THERMAL PERFORMANCE TEST OF EVACUATED TUBE AND FLAT PLATE SOLAR COLLECTORS UNDER CLIMATIC CONDITIONS OF EGYPT

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ABSTRACT

The main objective of the present study is to evaluate the thermal performance of two different solar collectors; evacuated tube collector (ETC) and flat plate (FPC) operated by thermo-siphon phenomenon. This study carried out on the roof of Agriculture faculty, Tanta University (latitude angle of 30.5ºN, longitude angle of 30.6ºE). FPC and ETC are tested using two different tilt angles (30.5° and 45.3°) and stationary non-tracking. The obtained results revealed that the tilt angle was the most important parameter affection solar collector's thermal performance. The data also showed that, the solar energy available and absorbed solar energy for the FPC were higher than the ETC. Meanwhile, the useful heat gain to storage and overall thermal efficiency for the ETC were higher than that for the FPC. The maximum overall thermal efficiency for the two solar collectors (ETC and FPC), respectively, were 77% and 71.3% which achieved at noon with tilt angle of 45.3° during March month. The difference in thermal performance between the two solar collectors can be attributed almost completely to the absorption efficiency and its effect on overall thermal efficiency. In general, the overall thermal efficiency with 45.3° tilt angle gave was higher values than that with 30.5° tilt angle during winter months due to the solar altitude angle.

INTRODUCTION

Solar water heater is the most widely used for different agricultural and industrial applications. Solar water heating (SWH) system is a special kind of heat exchanger that transforms solar radiant into heat energy. In the solar collector, energy transfer is from a distant source of radiant energy to an operating fluid. There are three common types of solar collectors used in SWH systems; flat plate solar collectors (FPC), evacuated tube solar collectors (ETC) and compound parabolic collectors (CPC).

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FPC and ETC are the most widely deployed solar collectors for small-scale water heating applications. Both collectors convert beam (direct) and diffuse (in-direct) solar radiation into heat. There are many parameters that affect solar water heater thermal performance. Tilt angle and orientation are considered as an important parameters affecting, not only the thermal performance but also the heat energy acquired **(Abdellatif et al., 2009)**.

For stationary non-tracking solar collector, the optimum tilt angle is equal to the latitude angle of the location minus the solar declination angle **(Duffie and Beckman, 2006)**. While, **Kalogirou (2003)** mentioned that the optimum tilt angle for the stationary non-tracking solar collector is equal to the latitude angle of the location with an angle variations of 10º to 15º more or less depending on the application and the time of the year. **Xiaoww and Ben . (2005)** stated that solar water heaters are the most popular means of solar energy utilization because of technological feasibility, good reliability and economic attraction compared with other kinds of solar energy utilization. Solar water heater technology has been well developed and can be easily implemented at low cost. Utilization of solar energy through SHW systems plays a big role in the quantity of conventional energy required. Solar water heaters have significant potential to reduce environmental pollution arising from the use of fossil fuels **(Kalogirou., 2004; Gunerhan and Hepbasli, 2007).**

Glazed flat plate collectors usually present a metal absorber in a flat rectangular housing. The glass cover on the upper surface and the insulation on other side limit the thermal losses. The solar energy absorbed by the black plate is transferred to the working fluid. The tubes are in good thermal contact with absorber surface. Air is present in the space between the plate absorber and transparent cover. In comparison, evacuated tube solar collectors allow to reduce the convection and the conduction thermal losses. This collector consists of glass vacuum- sealed tubes, the absorber surface is located into the inner glass tube and it can have several shapes. The choice of the optimal solar collector depends on the temperature level required by the specific application and the climatic conditions of the site of installation. Therefore, in terms of thermal efficiency, each solar collector displays features, which make it most suitable to a certain applications.

Abdellatif et al. (2009) tested four similar solar water heaters to determine the optimum tilt angle, orientation and their thermal efficiencies. The first solar water heater was continuously orientated and inclined with an optimum direction and tilt angle in order to track the sun's rays once each half an hour from sunrise to sunset. The second solar heater was continuously orientated and inclined with one tilt angle (optimum at noon). The third solar water heater was continuously orientated and inclined with one tilt angle equal the site latitude angle (31.045ºN). The last solar water heater was stationary non-tracking with an optimum tilt angle at noon. The overall thermal efficiencies values, respectively, were 72.83%, 65.85%, 61.60 and 55.98% for these solar water heaters. A comparative study between evacuated tube and flat plate solar water heaters was conducted by **Budihardjo and Morrison (2009)**. They showed that, the thermal performance of a typical 30 tube evacuated tube array was lower than a typical 2 panels flat plate array for domestic water heating in Sydney. Solar water heating systems for domestic and industrial applications were divided into two broad categories (passive and active), each of them operating in either direct or indirect mode **(Ogueke et al., 2009)**. The active systems generally have higher thermal efficiencies (35 – 80%) than those of the passive systems.

Ayompe et al. (2011) carried out thermal performance tests of the FPC and ETC; daily, monthly and annually basis and found that the annual average solar collector thermal efficiencies were 46.1% and 60.7% but the whole system thermal efficiencies were 37.9% and 50.3% respectively. **Pluta (2011)** reported that the poor solar radiation transmissivity of their cylindrical glass of evacuated tubes envelopes causes much smaller values of solar energy to be accumulated in certain ranges of radiation incidence angles compared with the energy obtained by flat plate collectors working in the same conditions. He also added that the overall coefficient of heat loss for flat plate collectors is usually in the range of 3.9 – 5.5 W/m^2 K and for evacuated tube solar collectors in the range of 1.5- 2.5 W/m^2 K. **Tang et al. (2011)** studied the thermal performance of water-in-glass evacuated tube solar water heaters with different solar collector tilt angles. They conducted the experiment at two different angles 22º and 46º. There was no significant variation in daily thermal efficiency. Outlet water temperature of the solar collector of water-in-glass evacuated tube domestic hot water system with natural circulation is generally more than the flat plate collector system. For flat plate collectors it is essential that the inclination of the collectors should be based on the latitude of that place for better performance **(Kasaein et al., 2014)**. Nevertheless, for evacuated tube solar collectors, there is no proof that the performance will be best for particular angle of inclination **(Selvakumar and Somasundaram, 2012)**. **Dabara (2013)** compared between two different tilt angles of 30º and 45º. The experimental results revealed that tilt angle had significant influence on the thermal performance of the evacuated tube solar collector along with reflector. Experiments also showed that, the thermal efficiency with 30º tilt angle evacuated tube solar collector with reflector (79.5%) was higher than that with 45º tilt angle (68.4%) under Indian conditions. **Ogie et al. (2013),** designed and constructed a solar water heater based on thermo-siphon principle and operated it under Nigerian conditions. The water gets heated and flows into a storage tank through thermo-siphon principle. Maximum fluid output temperature, collector temperature, and insolation obtained on a sunny day were 55ºC, 51ºC and 1480 W/m^2, respectively.

From the previous review, this study aims to (1) compare the thermal performance of two different solar collectors FPC and ETC under climatic conditions of middle-delta zone during winter season of 2014-2015, (2) Choose the best solar collector for utilizing in different agricultural applications.

MATERILAS AND METHODS

Two different thermosyphon solar collectors; flat plate solar collector and evacuated tube solar collector were functioned during this experimental work. The two solar collectors are situated on the roof of the Faculty of Agriculture, Tanta University (latitude angle of 30.5ºN, longitude angle of 30.6ºE) as demonstrated in **Fig. (1)**. Each solar collector having a net surface area of 1.5 m^2. The experimental work was concluded during winter season of 2014-2015 (December 2014, January, February and March 2015).

Flat plate collector (FPC)

It consists of six components (collector casing, absorber plate, copper pipes, insulator, glass cover and storage tank). The FPC casing was rectangular in shape (1.5 m long , 1 m wide, and 0.1 m deep) made of aluminum bar 25 mm thick. The absorber plate was formed of an aluminium slab 2.0 mm thick and painted with clear thermax^{TM} as a selective coating material in order to absorb the maximum amount of solar energy available. Copper pipes (7 pipes) 12.7 mm in diameter were arranged at an equidistance of 12 cm and attached well to the upper surface of the absorber plate using ties each 10 cm throughout the length of each pipe. They were also painted with selective coating material. A 40 mm and 20 mm thick layer of insulation material (polyurethane with 45 kg/m^3 density, and thermal conductivity of 0.038 W/m ºC) located at the back and sides of FPC, respectively. The storage tank is situated at a level above the top of FPC in thermosyphon system (150 liters) as shown in **Fig. (2)**. The flat plate solar collector is mounted on a movable steel frame to adjust the tilt angles with 30.5º and 45.3º.

Evacuated tube collector (ETC)

Evacuated tube solar collector is consists of 20 evacuated tubes made of borosilicate glass, 180 cm long using to provide hot water in a 150 liters horizontal storage as shown in **Fig.(3)**. Evacuated tube is composed of two coaxial borosilicate glass tubes jointed at the top and sealed at the bottom which contain a vacuum, the outer of 58 mm diameter and the inner 47 mm diameter as shown in Fig.(4). Hot water in the tube moves by natural convection (thermal buoyancy forces) upward to be replaced by colder water. The hot water gained will be accumulated in the storage tank. The evacuated tube solar collector is also mounted on a movable steel frame to adjust the tilt angles at 30.5° and 45.3°. The storage tank is equipped with an electrical heater to provide hot water at desired level for different applications when the intensity of solar radiation is insufficient to provide that level. Each tube of evacuated solar collector contains 2.6 liters of water. The thickness of inner and outer tubes, respectively, is 47 and 58 mm. The inner tube contains the water to be heated and its exterior is coated with a suitably dark absorbing material (nitrite aluminum) for collecting the maximum possible incident solar radiation which converting into heat and transferring to working fluid (water). The space between the outer and inner tube is being evacuated and using as a thermal insulator to reduce convection and conduction heat losses. Thus, the thermal trapping (greenhouse effect phenomena) continuously occurring due to the solar energy available inside the tube.

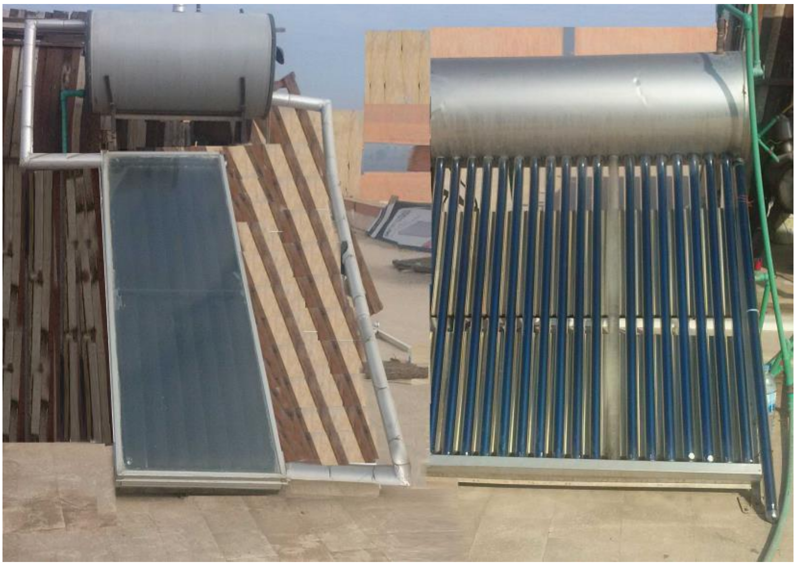
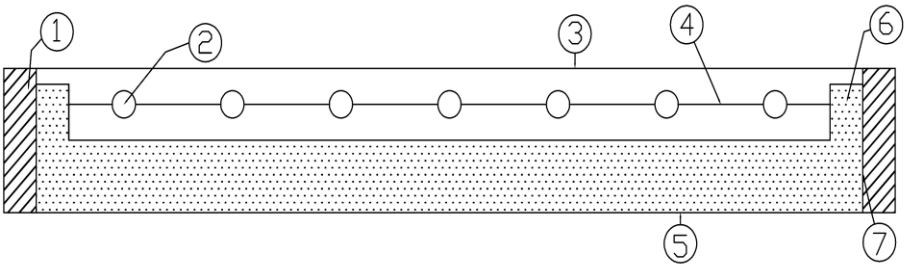


Fig. (1): Two different solar collectors, flat plate and evacuated tube.



Flat plate collector			
No.	part name	No.	part name
1	Anodized aluminum frame	5	Galvanized steel
2	Copper riser	6	Polyurethane
3	Tembered glass	7	EPDM rubber
4	Copper fins welded to riser		

Fig .(2): Schematic diagram of flat-plate solar collector.

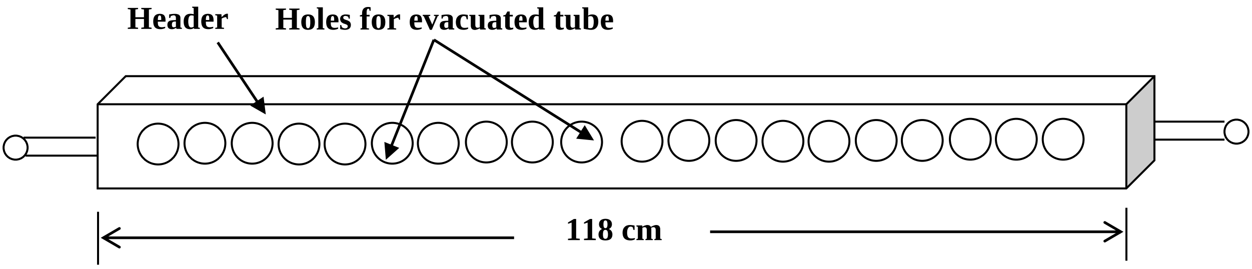


Fig. (3): Schematic diagram of evacuated tube header collector

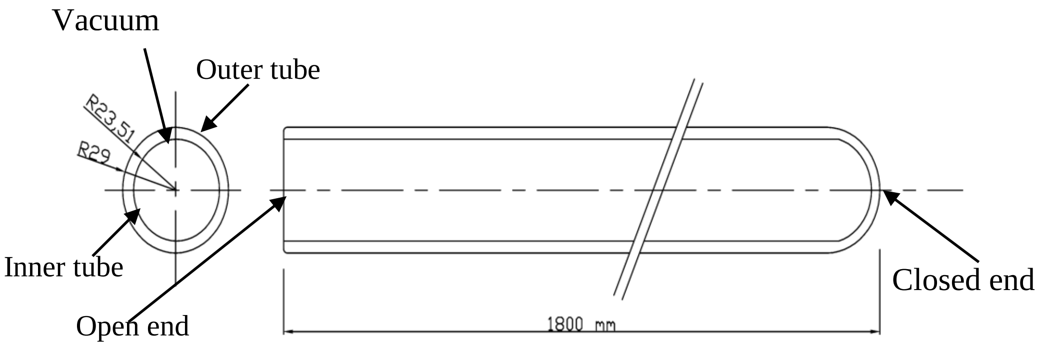


Fig. (4): Schematic diagram of cross-section of one ended evacuated tube.

Tilt angle (β)

Two different tilt angles were during the experimental period 30.5 and 45.3° with horizontal plane. The two solar collectors were orientated to south direction and stationary non-tracking (fixed at noon). A 30.5° tilt angle equal to the latitude angle of the experiment place. A 45.3° was selected based on an average of optimum tilt angles during winter months as shown in Table (1).

Table (1): Optimum tilt angles during the winter months.

Month	December	January	February	March	Average
Tilt angle (β_o)	53.5°	51.4°	43.5°	32.9°	45.3°

The previous optimums tilt angles were calculated for the stationary non-tracking solar collector, using the following equation **(Duffie and Beckman, 2006)**:

$$\beta_o = \Phi - \delta, \quad \text{degree} \quad \ldots\ldots\ldots\ldots\ldots\ldots \text{(1)}$$

Where, Φ, is the latitude angle in degree and, δ, is the declination angle in degree.

Instruments

Two thermocouples were functioned to measure the inlet and outlet water temperatures of each collector. These sensors were connected to a data logger system to display and record the obtained data throughout the experimental work. A digital solar power meter (TENMARS, TM-207) was used to measure the solar radiation flux incident on the surface of each solar collector at 30.5 and 45.3° tilt angles. The specifications of the solar power meter are; accuracy: typically within ± 10 W/m^2 or ± 5%, additional temperature induced error ± 0.38 $W/m^2/°C$, resolution: 1 W/m^2 and range 1999 W/m^2.

The parameters that affect the thermal performance of the solar collector and their relationships between them were studied and examined by **Duffie and Beckman (2006)**. The solar energy available (Q) could be calculated as a function of solar radiation flux incident (R) and solar heater surface area (A_c) as follows:

$$Q = R \; A_c, \quad \text{Watt} \qquad \text{.......... (2)}$$

The absorbed solar radiation (Q_a) could be computed in terms of the solar energy available (Q) and the optical efficiency (τ α) as follows:

$$Q_a = Q \, (\tau \, \alpha), \quad \text{Watt} \qquad \text{.......... (3)}$$

The absorption efficiency (η_a) could be determined as follows:

$$\eta_a = (Q_a / Q) \times 100, \; \%. \qquad \text{.......... (4)}$$

The useful heat gain to storage (Q_c) could be estimated as a function of the mass flow rate of working fluid (C_p), and the potential difference between outlet (T_{fo}) and inlet (T_{fi}) water temperatures as follows:

$$Q_c = m \, C_p \, (T_{fo} - T_{fi}), \quad \text{Watt} \qquad \text{.......... (5)}$$

Duffie and Beckman (2006) suggested the following formula for calculating the heat energy acquired by the working fluid based on the solar collector heat removal factor (F_R), overall heat transfer coefficient (U_o), and mean temperature of the working fluid passing inside the solar (T_m):

$$Q_c = Ac \, F_R \, [R - U_o \, (T_m - T_a)], \quad \text{Watt} \qquad \text{.......... (6)}$$

The heat transfer efficiency (η_h) could be calculated as follows:

$$\eta_h = (Q_c / Q_a) \times 100, \quad \% \qquad \text{.......... (7)}$$

The overall thermal efficiency (η_o) is generally considered as an instantaneous efficiency because it is a function of operating conditions including local climatic parameters such as the intensity of solar radiation, ambient air temperature, and wind speed. Therefore, the overall thermal efficiency can be estimated from the following equation **Hayek (2011)**:

$$\eta_o = (Q_c / Q) \times 100, \quad \% \quad \ldots\ldots (8)$$

The "normalized temperature rise" (DT) could be estimated in terms of the temperature difference between the inlet water (T_{fi}) and the ambient air temperature (T_a), and the solar radiation flux incident as follows:

$$DT = (T_{fi} - T_a)/ R, \quad °C\ m^2/W \quad \ldots\ldots (9)$$

The solar energy stored in the storage tank (Q_s) could be computed as a function of mass of water in the storage tank per unit time (m_s), specific heat of water (C_p), and the temperature difference between mean tank temperature at sunset time (T_{k2}) and at sunrise time (T_{k1}) as follows:

$$Q_s = m_s\, C_p\, (T_{k2} - T_{k1}), \quad Watt \quad \ldots\ldots (10)$$

The storage system efficiency (η_s) can be found as follows:

$$\eta_s = (Q_s/Q_c) \times 100, \% \quad \ldots\ldots (11)$$

The two solar collectors (FPC and ETC) are summarized and listed in **Table (2).**

Table (2): Specification of the two solar collector

Parameters	FPC	ETC
Effective transmittance, τ	0.90	0.91
Effective absorptance, α	0.95	0.90
Optical efficiency (α τ)	0.885	0.819
Overall heat transfer coefficient, U_o	3.5 $W/m^2\ K$	1.7 $W/m^2\ K$
Net solar collector surface area, A_c	1.5 m^2	1.5 m^2

Results and discussion

The solar radiation flux incident on the tilted surface of the solar collector is an important factor uses to analyze the thermal performance of solar collectors. Therefore, the solar radiation flux incident was measured during the experimental period. **Figs (5) and (6)** show the measured irradiation values flux incident on the tilted solar collectors using two different tilt angles (30.5 and 45.3°) during winter months. They reveal that, the highest value of solar radiation flux incident on solar collectors at 30.5° tilt angle was achieved during March month. While, the highest value of solar radiation flux incident on solar collectors with 45.3° tilt angle was achieved during February month as compared with the other months. The previous obtained data occurred due to the solar collector inclined by an angles of 30.5 and 45.3º were closest to the optimum tilt angles for March (32.9º) and February months (43.5º).

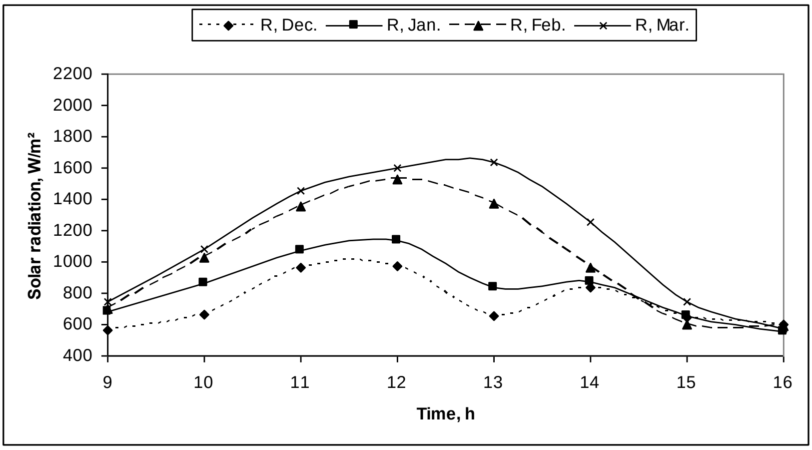


Fig. (5): Solar radiation flux incident on the solar collector with tilt angle of 30.5º during the experimental period.

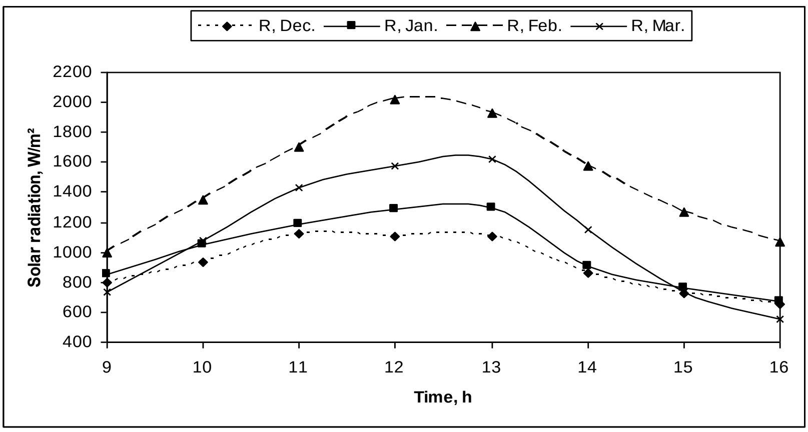


Fig. (6): Solar radiation flux incident on the solar collector with tilt angle of 45.3º during the experimental period.

In addition, the lowest value of solar radiation flux incident on the solar collectors tilted with both tilt angles (30.5 and 45.3º) occurred during December month because of these two tilt angles were lower than the optimum tilt angle for December (53.5º) by 23 and 8.2º, respectively. Therefore, the daily average solar radiation flux incident on the solar collectors (from 9:00 to 16:00 h) at tilt angle of 30.5° during the experimental period (from December to March), respectively, was 5.913, 6.689, 8.144 and 9.095 kW/m^2. Whilst, the daily average solar radiation flux incident on the solar collectors during the same time and period with tilt angle of 45.3° was 7.301, 8.017, 11.899 and 8.888 kW/m^2, respectively.

The solar radiation flux incident from sunrise to sunset throughout the experimental period varied from hour to hour and day to another during the experimental period due to variations in the portion of the three components of solar radiation (beam, diffuse and reflected). This portion of the three components was strongly affected by the tilt angle of the solar collectors as it greatly affecting the angle factor between the solar collectors and the sky, and the angle factor between the solar collectors and the ground. The variation in solar radiation flux incident from sunrise to sunset was also affected by the solar altitude angle during the experimental period. The thermal performance analysis for the two solar collectors with tilt angle of 30.5º during the experimental period was computed and listed in **Table (3)**. It evidently reveals that, the solar energy available during the experimental period for the two solar collectors (FPC and ETC) was 11.190 kWh due to the two collectors were at the same orientation and tilt angle (30.5º) under the same climatic conditions, there was no difference in the solar energy available between the two solar collectors. Under clear sky conditions, the solar energy available (Q), absorbed solar energy (Q_a), useful heat gain to storage (Q_c), and solar energy stored in the storage tank increased gradually with solar time from sunrise to sunset till they attained the maximum values at noon. They then declined until reached the minimum values prior to sunset. The thermal performance analysis of the solar collectors is mainly measuring by their overall thermal efficiency in converting solar radiation into solar thermal energy storage.

Table (3): The daily average solar energy available (Q), absorbed solar energy (Q_a), useful heat gain to storage (Q_c), overall thermal efficiency (η_o) solar energy stored (Q_s) and storage system efficiency (η_s) with tilt angle of 30.5° for the two solar collectors during the experimental period.

Month	Q, kWh/day	Q_a, kWh/day		Q_c, kWh/day		η_o, %		Q_s, kWh/day		η_s, %	
		FPC	ETC	FPC	ETC	FPC	ETC	FPC	ETC	FPC	ETC
Dec.	8.869	7.583	7.264	3.612	5.402	40.73	60.91	2.081	3.658	57.61	67.72
Jan.	10.033	8.578	8.217	4.552	6.267	45.37	62.46	2.773	4.450	60.92	71.01
Feb.	12.216	10.444	10.004	7.277	8.220	59.60	67.29	4.752	6.009	65.30	73.10
March	13.642	11.664	11.173	8.912	9.677	65.33	70.94	6.550	7.277	73.50	75.20
Total	**44.760**	**38.269**	**36.658**	**24.353**	**29.566**	**-**	**-**	**16.156**	**29.550**	**-**	**-**
Mean	**11.190**	**9.567**	**9.165**	**6.088**	**7.392**	**52.76**	**65.40**	**4.039**	**7.388**	**64.33**	**71.76**

They were obvious differences in solar energy available for the days recorded during the heating period. These differences in solar energy available can be attributed to the effect of the atmospheric conditions during the heating period and change in the solar altitude angles from month to another. The two solar collectors absorbed different amount of solar energy because they had various optical efficiency ($\tau\alpha$), which is the product of effective transmittance of the thermal clear glass cover and effective absorptance of the selective black absorber plate. The optical efficiency for the two solar collectors (FPC and ETC), respectively, was 0.885 and 0.819. Therefore, the daily average absorbed solar energy by the two solar collectors during the heating period from December to March was 9.567 and 9.165 kWh, respectively. The previous obtained data evidently showed that, the absorbed solar energy depends upon the optical efficiency of the solar collector. These two factors depend strongly on the angle of solar incidence.

The daily averages absorbed solar energy converted into useful heat gain to storage depends strongly upon the heat removal factor. Heat removal factor depends on three important parameters; the solar collector flow factor, the collector efficiency factor, and the temperatures difference between the operating fluid and the absorber plate. The daily averages absorbed solar energy converted into useful heat gain to storage during the heating season for the two solar collectors, respectively, were 6.088 and 7.392 kWh. Useful heat gain to storage varied from hour to hour, day to another and during the heating period due to the variations in working fluid temperature, ambient air temperature surrounding the solar collectors, and solar energy available. Mathematical analysis of the measured data showed that, during early and prior to sunset when the available solar radiation was less than 250 Watt and at the same times, the ambient air temperature was less than the operating fluid, little useful heat energy was acquired when the water passing through the solar collectors.

The difference between the absorbed solar energy and the useful heat gain to storage is the actual solar collector heat losses **(Duffie and Beckman, 2006).** The daily average heat energy lost from the two solar collectors during the heating period was 4.780 and 1.773 kWh, respectively. The obtained data evidently showed that, the highest heat energy losses from the two solar collectors (FPC and ETC) during the heating period (5.481 and 1.950 kWh, respectively) occurred during January month, due to the average ambient air temperature surrounding the solar collectors was lowered to 18.2ºC and otherwise, the heat energy stored in the storage tank was not consumed at nighttimes for any applications resulting in increasing the inlet water temperature (40.5ºC) during daylight-time next day. For the duration of heating season, the heat losses from the two solar collectors varied from day to day and month to another according to the operating fluid temperature and ambient air temperature.

The overall thermal efficiency is the ratio of the useful heat energy gained by the operating fluid (water) leaving the solar panels to the solar energy available. The daily averages overall thermal efficiency of the two solar collectors during the heating period from December to March, respectively, were 52.76% and 65.40%, consequently, 47.24%, 34.60%, of the solar energy available was lost**.** Heat transfer efficiency depends on the operating temperature of the absorber surface and the working fluid temperature. As the working fluid temperature increased, firstly; the operating temperature of the absorber surface increased above the ambient air temperature and heat energy losses are thus increased, secondly; the difference in temperature between the absorber surface and the working fluid is reduced, making the heat transfer less efficient. Due to the overall thermal efficiency of the two solar collectors is a combination of optical efficiency and heat removal factor; if one or both efficiencies increased the overall thermal efficiency is increased and solar collector thermal efficiency is thus increased. These data are in agreement with the data published by **ASHRAE (2005); and Duffie and Beckman (2006)**. The daily averages solar energy stored in the storage tank during the heating period from December 2014 to March 2015 were 4.039 and 7.388 kWh, which gave an average storage system efficiency of 64.33%, and 71.76%, respectively. The solar energy stored in the storage tank varied from day to day, month to another and during the heating season due to the effects of ambient air temperature, operating fluid temperature, wind speed, and solar energy available.

The thermal performance analysis for the two solar collectors with tilt angle of 45.3º during the experimental period was computed and listed in **Table (4)**. It evidently reveals that, the solar energy available during the heating period for the two solar collectors (FPC and ETC) was 13.039 kWh due to the two collectors were at the same orientation and tilt angle (45.3º) under the same climatic conditions, there was no difference in the solar energy available between the two solar collectors. The daily average solar radiation available on the top surface of the two solar collectors inclined with tilt angle of 45.3º was greater than that available with tilt angle of 30.5º by 16.52%. The daily average absorbed solar energy by the two solar collectors during the heating period from December to March was 11.076 and 10.588 kWh, respectively. The previous obtained data evidently showed that, the absorbed solar energy depends upon the optical efficiency of the solar collector. These two factors depend strongly on the angle of solar incidence which affected by the tilt angle of the solar collector. Therefore, the tilt angle of 45.3º increased the absorbed solar energy for both solar collectors by an average 15.65%. The daily averages absorbed solar energy converted into useful heat gain to storage during the experimental period for the two solar collectors, respectively, were 8.321 and 9.536 kWh. Useful heat gain to storage varied from hour to hour, day to another and during the heating period due to the variations in working fluid temperature, ambient air temperature surrounding the solar collectors, and solar energy available as mentioned previously. The useful heat gain to storage for the two solar collectors inclined with 45.3º tilt angle increased by an average 32.84% as compared with that value acquired with tilt angle of 30.5º.

For the duration of heating season, the heat losses from the two solar collectors varied from day to day and month to another according to the operating fluid temperature and ambient air temperature. The daily average heat energy lost from the two solar collectors during the heating period was 3.635 and 1.053 kWh, respectively. The daily average heat losses from the two solar collectors inclined with tilt angle of 45.3º was lower than that lost with tilt angle of 30.5º by 26.01%. The daily averages overall thermal efficiency of the two solar collectors during the heating period from December to March, respectively, were 62.53% and 72.63%, consequently, 37.47%, 27.37%, of the solar energy available was lost**.** Using tilt angle of 45.3º instead of 30.5º led to increase the overall thermal efficiency by 8.57%. The daily average solar energy stored in the storage tank during the experimental period from December 2014 to March 2015 was 6.143 and 7.495 kWh, which gave an average storage system efficiency of 72.81% and 77.99%, respectively. The solar energy stored in the storage tank varied from day to day, month to another and during the heating season due to the effects of ambient air temperature, working fluid temperature, wind speed, and solar energy available as mentioned previously. The solar energy stored in the storage tank for the two solar collectors inclined with 45.3º tilt angle increased by an average 26.77% as compared with that value stored with tilt angle of 30.5º.

Table (4): The daily average solar energy available (Q) , absorbed solar energy (Q_a), useful heat gain to storage (Q_c), overall thermal efficiency (η_o) solar energy stored (Q_s) and storage system efficiency (η_s) with tilt angle of 45.3° for both solar collectors.

Month	Q, kWh/day	Q_a, kWh/day		Q_c, kWh/day		η_o, %		Q_s, kWh/day		η_s, %	
		FPC	ETC	FPC	ETC	FPC	ETC	FPC	ETC	FPC	ETC
Dec.	10.951	9.363	8.969	5.486	7.415	50.10	67.71	3.697	5.355	67.39	72.22
Jan.	12.025	10.281	9.848	6.710	8.512	55.80	70.76	4.745	6.650	70.72	78.13
Feb.	15.848	13.260	12.617	11.725	12.255	73.98	77.33	8.899	10.042	75.90	81.94
March	13.332	11.398	10.918	9.362	9.960	70.22	74.71	7.230	7.934	77.23	79.66
Total	**52.156**	**44.302**	**42.352**	**33.283**	**38.142**	**-**	**-**	**24.571**	**29.981**	**-**	**-**
Mean	**13.039**	**11.076**	**10.588**	**8.321**	**9.536**	**62.53**	**72.63**	**6.143**	**7.495**	**72.81**	**77.99**

The overall thermal efficiencies (η_o) for the two solar collectors and two tilt angles are plotted against "normalized temperature rise" (DT) as shown in **Fig.(7)**. Regression analysis revealed a high significant linear relationship (r = 0.9993; P ≤ 0.001) between these parameters. The regression equations for the best fit were:

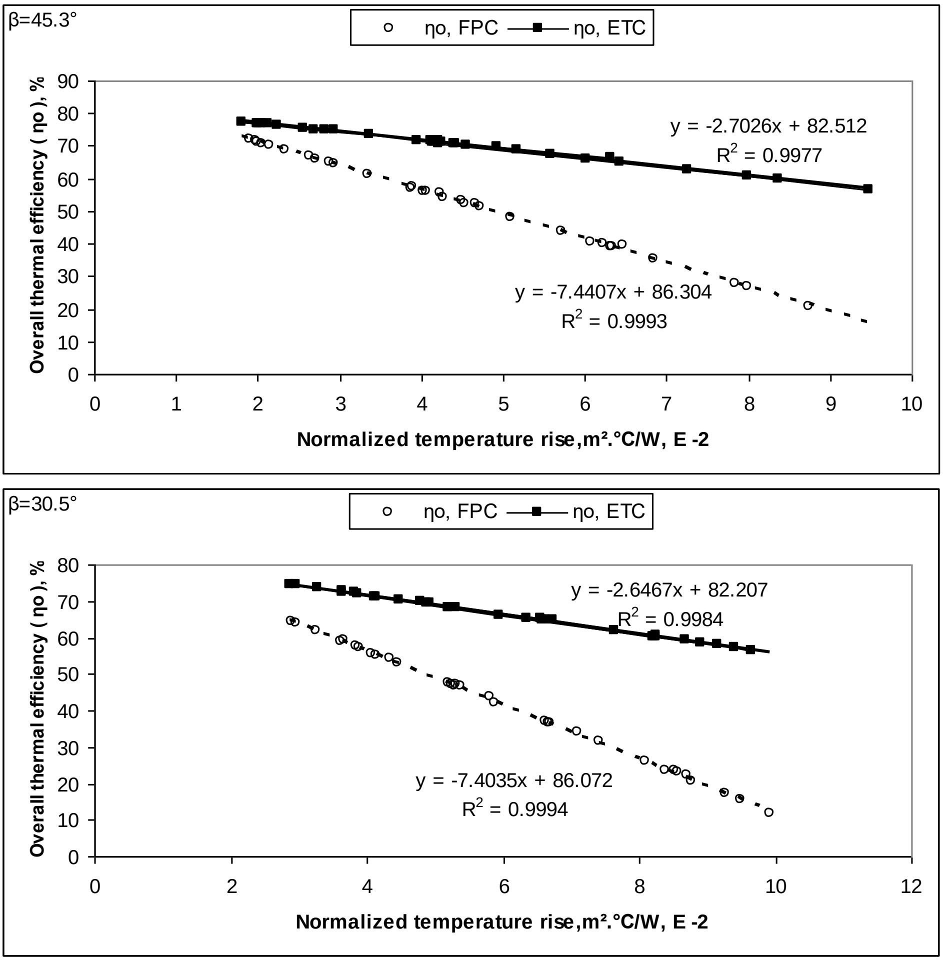


Fig. (7): Overall thermal efficiency against "normalized temperature rise" with two different tilt angles (30.5 and 45.3°) during the experimental period from December 2014 to March 2015.

With 30.5 °, tilt angle:

$$\eta_o\,(FPC) = 86.072 - 7.4035\,D_T \qquad R^2 = 0.9994 \qquad (12)$$

$$\eta_o\,(ETC) = 82.207 - 2.6467\,D_T \qquad R^2 = 0.9984 \qquad (13)$$

With 45.3 °, tilt angle

$$\eta_o\,(FPC) = 86.304 - 7.44070\,D_T \qquad R^2 = 0.9994 \qquad (14)$$

$$\eta_o\,(ETC) = 82.512 - 2.70267\,D_T \qquad R^2 = 0.9984 \qquad (15)$$

The regression analysis also clarified that, the overall thermal efficiency of the solar water heaters could be expressed as:

$$\eta_o = \frac{Q_c}{Q} = F_R\,(\tau\alpha) - U_o\,F_R\left[\frac{T_{fi} - T_{ao}}{R}\right] \quad (16)$$

$$\eta_o = F_R\,(\tau\,\alpha) - U_o\,F_R\,(DT) \quad (17)$$

$$\eta_o = a - U_o\,F_R\,(DT) \quad (18)$$

Regression equations are definitely the numerical expression of Equation (18). The Y-intercept (a) is equal to the product of the heat removal factor (F_R), and optical efficiency ($\tau\alpha$). The slope is equal to the product of the heat removal factor and overall heat transfer coefficient (U_o). The plot of overall thermal efficiency (η_o) versus normalized temperature rise (D_T) was straight line with Y-intercept F_R ($\tau\alpha$) and slope (- $F_R U_o$). It is clear that (U_o) is a function of temperatures difference between absorber plate and ambient air surrounding the solar collectors and wind speed. Some variations of the relative proportions of direct, diffuse, and ground-reflected components of solar radiation occurred. Thus scatter in some data were to be expected, because of temperature dependence and wind effects. In addition, the heat removal factor (F_R) is a weak function of U_o.

CONCLUSION

The obtained data of this experimental work can be summarized and concluded as follows:

(1) The solar radiation flux incident on tilted surface varied with tilt angle of the two solar collectors during the winter months.

(2) The solar collector tilt angle had a significant effect on the thermal performance included; absorbed solar energy, useful heat gain to storage, overall thermal efficiency, and solar energy stored in the storage tank. For the duration of the experimental period, the tilt angle of 45.3° gave thermal performance greater than that with the tilt angle of 30.5°.

(3) The daily average overall thermal efficiencies for the two solar collectors (ETC and FPC) during the heating period was 62.53% and 72.76%, respectively, which achieved with a tilt angle of 45.3º

(4) Thermal performance analysis of the evacuated tube solar collector (ETC) revealed that, this type of solar water heating system has a good reliability and economic characteristics as compared with the flat plate collector for most of solar energy applications in different agricultural fields.

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الملخص العربي

اختبار الأداء الحراري للمجمع الشمسي المفرغ والمسطح تحت الظروف المناخية في مصر

محمد رمضان*

تعتبر المجمعات الشمسية هي الوسيلة المثلي لتحويل الطاقة الشمسية إلي طاقة حرارية من خلال تسخين الموائع التي تمر خلال المجمعات طبقا لظاهرة البيوت المحمية والتي تسبب الاحتباس الحراري مؤدية إلي تسخين الموائع التي تمر بداخلها.

وتوجد أنواع عديدة من المجمعات الشمسية ومنها : المجمع الشمسي المفرغ والمجمع الشمسي المسطح والمجمع الشمسي المركز.

ونظرا لأن كلا المجمعين الشمسيين المفرغ والمسطح يجمعان أنواع الاشعاع الشمسي الثلاثة (المباشر، المشتت و المنعكس) فيكثر استخدامهم في التطبيقات الهندسية المختلفة.

لذا كان الهدف من الدراسة مقارنة الأداء الحراري لكلا المجمعين تحت ظروف الشتاء في مصر وكذلك اختيار أفضلهما في التطبيقات المختلفة استنادا لتحليل الأداء الحراري لكل منهما

أجريت الدراسة بين المجمع الشمسي المفرغ والمجمع الشمسي المسطح اللذان يعملان بالحمل الطبيعي تحت ظروف فصل الشتاء ٢٠١٤ ، ٢٠١٥ م (ديسمبر ، يناير، فبراير، مارس) وذلك فوق سطح كلية الزراعة – جامعة طنطا .

وكانت مساحة كلا من المجمعين المستخدمين ١,٥ م^{٢} وحجم الخزان بكل منهما ١٥٠ لتر . وقد تم استخدام زاويتي ميل وهما 30.5° (مساوية لخط عرض مكان إقامة التجربة) و 45.3° (مساوية لمتوسط زاوية الميل المثلي في أشهر الشتاء).

وكانت أهم النتائج المتحصل عليها هي :

١- اختلفت قيم الاشعاع الشمسي الساقط علي المجمعين الشمسيين بإختلاف زاوية الميل خلال أشهر الشتاء .

٢- كان لزوايا الميل أكبر الأثر علي الأداء الحراري للمجمعات الشمسية خلال التجربة خاصة : الطاقة الشمسية الممتصة ، الطاقة الشمسية المكتسبة والتي يستفاد بها للتخزين، الكفاءة الحرارية الكلية، الطاقة الشمسية المخزنة . وخلال فترة التجربة أعطت الزاوية 45.3° كزاوية ميل افضل نتائج في الأداء الحراري للمجمعات الشمسية مقارنة بزاوية الميل 30.5° خلال كل أشهر التجربة.

٣- المتوسط اليومي للكفاءة الحرارية لكلا المجمعين الشمسيين (المفرغ والمسطح) أثناء فترة التسخين كانت ٦٢,٥٣ % و ٧٢,٧٦ % - علي التوالي – عند استخدام زاوية ميل ٤٥,٣° لكلا المجمعين.

٤- التحليل الحراري للمجمع الشمسي المفرغ أظهر أن استخدام مثل هذا النوع في النظم الشمسية لتسخين الماء هو أكثر معولية وأفضل اقتصاديا إذا ما قورن بالمجمع الشمسي المسطح وذلك إذا ما استخدم في معظم تطبيقات الطاقة الشمسية في مختلف المجالات الزراعية .

*** مدرس الهندسة الزراعية – كلية الزراعة – جامعة طنطا**