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Experimental Investigation of Solar Thermal Collector on the Open Parabolic Trough

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Abstract: Experimental study of solar heat transfer in a Parabolic Trough Solar Collector (PTSC) recording to the Iraq weather conditions in Ad Diwaniyah city (32°N, 45°E). Different parameters used included varying the flow rate, focal length to test their effects on the performance of the collector. Three rates of water flow were used (2, 2.5 and 3 L/min). Results showed that; the performance of the collector increases when the mass flow rate increases. Furthermore, when the flow rate increased from 2-3 L/min, the useful heat gain and efficiency of the collector increased by 29 and 28%, respectively. It also, can be seen the performance of the collector decreases as the focal length increase. Two different methods have been used to increase the energy obtained from the solar collector. The first method by using of secondary reflectors and the second method by using of fins. Two configurations of secondary reflectors were used named as flat reflector and curved reflector. By using the first method, the efficiency of the collector increasing from 34.7-40.8% while it increasing from 35.5-38.44% when the second method used.

Key words: PTSC, solar collector, parabolic trough, collector thermal efficiency, secondary reflectors, energy obtained

INTRODUCTION

The planet is exposed to environmental pollution due to the emission of carbon dioxide and other gases that led to global warming, increase the temperature of the atmosphere, the fall of acid rain, melting of snow and the erosion of arable land and the lack of rain from other areas, leading to desertification. Furthermore, our world is facing an ongoing economic crisis due to high-energy prices and increasing of demands because they are associated with fossil or conventional fuels (oil, gas and coal). For that, solar energy is one of the most important sources of renewable and clean energy which the world depends heavily in recent years on it for treating the energy problem. These renewable and sustainable energies are available in all parts of the world and they are clean and non-polluting energies. Recently, it has great importance and attention by the scientists because of the development of technologies that produced (Pearson *et al*., 2012).

Thermal energy can be produced from the sun by using solar thermal concentrators. As a result of multiple purposes, solar thermal concentrators can be divided into three types: low concentration concentrates, medium concentrates concentration and high concentration concentrates (O'Neill *et al*. 2002). High concentration solar concentrators used convex lenses or mirrors to focus the sun and produce high temperatures. Flat reflective surfaces cannot produce temperatures above 250•C while lenses and convex mirrors have been developed to produce temperatures greater than 1000•C. It used to evaporate water and operate steam boilers to generate electricity (Karp and Ford, 2010; Karp *et al*., 2010).

The most important design used to focus the sunrays is the parabolic trough Fig. 1 where convex mirror surfaces are used to reflect sunlight on glass surfaces containing tubes filled with special fluids that fill the entire size of the parabolic trough (Salomoni *et al*., 2010).

Now a days the most prevalent solar system for electricity production or steam generation for industrial processes is the parabolic trough technology. Thus, in

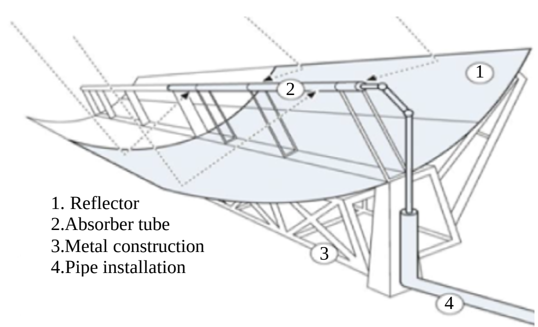

Fig. 1: Parabolic trough solar thermal collector

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this field many researches have been working and trying new ideas to optimizing the existing collectors (De Risi *et al*., 2013; Cheng *et al*., 2015).

In 1913, the English Engineer F. Shuman and the American C.V. Boys built a 45 kW (50 Hp) pumping plant (solar engine) for watering plantations in Meadi, Egypt. This plant used trough collectors to collect the solar energy and produced steam which is used to drive the pumps. The length of the parabolic trough collectors were 62 m and width of 4 m with 1.200 m^2 total aperture area. The maximum mass flow rate of the plant was 27.000 L/min of water. This plant was shut down in 1915 due to World War I, (Kryza, 2003). In the 1960s, attention returned to the solar concentrator again. Lof (1962) developed a technique for a concentration solar collector's optimization design through a detailed study of the energy balances. The collector was a parabolic-cylindrical reflector with receivers as a tube of different diameters. The result of this study shows that when increased the size of the receiver, the thermal losses and the intercept factor increased too. Edward and Cherng (1976) studies theoretically the effect of target geometry on the maximum concentration. The result shows that for the same aperture value, the elliptic cylindrical target and flat plate will obtain a maximum concentration as the optimum target.

Jeter *et al*. (1983) studied the effects of geometric, especially end-effect on the performance of PTSC. The result shows that when short troughs are considered the significance of end-effects particularly increases and for obtaining test results, it is necessary to eliminate this effect . Odeh *et al*. (1998) conducted a study to analysis the performance of PTSC with two types of working fluids (synthetic oil and water). Depending on the absorber wall temperature, formulations for efficiency of PTSC have been developed to prognosticate the performance of the system with any working fluid (Geyer *et al*., 2002). "A group of researcher from many European countries" improved a new design of PTSC called (Euro trough) through the cost reduced and development of a generation of solar concentrators. Two types of concentrates called (100 and ET 150) were designed, manufactured and developed to benefit in the production of steam used in solar thermal electric power generation.

A new PTSC for hot water production improved by Valan and Somakumar (2006). The difference between outlet water temperature in the collector and the temperature of the water storage tank is 37. George and Jabal (2016) Conducted a study aimed to develop Rabl mathematical model of Compound Parabolic Collector (CPC) using cylindrical receiver rather than the flat receiver. The reflection of direct and indirect solar radiation falling on the CPC was simulated. The result showed that the efficiency of CPC is reduced by increasing the receiver radius and by increasing its length at the same inlet temperature of the working fluid. Also, showed that at the same conditions, the efficiency of CPC with cylindrical receiver is higher than collector with flat receiver.

In this study, a parabolic trough solar collector was designed, manufactured and tested under the local weather conditions. The main purpose of this study is the parametric investigation of the effects of flow rate, focal length, secondary reflectors and absorber fin on collector thermal efficiency at different levels of solar insolation for the climatic conditions of AD Diwaniyah City, Al-Qadisiyah, Iraq.

PTSC design: In PTSC consist of a parabolic cross sectional shape concentrator and a receiver located along the focal line of the parabola. The trough focuses the sun rays on a small area (receiver) through which a flowing fluid (water) absorbs the heat that transmitted through the receiver wall. The cross section of the trough is shown in Fig. 2. In Cartesian coordinates, the simple parabolic Eq. 1 is:

$$x^2 = 4Py \quad (1)$$

The focal length, P is related to rim angle • and aperture width, s as (Riveros and Oliva 1986):

$$s = 4P\tan\left[\frac{\varphi}{2}\right] \quad (2)$$

The height of the parabola is given by:

$$l = \frac{s^2}{16P} \quad (3)$$

The aperture A_{ap} area is calculated as:

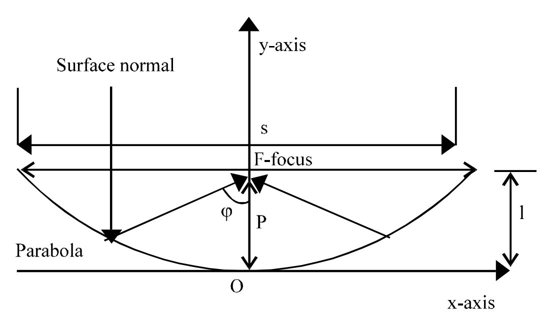

Fig. 2: The cross section of the trough

Table 1: The geometrical data of the parabolic trough collector

Items	Sample	Values
Length	Z	1 m
Width	s	0.75 m
Rim angle	•	102°
Focal length	P	15 cm
Height	i	23 cm
Concentration ratio	C_r	36
Length of the parabolic arc	w	91cm
Absorber tube length	L	3 m
Tube outer diameter	d_o	0.937 cm

$$A_{ap} = s \times z \quad (4)$$

where, z: is the collector length. The length of the parabolic arc (w) can be calculated from:

$$w = \left[\frac{s}{2}\sqrt{\left(\frac{4l}{s}\right)^2 + 1}\right] + 2P\,\text{In}\left[\frac{4l}{s} + \sqrt{\left(\frac{4l}{s}\right)^2 + 1}\right] \quad (5)$$

Geometrical concentration ratio cr is defined as "the ratio of the collector aperture area A_{ap}*| to the receiver aperture area" A_r:

$$C_r = \frac{A_{ap}}{A_r} \quad (6)$$

The geometrical data of the parabolic trough are given in Table 1.

MATERIALS AND METHODS

Experimental setup: The test apparatus was manufactured at the Department of Mechanical Engineering, University of Al-Qadisiyah and tested under the weather conditions of AD Diwaniyah City (32°N, 45°E) which is one of the provinces of the Middle Euphrates in Iraq.

The collector is opened, fixed (South-North axis), so that, the direct beam radiation reflected to the absorber without tracking system. The test rig consists of three main parts: parabolic trough (which reflects sunlight), receiver (which absorbs solar energy) and metallic base.

Parabolic trough: Which is consists of two parts: supporting structure and the reflector.

Supporting structure: Square cross section metal tubes are folded using a rolling machine to form the supporting structure which carries the reflector surface in order to support and stabilize it.

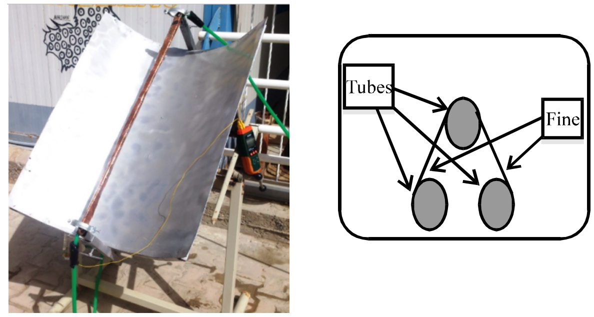

Fig. 3: a) The photograph of test rig and b) Cross section of receiver

The reflector: A steel plate of thickness 1 mm is folded to take shape of the supporting structure. In order to increase the reflectivity, the steel plate is covered with aluminum sheet.

Receiver: The receiver was from unshielded multi-pass type. A copper tube with a diameter 0.937 cm was used.

Metallic base: Made of iron bars to carry the weight of the solar collector, slope or tilt angle (• can be changed and modified simply by a lever. The photograph of test rig is shown in Fig. 3.

During the experiment test, the inlet and outlet water temperature of the absorber tube as well as the ambient temperature and the water flow rate and the solar radiation are measured continuously. The tests were carried during February and March 2018.The useful heat absorbed by the water can be calculated from:

$$Q = \dot{m}c_p\,(T_o - T_i) \quad (7)$$

The source of heat is the solar energy and the input power is usually the solar radiation, I, reflected by the surface of the trough to the receiver. This energy absorbed and then transferred to the working fluid. The overall efficiency can be defined as:

$$\eta = \frac{mc_p * (T_o - T_i)}{A_{ap} I} \quad (8)$$

RESULTS AND DISCUSSION

The effect of collector water flow rate: An experimental work was carried out by passing water through the collector at different flow rates (2, 2.5 and 3 L/min) during 4-6th of March 2018. The inlet water temperature is relatively constant (varies slightly ±1°C) during the test

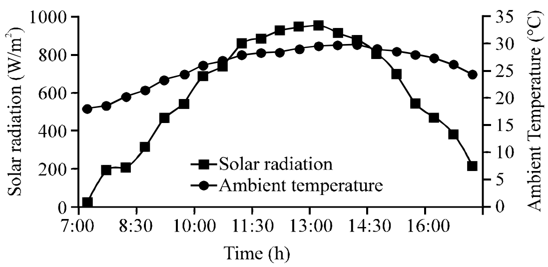

Fig. 4: Values for solar radiation and ambient temperature (1 March 2018)

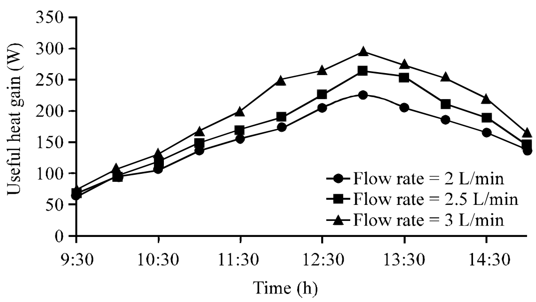

Fig. 5: The variation of collector heat gains with time at a different mass flow rate

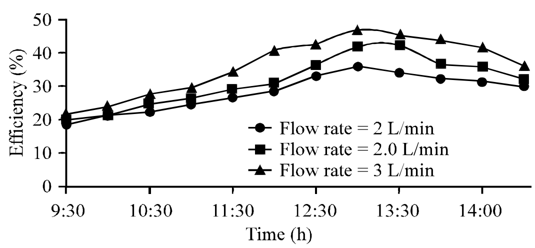

Fig. 6: The variation of collector efficiency with time at different mass flow rate

time. Tilt angle (•) have been selected to be equal to 35° to collect maximum solar heat during the experimental test (Sultan *et al.*, 2012). The environmental measured data has been taken for several days. Figure 4 illustrate the solar irradiance and the ambient temperature for a present day. The ambient temperature rises as the solar radiation rises and the maximum values indicated after solar noon and then it decreases gradually. Figure 5-7 shows the variation of collector heat gain with time at different mass flow rate. From Fig. 5, it can be observed that the heat gain of the collector increase as the solar radiation increases until it reaches a maximum value around noon (01:00 pm) and then decrease slowly afternoon due to decrease in solar radiation. At constant flow rate; the thermal efficiency increases with the increases of solar radiation as shown in Fig. 6. It is clearly

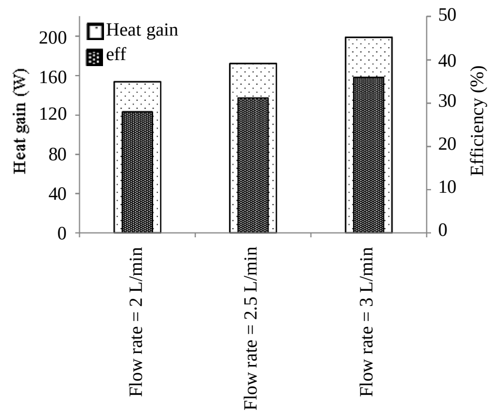

Fig. 7: The effect of mass flow rate on the performance of the collector

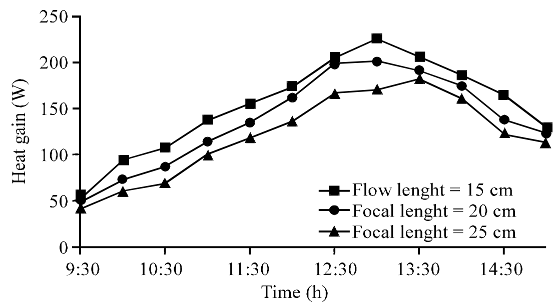

Fig. 8: The variation of collector heat gains with time at a different focal length

can be seen that when the flow rate increase, the heat gain increases. For the high flow rate ($\dot{m}$ = 3 L/min) the heat gain (Q_{gain}) becomes equal to 198.78 W while Q_{gain} 153.71W when $\dot{m}$ = 2 L/min. Figure 7 presented to show the effects of mass flow rate on the performance of the collector. It is indicated the higher efficiency corresponds to high flow rate case which has lower outlet temperature due to remove as much as possible of heat from the collector.

The effect of focal length: To study the effect of focal length on the performance of the solar collector three different length have been used (P = 15, 20 and 25 cm). Figure 8 and 9 shows that the collected heat gain and efficiency of the collector decreased with increased the focal length. This happened due to the decreasing in the concentrated sunray reaching the absorber tube. For constant flow rate of water (2 L/min), the heat gain and the efficiency decreases from 152.3 W and 26.8% to 119.6 W and 20.95% when the focal length increase from 15-25 cm, respectively. The optimum focal length of this collector have been selected to be equal to 15 cm.

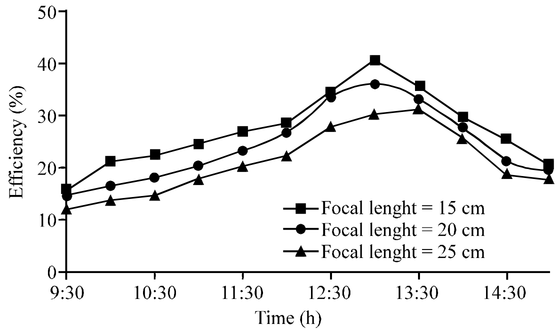

Fig. 9: The variation of collector efficiency with time at different focal length

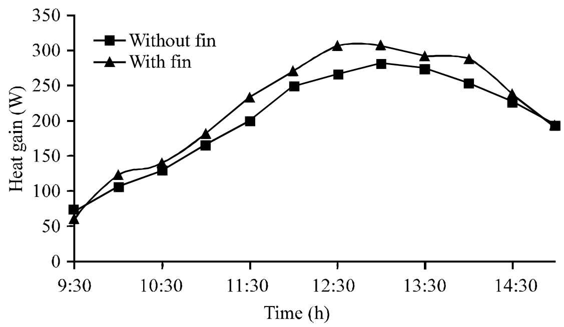

Fig. 10: The variation of collector heat gains with time when fins are used

The effect of fin addition: A large amount of solar radiation escapes through the receiver tube to the space therefore, fins added between the tubes to increase the heat gain. The cross-section of the receiver is shown in Fig. 3b.

Figure 10 show the effect of fin on the performance of the collector for constant water flow rate. It found that; the outlet water temperature increase due to adding fins to the absorber tube because of increasing surface area to collect solar irradiation energy. The heat gain and the efficiency are increased from 200.62 W and 35.5% to 218.55 W and 38.44% when fins are used.

Effect of secondary reflectors: Secondary reflectors have been used to increase the efficiency of the solar collector. The secondary reflectors are attached over the receiver to reflect the concentrated solar rays again on the absorber tube. Two configurations of secondary reflectors made from a polished aluminum were used named; flat reflector and curved reflector.

The heat gained and thermal efficiency of the PTC with and without a secondary reflector presented in Fig. 11 and 12. It is clear that the use of a secondary reflector led to an increase in the performance of the solar

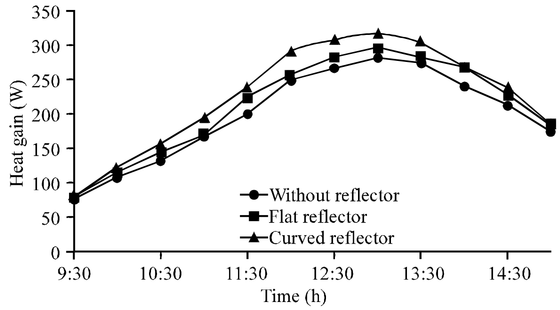

Fig. 11: The variation of collector heat gains with time when secondary reflectors are used

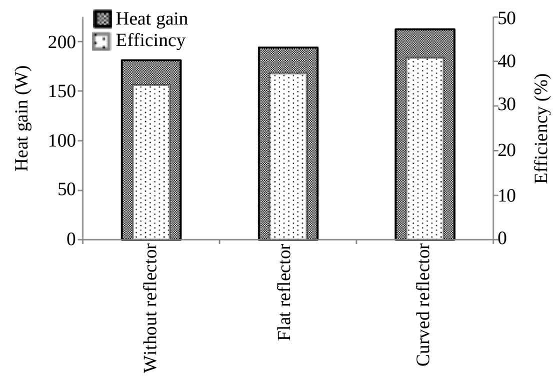

Fig. 12: The effect of secondary reflectors on the performance of the collector

collector. Additionally, the performance of the collector are increased when the curved secondary reflector have been used compared with flat reflector. After the secondary reflectors has been attached, the efficiency of the trough was increased from 34.7-37.3 and 40.8% on the other hand, the heat gain was increased from 181.2-193.95 and 212.39 W when flat and curved reflectors are used, respectively.

CONCLUTION

A Parabolic Trough Solar Collector (PTSC) were designed, constructed and tested recording to the Iraq weather conditions in AD Diwaniyah City (32^0 N, 45^0 E). It is done on consecutive days where the values of solar radiation were close to each other. Results showed that; the performance of the collector increases when the mass flow rate increases. The useful heat gain and efficiency of the collector increased by 29 and 28% when the flow rate increased from 21-31/min, respectively. In addition when the focal length increase, the performance of the collector decreases. The useful heat gain and efficiency of the collector increased significantly when using fins between the receiver's tubes. Significant increases in energy output and efficiency of the collector when the secondary reflectors used. It was increased from 34.7-37.3 and 40.8% when a flat and curved reflector is used respectively. The peak thermal efficiency obtained during the test was 50.4% when a curved secondary reflector and a flow rate of 3 L/min were used.

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