD2) and pyramid shape (SD3). The three solar dryers was designed and installed at the Department of Agricultural Engineering, Faculty of Agriculture, Suez Canal University (latitude angle of 30.62°, longitude angle 32.27° and 5m above the sea level) during September 2015. The tested dryers were operated under three different air velocities of 0.5, 1, 1.5 m/s. The thermal performance analysis of the dryers was conducted based on the thermal balance equations. The obtained results revealed that, overall thermal efficiency for the three different solar dryers (SD1, 2 and 3) were (55.6, 52.2 and 51.1%), (62.04, 58.6 and 57.1%) and (50.6, 47.6 and 46.2%) at air velocity of 0.5, 1, 1.5 m/s, respectively. The predicted heat energy for the three solar driers was found to be very close with that measured during the experimental period. From the three different shapes, the study recommended that the Quonset shape (SD1) is the best shape solar dryer due to largest surface area which observed greatest amount of solar radiation, increased solar energy and drying air temperature.

Keywords: Solar greenhouse dryer - Thermal performance.

INTRODUCTION

Solar drying considered one of the most important applications of solar energy for agricultural products. The radiant energy from the sun can be used either to heat the ambient air in a solar air collector and utilize that air to dry the agricultural products or directly to heat the products through absorption of solar radiation (Joshi *et al.*, 2004). The geographical location of Egypt has a great amount of natural energy such as solar energy. The heated air by solar energy can be utilized for drying different agricultural products (Abdellatif and Helmy, 1993).

Solar drying process can be successfully employed for drying techniques. It has got several attractive features in which energy is available free of cost and can be harnessed in the site itself. Drying under controlled condition is also possible by this method which enhances the quality of the dried product. Solar drying systems must be designed in a proper way to meet particular drying requirements of different crops and to give satisfactory performance with respect to energy requirements.(Aravindh and Sreekumar, 2015).

The basses of available designs of solar dryers may be classified into several general categories, depending upon the mode of heating or the operational mode of heat derived from the solar radiation and the subsequent use of this heat to remove moisture from the wet product. Solar dryers are available in a range of designs which can be used for drying various agricultural products. In general various types of dryers are available to suit the requirements of farmers. They can be classified into several categories depending on design, working principles and type of product to be dried. (Aiswarya, 2015).

Studying the possibility of using solar energy for heating air inside a green-house and the use of that heated air in drying some agricultural crops under Egyptian climatic conditions has been investigated by many investigators (Radwan, 2002, Abu-Habaga *et al.*, 2010, Abdellatif *et al.*, 2010). However, there is no readily available enough information about the effect of different geometrical shapes of the green-house type solar dryers on solar energy collection and drying efficiency.

Abdellatif *et al.* (2010) analyzed the thermal performance of solar tunnel greenhouse solar dryer for drying seedless grapes. The obtained results revealed that, the daily average solar energy available outside the solar driers was 16.727 kWh of which mean that 12.572 kWh was available inside the dryer with an average effective transmittance of 75.16%. The daily average solar energy available inside the three studied solar tunnel dryers during the experimental work was 12.572 kWh of which 6.993, 7.699, and 6.687 kWh, respectively, converted into useful heat gain. The daily average overall thermal efficiencies of the three solar tunnel greenhouse driers during the experimental period were 55.62%, 61.24%, and 53.19%, consequently, 44.38%, 38.76%, and 46.81% of the solar energy available inside the solar driers was lost, respectively. Almuhanna (2012) tested and evaluated the possibility of using the solar greenhouse as a solar dryer for dates drying. He analyzed the thermal performance and thermal balance of the solar dryer. For the experimental work, a gable-even span greenhouse was used. The thermal performance analysis for the studied solar dryer was processed using the thermal balance equations. The results showed that the daily average solar energy available outside the solar dryers was 15.921 kWh, and it was12.335 kWh inside the solar dryer for an effective transmittance of 77.48%. It was also found that, out of 12.335 kWh solar energy available inside the solar dryer (7.414 kWh) was converted into useful heat gain. This heat gain could be used for the drying process of dates. Meanwhile, 3.947 kWh was lost by conduction and convection, and 0.686 kWh was lost by thermal radiation.

The main goal of the present work is to study the possibility of using the green-house type solar dryers for drying dates. The specific objectives included analysis of thermal performance of three different geometric shapes of the greenhouse type solar dryer operated under three different levels of air velocity. The evaluation basis included air temperature, overall thermal efficiency, and energy balance for each dryer.

MATERIALS AND METHODS

Three different geometric shapes of the greenhouse type solar dryers were designed, built and installed on the roof of the Agricultural Engineering Department at Suez Canal University (latitude angle of 30.62°, longitude angle 32.27° and 5m above the sea level). The gross surface area of each dryer was 2.0 m^2. The three shapes of the dryer were orientated in the East-West direction to maximize the intensity of the solar radiation. As shown in Fig.(1) the first geometrical shape of the greenhouse type solar dryer was established on an iron base with gross dimensions of 2.0 m long, 1.0 wide, and 0.9 m high. The second dryer was a gable-even-span established on an iron base with gross dimensions of 2.0 m long, 1.0 wide, and 0.9 m high. The third dryer was Pyramidal shape with square surface area of 1.14 m side length and it's side walls orientated and inclined with a tilt angle equal to the latitude angle of the location (30°N).

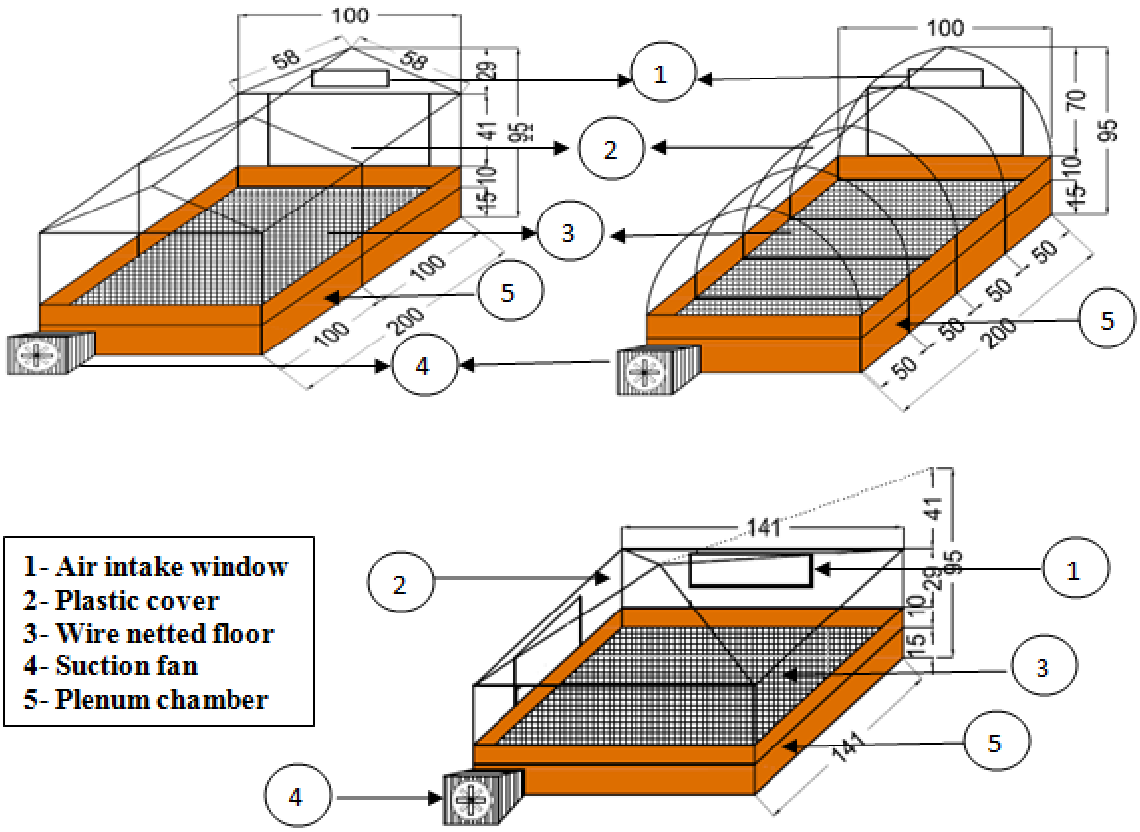

Fig. 1. Schematic diagram for the three different geometric shapes of the solar dryers.

The three different dryers were constructed of iron frame covered by single layer of polyethylene sheet with effective transmittance of 88.48% . Wire netting makes a drying floor was fixed at 15 cm above the bottom of the greenhouses forming a plenum chamber under the wire netted floor. Each solar dryer is equipped with a centrifugal fan driven by a 0.33 hp electric motor placed at one side of the dryer. It was controlled by vertical gate to maintain and provide the desired levels of air velocity. An open window with surface area of 0.053 m^2 was positioned at the top of the opposite side of a suction fan position for air intake through the dryer. The drying air was continuously introduced from the top position of the solar collector and leaves through the bottom position under the drying chamber via the suction fan as shown in Fig.(2). All dryers were operated at three different air velocity (0.5, 1,1.5 m/s) during the experimental work. The experimental work was run only through the period from 7 am to 5 pm, solar time.

Meteorological data

The meteorological data included the solar radiation flux incident on a horizontal surface (Pyranometer), dry-bulb, wet-bulb, and the relative humidity of the air (hygrometer) were obtained from the meteorological station (Vantage Pro 2, Davis, USA) which was located approximately 2.0 m above the solar dryers.

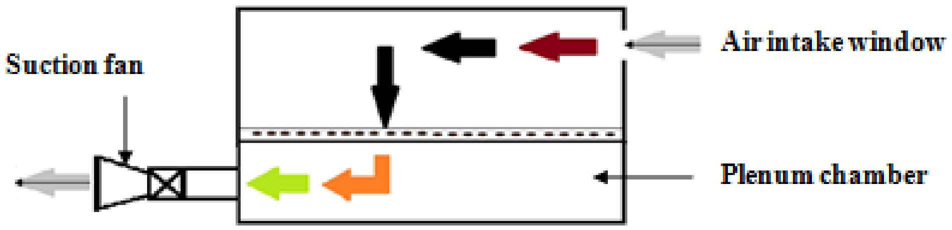

Fig. 2. Drying air movement through the dryers.

Measuring Equipments and Data Acquisition

Air temperatures inside the Solar dryers

Thermocouple sensors were fixed at different locations of each studied solar dryer to measure dry and wet bulb temperatures at different locations of each solar dryer. The thermocouples were connected to a data-logger system (Lab-Jack logger, powered by USB cable, supply 4-5.25 volt, USA) to display, and record the data during the experimental work. All the thermocouple sensors were calibrated with an electronic thermometer (-10 up to 100ºC). The output data were recorded every ten minutes.

Air velocity

The velocity of drying air was measured using vane type anemometer (model YK-80AM).

Mathematical Modeling

The studied greenhouse type solar dryers were operated under quasi steady-state conditions. In these circumstances, the thermal performance of each solar dryer is described by a thermal balance that shows the distribution of the incident solar energy into useful energy gain (Q_u), and thermal losses (Q_{loss}) as used by several investigators (Bargach *et al.*, 2000; Shanmugam and Natarajan, 2006; Hossain and Bala, 2007; Abdellatif *et al.*, 2010). The heat energy balance could be computed as follows

$$Q = Q_u + Q_{loss}, \quad \text{Watt} \qquad (1)$$

The solar energy available inside the dryer could be as follows :

$$Q = R\ A_d, \quad \text{Watt} \qquad (2)$$

where :

R = The solar radiation flux incident inside the solar dryer, W/m^2.

A_d = the net surface area of the drying chamber, m^2.

The useful heat gain by the dryer could be calculated as:

$$Q_u = m_a\ C_p\ (T_{ai} - T_{ao}), \quad \text{Watt} \qquad (3)$$

where:

m_a = The air flow rate, kg/s

C_P = The specific heat of the air, J/kg ºC

T_{ai} = The air temperature inside the dryer, ºC

T_{ao} = The outside air temperature, ºC.

The thermal efficiency (η_o), could be calculated using the following relationship :

$$\eta_0 = \frac{Q_u}{R\ A_d} \times 100, \quad \% \qquad (4)$$

The total heat losses from the dryer (Q_{loss}) to the outside could be calculated from the following formula:

$$Q_{loss} = q_c + q_e + q_r, \quad \text{Watt} \qquad (5)$$

The heat losses from the solar dryer by conduction and convection could be calculated from the following equation:

$$q_c = U_o\ A_c\ (T_{ai} - T_{ao}), \quad \text{Watt} \qquad (6)$$

Where :

U_o = The overall heat transfer coefficient, W/m^2 ºC.

A_c= The total surface area of the dryer plastic cover, m^2

T_{ai} = Air temperature inside the dryer, ºC

T_{ao} = Outside air temperature, ºC

The heat energy loss by forced air exchange (q_e) could be calculated as follows:

$$q_e = V\ \rho\ C_p\ (T_{ai} - T_{aex}), \quad \text{Watt} \qquad (7)$$

Where :

V = Rate of extracting fan discharge, m^3/s

ρ = Air density, kg/m^3

C_p = Specific heat of air at constant pressure, J/kg. °C

T_{ai} = The air temperature inside the solar dryer, ºC

T_{aex} = The air temperature leaving the solar dryer, °C

The heat energy loss by thermal radiation (q_r) could be computed as follows:

$$q_r = \varepsilon\ \tau\ \sigma\ A_d\ (T^4_{ai} - T^4_{sky}), \text{Watt} \qquad (8)$$

Where :

ε = The mean emittance factor of the during substances

τ = The transmissivity coefficient at long-wave radiation

σ = The Stefen-Boltzmann constant, W/m^2 K^4

A_d = Floor surface area of the solar dryer, m^2.

T_{sky} = Temperature of the sky, ºK

$$T_{sky} = 0.0552\ (T_{ao})^{1.5}, \quad °K \qquad (9)$$

A mathematical developed model based on the previous equations was used for computing the thermal performance analysis of the three shapes of solar dryers at different levels of air velocities. The equations were solved using a computer program written in MATLAB (MATrix LABortary, USA) to predict the heat energy available inside the solar dryers. Table (1) lists all inputs data required to run the program. The output data of the computer model (predicted) were then compared with the experimental data (measured). Simplified flow chart of the program is shown in Fig. (3).

Table 1. Input parameters for MATLAB program.

Configuration file input	Value of Quonset dryer	Value of gable even span dryer	Value of pyramidal dryer
Floor surface area of the solar dryer (A_d), m^2	2.00	2.00	2.00
Cover surface area of solar dryer (Ac), m^2	5.95	5.06	3.95
Specific heat of dry air, (C_p), J kg^{-1} °C^{-1}	1006.6	1006.6	1006.6
Overall heat transfer coefficient (U_o), W m^{-2} °C^{-1}	6.80	6.80	6.80
Transmissivity coefficient of long wave radiation	0.43	0.43	0.43
Stefan-Boltzmann constant (σ), W m^{-2} k^{-4}	5.67×10^{-8}	5.67×10^{-8}	5.67×10^{-8}
Mean emittance factor of the dryer cover (ε),	0.77	0.77	0.77

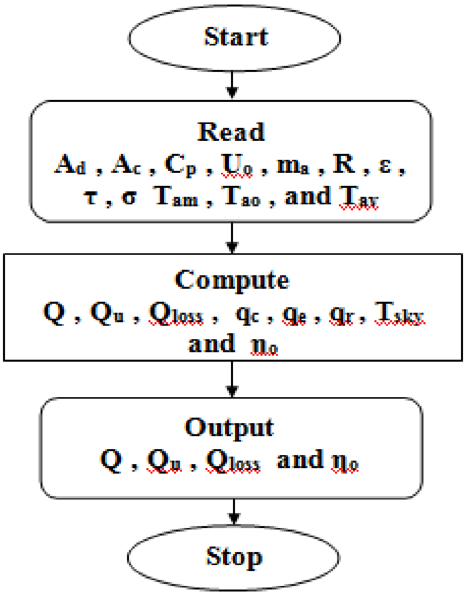

Fig. 3 .Simplified flowchart for MATLAB program.

RESULTS AND DISCUSSION

1. Solar Radiation Outside and Inside the Solar Dryers

The average hourly solar radiation outside and inside studied the solar dryer (SD1) was 554.7 and 490.8 W/m^2, respectively. While it was 484.4 and 428.6 W/m^2 for the solar dryer (SD2) and 471.1 and 416.8 W/m^2 for the solar dryer (SD3), respectively. Fig.(4) shows the measured solar energy flux incident outside and inside the solar dryers (SD1, SD2 and SD3) at air velocity of 1m/s. The hourly average solar energy flux incident outside and inside the dryers varied from hour to hour due to the effect of atmospheric conditions, the variation in solar altitude angle from early morning to late afternoon and the solar incident angle.

2. Solar Energy Available Inside the Solar Dryers

The daily average solar energy available inside the solar dryers (SD1, SD2, SD3) were (13.776, 12.425 and 12.425 kWh), (13.512, 12.265 and 12.265 kWh) and (13.334, 12.014 and 12.014 kWh) at air velocity of (0.5, 1, 1.5 m/s), respectively. There were obvious differences in the solar energy available inside the dryers which can be attributed to the effect of different geometrical shapes of the dryers on solar energy collection. It can be observed that the highest value of solar energy available was achieved with the Quonset shape (SD1) solar dryer due to the largest surface area of this shape which exposed to the solar radiation. This condition increased the solar energy available and thus, the drying air temperature.

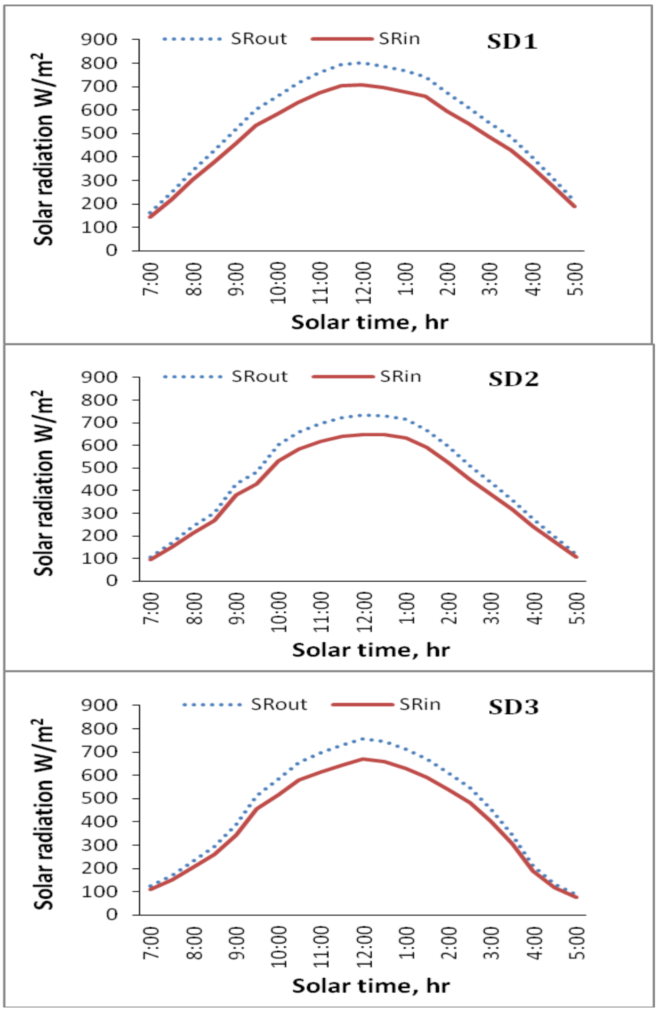

Fig. 4. Average hourly solar radiation flux incident outside and inside the studied solar dryers at air velocity of 1m/s.

3. Air Temperature and Relative Humidity Outside and Inside the Dryers

The hourly average air temperature inside the three studied shapes of solar dryers (SD1, 2 and 3) were 56.8, 52.7 and 50.4 °C at the minimum air velocity of 0.5 m/sec respectively. While, the ambient air temperature was 31.4°C. However, as shown in Fig.(5) at air velocity of 1 m/sec, the hourly average air temperature were 50.1, 45.8 and 44.1°C for the three different solar dryers, respectively, when the ambient air temperature was 30.7° C. The corresponded values at the maximum air velocity of 1.5 m/sec were 44.7, 41.5 and 40.3°C, respectively at 30.8°C ambient air temperature.

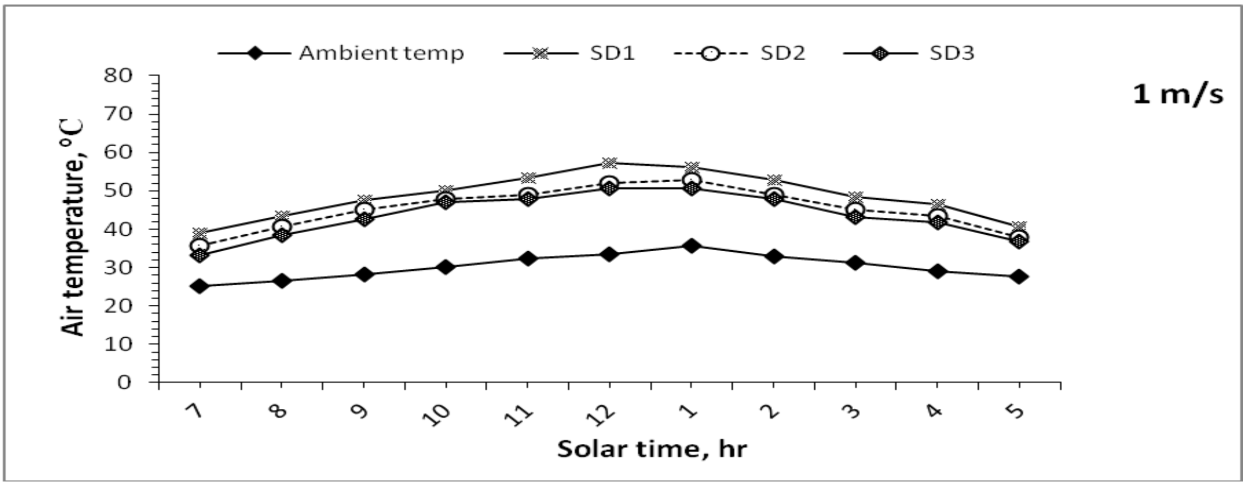

Fig. 5. Air temperatures outside and inside the three studied solar dryers at air velocity of 1 m/s.

At the same time, the hourly average air relative humidity outside the three studied dryers during operating the solar dryers at the minimum air velocity of 0.5m/sec was 48.2 %, while the hourly average air relative humidity inside the three dryers (SD1, 2 and 3) were 23.21%, 26.80% and 28.58%, respectively. Also at air velocity of 1 m/sec, the daily average air relative humidity outside the three solar dryers was 51.4% while the average air relative humidity inside the dryers (SD1, 2 and 3) were 29.42%, 31.06% and 33.26%, respectively as shown in Fig.(6). However, at the maximum air velocity of 1.5 m/sec, the daily average air relative humidity outside the dryers was 52.13% while the average air relative humidity inside the three dryers (SD1, 2 and 3) were 31.9%, 34.17% and 34.38%, respectively. Consequently, the three different solar dryers reduced the air relative humidity on an average of 22.40%, 19.91% and 18.50%, respectively.

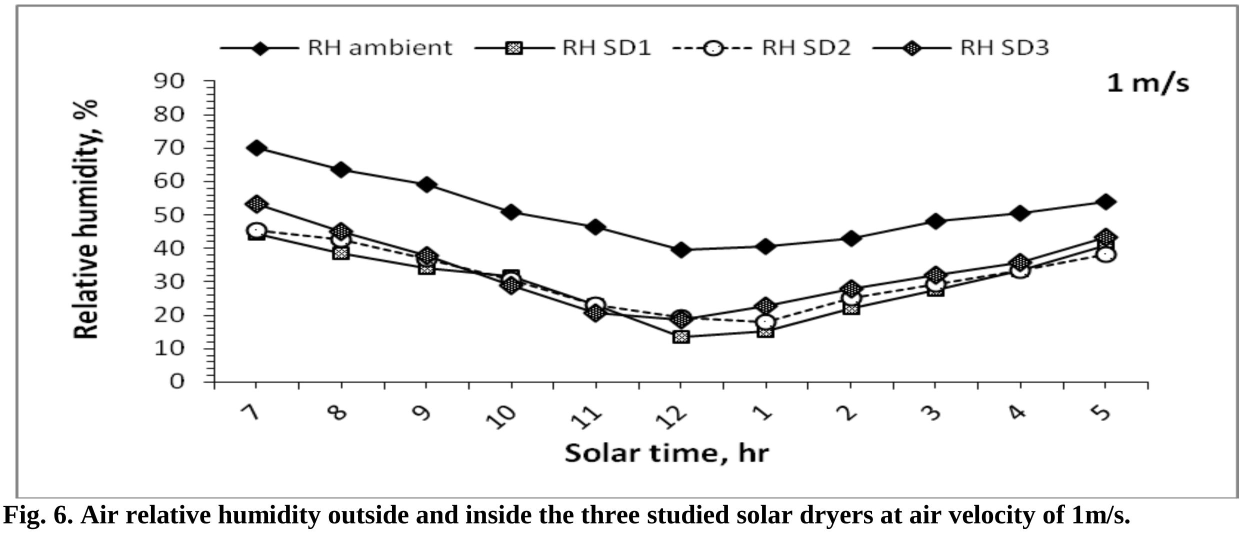

Fig. 6. Air relative humidity outside and inside the three studied solar dryers at air velocity of 1m/s.

4. Useful Heat Gain of the Solar Dryers

The daily average useful heat gain for the three solar dryers (SD1, 2 and 3) at minimum air velocity of 0.5m/sec were 7.656, 6.488 and 5.946 kWh, respectively. While, at air velocity of 1 m/sec, they were 8.383, 7.195 and 6.466 kWh, respectively, and they were 6.746, 5.726 and 5.173 kWh at the maximum air velocity of 1.5 m/sec, respectively. These differences in useful heat gain could be attributed to the effect of different geometric shapes of the three dryers, the variation in the mass flow rate of air and the air temperature difference between inside and outside the dryers.

5. Total Heat Losses from the Solar Dryers

The daily average total heat losses from the three different solar dryers at three different levels of air velocity (0.5, 1, 1.5 m/s) are summarized and listed in Table (2). It can be observed that, there were obvious differences in daily average total heat losses for the three solar dryers (SD1, 2 and 3) at the same velocity of air. This results could be attributed to the effect of different geometric shapes of the dryers on temperature difference between inside and outside the solar dryer of each shape.

Table 2. The daily average total heat losses and the overall thermal efficiency for the three studied solar dryers .

Parameter	Air velocity	SD1	SD2	SD3
	0.5 m/s	3.129	3.156	3.014
Heat losses by conduction and convection	1 m/s	2.231	2.344	2.186
	1.5 m/s	2.083	2.158	1.976
	0.5 m/s	1.630	1.619	1.579
Heat losses by air exchange	1 m/s	2.041	2.004	1.985
	1.5 m/s	3.683	3.435	3.410
	0.5 m/s	1.361	1.162	1.092
Heat losses by thermal radiation	1 m/s	0.856	0.722	0.687
	1.5 m/s	0.822	0.694	0.638
	0.5 m/s	55.6 %	52.2 %	51.1 %
Overall thermal efficiency	1 m/s	62.04 %	58.6 %	57.1 %
	1.5 m/s	50.6 %	47.6 %	46.2 %

6. Thermal Efficiency of the Studied Dryers

As shown in Table (2) the highest thermal efficiency was 62.04 % for the solar dryer (SD1) at air velocity of 1 m/s, consequently, 37.96% of the solar energy available inside the dryer was lost. While the lowest thermal efficiency was 46.16 % for the solar dryer (SD3) at air velocity of 1.5 m/s, consequently, 53.84 % of the solar energy available inside the solar dryer was lost.

7. Heat Energy Balance for the Solar Dryers

The heat energy balance was affected by useful heat gain, differences in air temperature inside and outside the dryer, ambient air temperature and heat energy losses. The predicted heat energy gained and lost and the measured heat energy available inside the dryers at different levels of air velocity were functioned in the regression analysis .For instance Fig.(7) present the predicted heat energy available versus that measured inside the three different solar dryers at air velocity of 1 m/s. In general, an excellent agreement could be obtained for the predicted heat energy available inside the dryers and that measured during the experimental period.

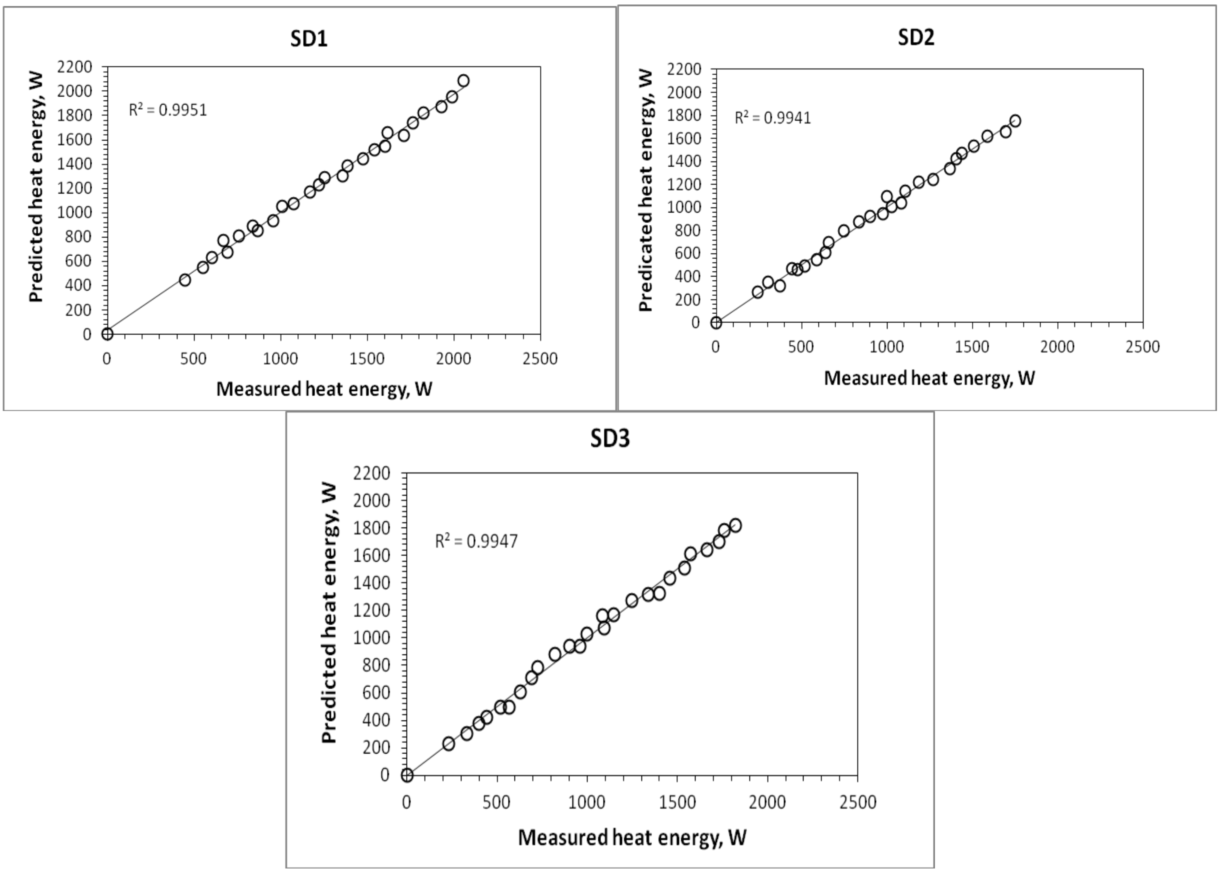

Fig. 7. Measured and predicted heat energy available inside the three different solar dryers at air velocity of 1m/s.

CONCLUSION

The primary objective of the present study is to estimate the ability of different shapes of greenhouse type solar dryer in converting the solar radiation into useful heat gain and investigate the effective uses of that heat gain in increase the drying efficiency. For the duration of this research work the solar energy available was considered as the most important parameter affecting thermal performance of the three different shapes of the greenhouse type solar dryers. The heat energy available and the useful heat gain were found to be affected mainly by the different geometric shapes of the dryers and the variation in air velocity. The overall thermal efficiency for the three different solar dryers (SD1, 2 and 3) were (55.6, 52.2 and 51.1%), (62.04, 58.6 and 57.1%) and (50.6, 47.6 and 46.2%) at air velocity of 0.5, 1, 1.5 m/s, respectively. The predicted heat energy for the three solar driers was found to be very close with that measured during the experimental period.

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تحليل الاداء الحرارى لثلاثة أشكال هندسية مختلفة للبيوت المحمية المستخدمة كمجففات شمسية

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يتناول البحث اجراء دراسة تحليلية لتقييم وتحليل الاداء الحرارى لثلاث اشكال هندسية مختلفة للبيوت المحمية المستخدمة كمجففات شمسية وامكانية استغلالها كمجففات شمسية للبلح. الاشكال الهندسية موضوع الدراسة هى الشكل النصف اسطوانى والشكل الجمالونى والشكل الهرمى. وتم اجراء التجارب بقسم الهندسة الزراعية, كلية الزراعة, جامعة قناه السويس (خط عرض 30.62°, خط طول 32.27 ° وارتفاع عن سطح البحر 5 سم) خلال سبتمبر 2015. تم تشغيل المجففات الثلاثة تحت ثلاث سرعات مختلفة من هواء التجفيف هى 0.5 - 1 - 1.5 م/ث. اعتمد تقييم الأداء الحرارى للمجففات الشمسية على معادلات إتزان الطاقة داخل المجفف. أظهرت النتائج المتحصل عليها ان متوسط الكفاءة الحرارية للمجففات الشمسية الثلاثة (SD1,SD2 and SD3) عند سرعة هواء 0.5 م/ث حوالى 55.6% , 52.2 % , 51.1 %على التوالى وعند سرعة هواء 1 م/ث حوالى 62.04 % , 58.6 %, 57.1 % على التوالى بينما عند سرعة هواء 1.5 م/ث حوالى 50.6 , 47.6 ,46.2% على التوالى. اتزان الطاقة الحرارية للمجففات الشمسية اوضحت ان الطاقة الحرارية المتوقعة للمجففات الثلاثة كانت متوافقة جيدا مع تلك التى تم قياسها خلال فترة التجربة. وذلك لزيادة كمية الطاقة الشمسية المتاحة داخل المجفف (SD1) توصى النتائج باستخدام المجفف نتيجة كبر المساحة السطحية المعرضة للاشعة الشمسية وبالتالى ارتفاع درجة حرارة الهواء داخل المجفف.