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DESIGN, CONSTRUCTION, AND TESTING OF A PARABOLIC TROUGH SOLAR CONCENTRATOR SYSTEM FOR HOT WATER AND MODERATE TEMPERATURE STEAM GENERATION

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ABSTRACT

Three parabolic trough collectors, with its two axes sun manual tracking system were designed, constructed, and operated in order to generate hot water and moderate temperature steam. An experimental investigation for testing the performance of a PTC is presented. The tests have been carried out in NAJAF climatic conditions (32.02º N, 44.33º E) during selective days of August. The thermal performance of PTC evaluated according to the Standard ASHRAE 93-1986 (RA 91) and the efficiency curve for the PTC was estimated. In the performance analysis of the PTC array, the effects of collector inlet temperature, ambient conditions, two cases for glass receiver and the variation in mass flow rate of the working fluid were investigated. The tests were performed by collecting the data from the outdoor measurements to evaluate the instantaneous thermal efficiency for PTC. A peak efficiencies close to (50%, 18.8%) were obtained for solar collectors with evacuated and non-evacuated glass receiver respectively at higher flow rate. The collector efficiency equation that is obtained in the present work agrees with other researches.

KEYWORDS: Concentrated solar energy; parabolic trough concentrator; hot water production; moderate temperature steam production; collector thermal efficiency.

تصميم، بناء واختبار منظومة مركزات شمسية ذات القطع المكافئ لإنتاج المياه الساخنة والبخار عند درجة حرارة متوسطة

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الخلاصة

تم تصميم وبناء واختبار ثلاثة مجمعات حوضية ذات القطع المكافئ (PTC) مع نظام يدوي بمحورين للتتبع الشمس، لغرض توليد الماء الساخن والبخار عند درجة حرارة متوسطة. تم تقديم بحث عملي لاختبار أداء أل(PTC). الاختبارات العملية نفذت تحت الظروف المناخية لمحافظة النجف الأشرف (32.02º N, 44.33º E) خلال أيام مختارة من شهر أغسطس. تم حساب الأداء الحراري لل(PTC) طبقا ل (STANDARD ASHRAE 93-1986) وتم إيجاد منحني الكفاء لل(PTC). في تحليل أداء أل(PTC) تم بحث تأثير درجة حرارة الدخول، الظروف المحيطة، حالتين للمستلم الزجاجي والتغير في معدل جريان مائع التشغيل. الاختبارات نفذت بواسطة جمع البيانات من القياسات الخارجية لحساب الكفاءة الحرارية اللحظية لل(PTC). ذروة الكفاءات المستحصلة كانت (50%، 18.8%) للمجمعات الشمسية مع المستلم المفرغ وغير المفرغ على التوالي عند معدل الجريان الأعلى. معادلة كفاءة المجمع المستحصلة في العمل الحالي تمت مقارنتها مع بحوث أخرى.

1. INTRODUCTION

The parabolic trough concentrator (PTC) is a solar concentration technology that converts solar beam radiation into thermal energy in their linear focus receiver. This type of concentrator is commonly provided with one-axis solar tracking to ensure that the solar beam falls parallel to its axis. PTC applications divided into two main groups. The first, and most developed, is concentrated solar power (CSP) plants. Currently, several commercial collectors for such applications have been successfully tested and operated.The temperature reached in those systems ranges from 300 to 400 ºC. CSP plants with PTC are connected to steam power cycles both directly and indirectly. Actually, there are an increasing number of projects under development or construction around the world (Fernández-Garcia et al. 2010). The second group is meant to provide thermal energy to applications that require temperatures between 85 and 250 ºC. These applications use primarily industrial process heat These applications use primarily industrial process heat, such as cleaning, drying, evaporation, distillation, pasteurization, sterilization, cooking, among others, as well as applications with low-temperature heat demand and high consumption rates (domestic hot water, space heating and swimming pool heating), and heat driven refrigeration and cooling. Typical aperture widths are between 1 and 3 m, total lengths vary between 2 and 10 m and geometrical concentrating ratios are between 15 and 20.

Currently the term “medium temperature collectors” is used to deal with collectors operating in the range of 80 to 250 ºC. One of the aims of solar thermal engineering is to develop collectors that are suitable for applications in this temperature range. Up to now only very limited experience exists for this temperature interval (Task 2008). In 2008, one of the objectives of the International Energy Agency’s (IEA) Task 33/IV program for solar industrial processes heat was to develop, improve and optimize solar thermal collectors for medium temperature. Most solar applications for industrial processes have been on a relatively small scale and are mostly experimental in nature. Only 85 solar thermal plants for process heat are reported worldwide, with an installed capacity of 25 MWth (35,700 m2) and an average size of 320 kWth (the capacities of the systems are in the range of 50 kWth and 1.5 MWth) (Weiss and Rommel 2005).

It is common to find industrial processes that use hot water and steam with temperatures between 80 and 180 ºC. Taking into account the potential reduction in the use of conventional energy sources that lead to the abatement in carbon dioxide emissions, studies into solar heat systems that can achieve these temperature levels are of great relevance.

This work intends to present the applied research and technological development of a hot water and medium temperature parabolic trough collectors that has great versatility due to its low cost, and ease of installation and operation. This paper presents a PTC model. This model is small and modular collectors that are lightweight, structurally rigid and have a low cost of production. The device was designed to produce hot water and medium temperature steam (close to 155 ºC and a pressure of 5 bar [absolute]) and to be constructed without complicated manufacturing processes, ensuring easy duplication.

2. DESCRIPTION OF PTC SYSTEM

The PTC system used here for hot water and moderate temperature steam generation based on concentration the solar radiation by parabolic trough collectors presented in Fig. 1.The model locally designed, constructed, and tested. The PTC system mainly consists of three collectors (reflectors), inserted copper pipes (absorber), evacuated glass tube, storage tank, centrifugal pump, support structure, and other accessories. The collectors arranged in series so that the heat transfer fluid (HTF) gain heat gradually as it flows through the tubes one by one. The glass receiver composed of two coaxial borosilicate glass tubes with one open end and another sealed. The outer of (58mm) diameter (1800mm) length (cover tube) and the inner (47mm) diameter and (1720mm) length of the absorbing tube. The water flows inside the copper absorber pipe that is enclosed inside the glass receiver tube. On the other hand, the collectors continuously oriented to the sun to achieve maximum efficiency.

Fig. 1. The PTC System.

3. DESIGN AND CONSTRUCTION OF PTC SYSTEM

3.1. Design and Construction of Reflectors

The function of this part is to reflect and concentrate the parallel solar rays on the receiver to achieve the focus line finally. In order to reduce construction expenses commercially available "off-the-shelf" aluminum composite material panels A.C.M.P that are consist of two aluminum cover sheets 0.5mm thick and a core made of polyethylene 3mm used, as part of the design of the PTC. To calculate the dimensions of the PTC, considering the curve length of the reflective surface. This dimension consistent with the width of the aluminium panel. The parabolic curve length was drawn by using Parabola Calculator Program.Whereas the following dimensions introduced into this program: the aperture width (diameter of trough) wa =1.04m and depth of trough = 29cm, at which is giving the resulting: the curve length (1.22m) and length of the focus (f= 23.31cm). Then, the mirror plates are curved into parabolic shape by using a metal sheet-bending machine. The parabola drawing was checked for consistency with the following equations (Duffie and Beckman 2013):

$$x^2 = 4fy \qquad 1$$

Two edge ribs for each trough have been fabricated by using aluminum composite material panel. The ribs given by the shape of the parabolic profile. Each rib has a circular hole that drilled on it to hold the glass receiver. This hole is concentric with the hole placed in tilting base structure for each PTC and in this point; the parabola focus coincides with rotation axis of PTC structure, maintaining the absorber tube and rotation without translational. The specifications of the PTC system are detailed in Table 1.

3.2. Design and Construction of the Support Structure

The support structure for this model consists of two main mechanical assemblies: stationary base and the other moving base. They are represent a metal support frame and manual tracking for the model in the same time.

3.2.1. The Stationary Base

The Stationary base has been fabricated to undergo, support and rotate the model at which is composite of a rectangular steel pipe welded together in the form of a square frame and fixed on concrete ground base by anchor bolt. This base consists of a stationary steel pipe that is welded vertically in the center of base with (2.5´´) diameter and (13cm) length in order to fixing the moving base on this base.

Table 1. Parabolic Trough Collector System Specifications.

Item	Value/Type
Collector aperture width	1.04m
The effective aperture width	75 cm
Collector length	1.80m
Parabolic curvature	1.22m
Collector aperture area	3.73m2
Mirror material	Aluminum composite panel
Rim angle	77.72
Focal distance	23.31cm
Glass envelope external diameter	58mm
Receiver external diameter	47mm
Inlet and outlet absorber material	Copper painted black
Copper pipe diameter	15.87mm
Mode of tracking	Two axis
Concentration ratio	4.68

The moving base has two types of motion, axial and tilting motion.

3.2.2. The Axial Motion Base

The first motion for this model is called an axial motion that satisfy the axial motion for a model about 360° horizontally. A metal base fabricated to achieve this axial motion. This base composite of a set of a rectangular steel pipe welded in the form of (I) frame, and it consists of cylindrical hole that drill in the center of base frame. The axial motion, which is in charge of the horizontal movement, was fixed on the central stationary base tube through the hole in the moving base.

3.2.3. The Tilting Motion Base

The second motion for this model represent the tilting motion that satisfy the tilting of model up to 60 degree with the horizon. A metal base fabricated from two square steel pipe that made in the form of tow arcs to achieve this tilting motion. Moreover, the metal arcs linked together by another square steel pipe. Then the arcs fixed on them two parallel rectangular steel pipes. The rectangular steel pipes used to fix on them the collectors, storage tank, pump and other accessories. These two arcs are mounting and sliding above the axial motion base, and which must be lead to perform the function of the tilting motion properly and successfully.

4. EXPERIMENTAL SETUP AND PROCEDURE

The experimental setup used for testing the PTC system shown schematically in Fig. 2. It consists of the constructed (1) three PTC, (2) a 35-liter storage tank (3) a circulating pump and (4) support structure with manual tracking

First, cleaning the reflector (mirrors) from the accumulated dusts. Then, the storage tank filled up from the main water supply, the water circulation is an open one, thus, the system with the storage tank is filled with 40 litter of water. The storage tank connected to the troughs system by connecting the storage tank inlet to the troughs outlet and the storage tank outlet to the troughs inlet. After that, the tracking system of all troughs guide and adjustment so that the sun directly over the troughs. Water is pumped from the storage tank to the PTC. The flow meter, which is placed after the pump, measures the flow rate of water passing through the pipes. After water collects heat and gets hot, it goes back to the storage tank. The cycle repeats throughout the test period temporarily steam production. In the meantime, the fluid temperatures in locations of mentioned in schematic diagram (the points 1 to 7), ambient temperature, wind speed and solar radiation intensity are continuously measured and recorded during the experiment.

5. PERFORMANCE OF PTC

5.1. Optical Performance of PTC

In ideal conditions, 100% of the incident solar energy is reflected by the concentrator and absorbed by the absorber. However, in reality, the reflector does not reflect all solar radiation due to imperfections of the reflector causing some optical losses. The optical efficiency relies on many factors such as tracking error, geometrical error, and surface imperfections.

As mentioned before, Optical efficiency is defined as the ratio of the energy absorbed by the receiver to the energy incident on the collector's aperture. (Garcia-Valladares and Velázquez 2009):

$$\eta_o = \frac{S}{I_b} \qquad 2$$

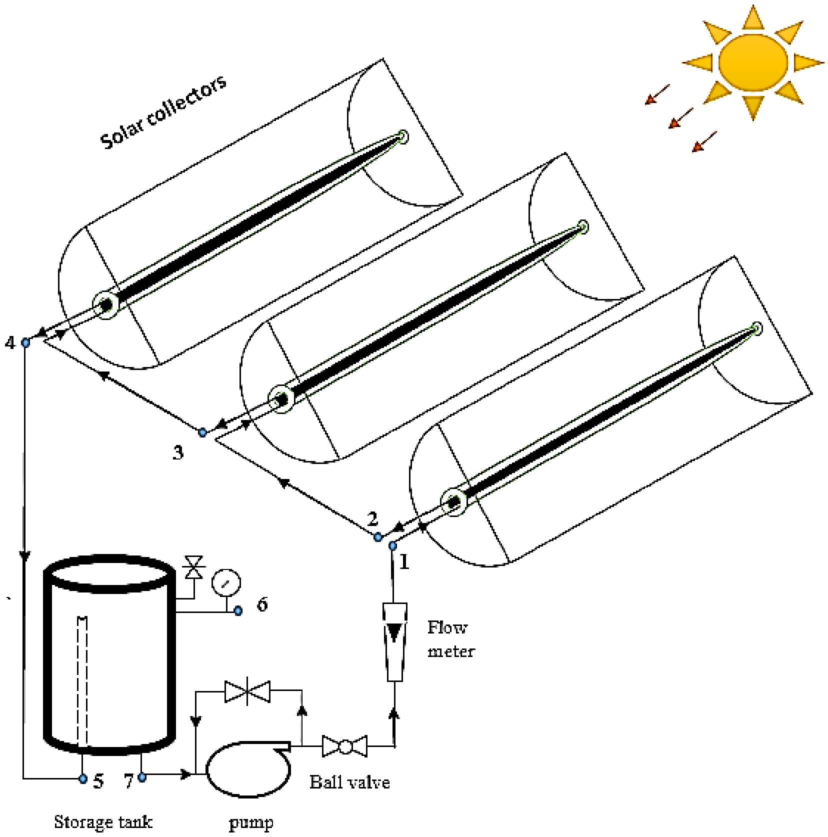


Fig. 2. Schematic Diagram of Experimental Setup.

With all of the modifiers taken into account, the absorbed radiation, S, or the actual amount of radiation on the receiver is calculated by (Garcia-Valladares and Velázquez 2009; Jacobson et al. 2006).

$$S = I_b\,(\rho\ \tau\ \alpha\ \gamma)\ K(\theta) \qquad 3$$

Where I_b is the beam radiation, ρ is the mirror reflectance, τ is the glass envelope transmittance, α is the absorber surface absorptance, γ is the intercept factor (defined as the fraction of the reflected radiation that is incident on the absorbing surface of the receiver), θ is incident angle modifier that is equal to unity at direct tracking.

The optical efficiency η_o and the factors (ρ, τ, α, γ) of this PTC are reported in Table 2. It is important to point out that the optical efficiency η_o was carried out by considering the angle of incidence θ as equal to zero. This value is commonly used in the calculation of the thermal efficiency as shown in the next section.

Table 2.The Optical Efficiency and the Geometric Parameters of the PTC.

Parameters	Value
η_o	0.55
ρ	0.80
τ	0.91
α	0.90
γ	0.85

5.2. Thermal Performance of PTC

The thermal performance of the PTC was evaluated experimentally according to the ASHRAE 93-1986 (RA 91) standard (Standard and others 1977). The purpose of this standard is to provide test methods for determining the thermal performance of solar energy collectors that use single-phase fluids and have no significant internal energy storage.

In section 8.2.1.1 of the ASHRAE 93 1986 (RA 91) standard is described a test method for determining the thermal efficiency η_{th} of a concentrating collector. This method is widely known to obtain the thermal efficiency in order to be compared with similar solar collectors. The performance of the PTC carried out in NAJAF climatic conditions (32.02° N, 44.33° E) by using outdoor experimental measurements. The evaluation of the PTC was conducted to determine the thermal instantaneous efficiency.

5.2.1. Thermal Instantaneous Efficiency

The beam solar radiation, useful heat gain, and aperture area applied into the following equation to determine the thermal efficiency, ηthi (Garg and others 2000; Ma et al. 2010).

$$\eta_{th} = \frac{\dot{m}\, C_p (T_{f,o} - T_{f,i})}{A_a I_b} \quad (4)$$

where $T_{f,i}$ and $T_{f,o}$ are the inlet and the outlet temperatures, respectively, $\dot{m}$ is the mass flow rate, C_P is the specific heat, A_a is the aperture area of collector, and I_b is the direct solar irradiance component in the aperture plane of the collector.

5.2.2. Thermal Collector Efficiency

The thermal collector efficiency ηth of the concentrators through the First Law is given by Kalogirou (Soteris, 2013).

$$\eta_{th} = F_R \left[\eta_o - \frac{U_L \left(T_{f,i} - T_a\right)}{I_b\, C} \right] \qquad 5$$

Where C = Wa-D/π D the concentration ratio, Wa the aperture width, D the diameter of receiver, Ta the ambient temperature.This equation has the form of y = b + mx, which can help to experimentally obtain the heat removal factor FR and the overall heat loss coefficient UL (Soteris A Kalogirou 2013). Linear models of thermal efficiency described by Duffie and Beckman (Duffie and Beckman 2013) and Stine and Harrigan (Stine and Harrigan 1985) were imposed on the experimental data according to Equation (5), where FRUL/C is the slope of the line and FR ηo is the y-intercept. It is important to indicate that for a collector operating under steady irradiation and fluid flow rate, FR ηo and FRUL/C are nearly constant (Soteris A Kalogirou 2013). Therefore, Equation (5) plots as a straight line on a graph of efficiency versus the heat loss parameter ΔT/Ib.

6. RESULT AND DISSECTION

6.1. Variation of Temperatures Difference through the Collectors at Varying Flow Rates in Case Evacuated/Non-Evacuated Glass Receiver:

The experiments on the PTC by using two case evacuated/non-evacuated glass receiver were carried out during eight clear sky days (5, 6 and 8 to13 August 2016) under similar weather conditions from 9:00 am to 13:00 pm. The intensity of solar radiation for experiment days was measured virtually using solar power radiation meter (TES 1333).

The effects of collector inlet temperature, ambient conditions and the variation in mass flow rate of the working fluid on PTC system were investigated. Different flow rates of the water (100 L/hr., 300 L/hr., 500 L/hr., and 650 L/hr.) implement for these experiment days.

It is observed from Fig. 3. that the increase in inlet and outlet water temperatures to/from the collector for both case of receivers continues to rise during time in the form of two parallel lines until reach to end of the experiments. This phenomenon can be attributed to the fact that received solar radiation is fill directly on the collectors due to tracing of the collectors direct to the sun continuously.

Moreover, it is observed from Fig. 4. , as the mass flow rate through the collector increases, the temperatures difference through the collectors decrease, for example, when the flow rate was 100 L/hr., the temperatures difference was highest, while, when the flow rate was 650 L/hr. the temperatures difference was lowest. Thus, the temperatures difference increases with the decrease of the mass flow rate. This phenomenon can be attributed to the fact, whichever fluid moved slower, it could gain greater heat from the solar rays. This behavior is the same as the selected flow rates that was by using non-evacuated glass receiver. However, the temperatures difference through collectors is lower than these temperatures difference at using the evacuated receiver. This because evacuation of the air reduces convection and radiation losses to the atmosphere.

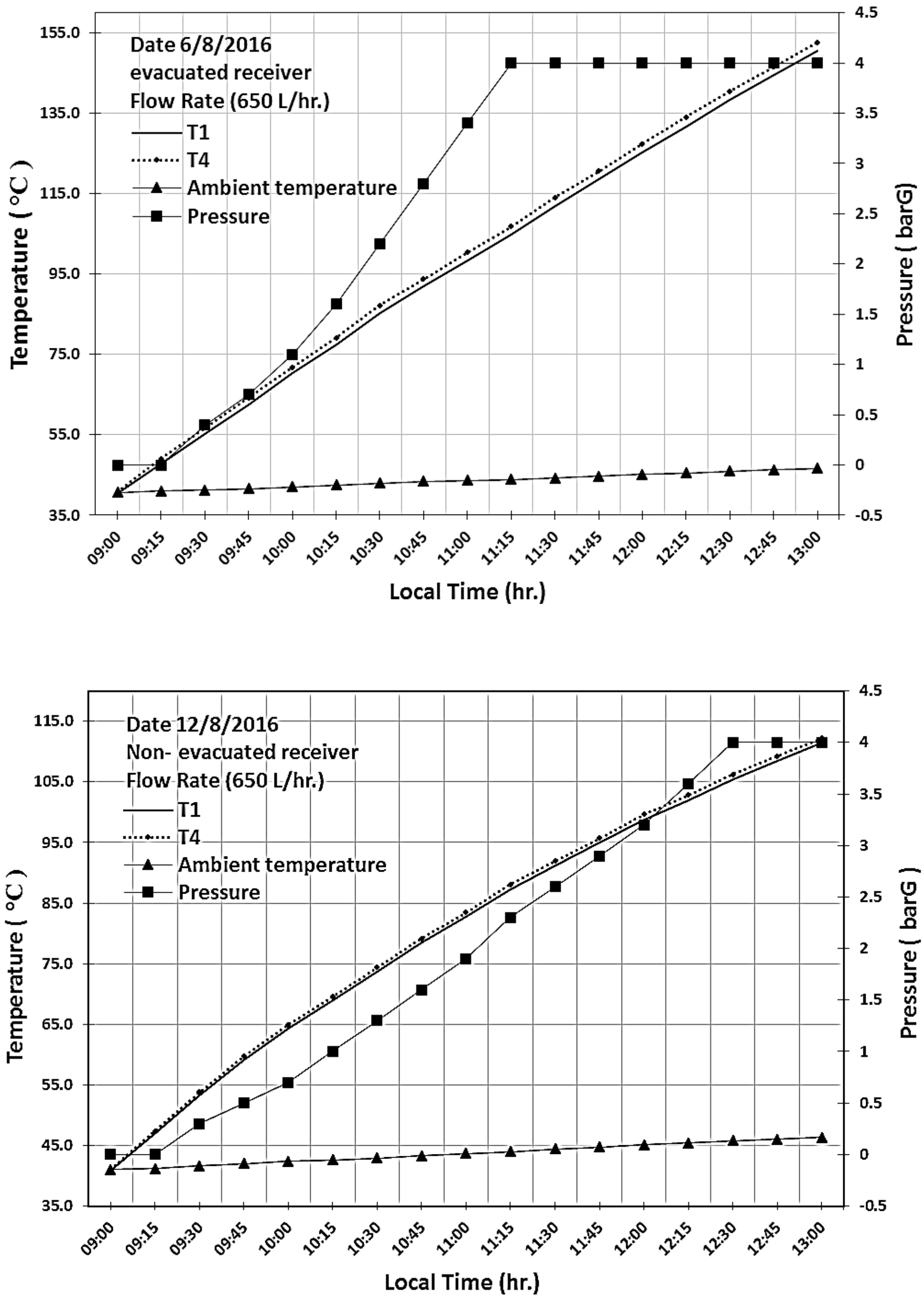


Fig. 3.The Inlet and Outlet Water Temperatures of Collectors, the Ambient Temperature, and the Pressure of Tank with Respect to Local Time for Evacuated / Non-Evacuated Glass Receiver.

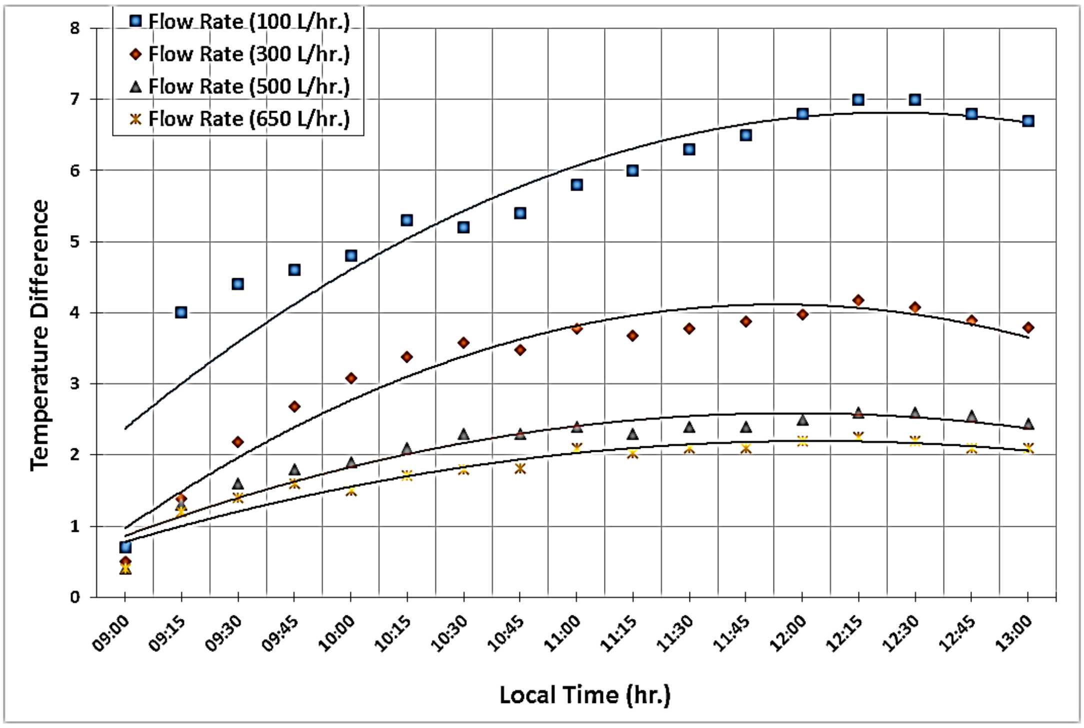


Fig. 4.The Temperatures Difference of Water through the Collectors with Respect to Local Time in Case Evacuated Glass Receiver.

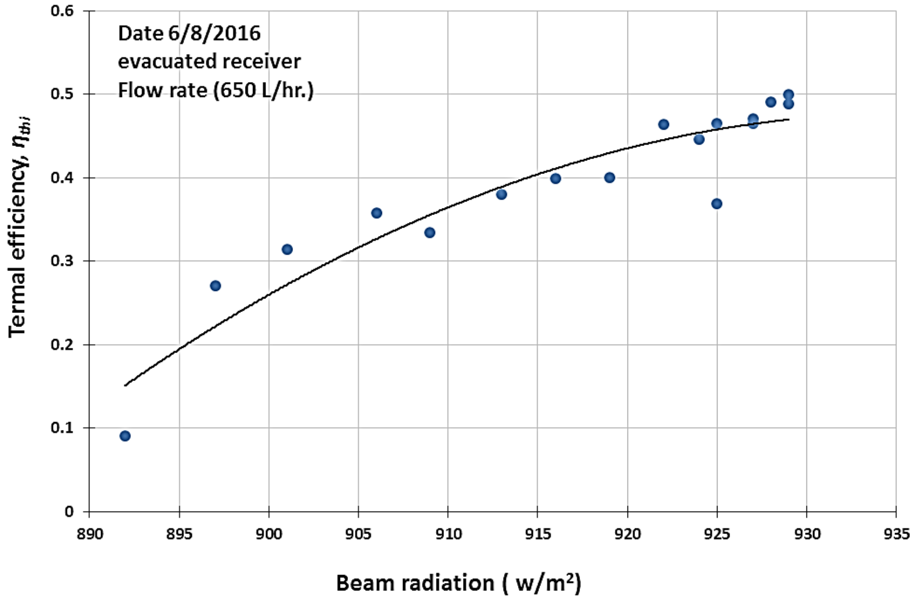
6.2. Thermal Instantaneous Efficiency

The data measured were collected for eight days under similar weather conditions at different flow rates by using evacuated and non-evacuated glass receiver in the PTC. To investigate the performance of the PTC. All the tests were done between 9:00 am and 13:00 pm and the required data measured at quarter-hour intervals.

Fig. 5. shows the relation between the variation of the thermal efficiency, ηthi, and the beam solar radiation, Ib for an evacuated/a non-evacuated glass receiver at (650 L/hr.) flow rate. It can be observed that the thermal efficiency of the collector first starts to increase as the solar radiation increases until it reaches a maximum value around noon (12:15 p.m.) and then starts to decrease slowly as the time passes due to decrease in solar radiation. Thus, the thermal efficiency increase with the increase of solar radiation

Generally, it is noted that the general pattern of variation of efficiency over day is the same as that of the useful heat gain because the value of efficiency depends on both the incident beam radiation and the useful heat gain.

On the other hand, it is observed from Fig. 6. that the thermal efficiency increases with the increase of feed water flow rate whereas the thermal efficiency, ηthi, varies from (0.02 to 0.27), (0.05 to 0.43), (0.07 to 0.45), and (0.09 to 0.5) kW at flow rates (100) L/hr., (300) L/hr., (500) L/hr. and (650) L/hr., respectively, by using an evacuated glass receiver. While when the feed water flow rates were (100) L/hr., (300) L/hr., (500) L/hr. and (650) L/hr, the thermal efficiency varies from (0.01 to 0.1), (0.04 to 0.15), (0.05 to 0.18), and (0.07 to 0.19) respectively, by using a non-evacuated glass receiver. Thus, the thermal efficiency increases with the increases of the mass flow rate. This phenomenon explained by the fact that the higher heat gained and absorbed is at higher water flow rate, which in turn decreases the heat losses, thus the thermal efficiency will be increase. It can also be seen that the thermal efficiency of the system is better with an evacuated glass receiver rather that a non-evacuated glass receiver for the same flow rates.



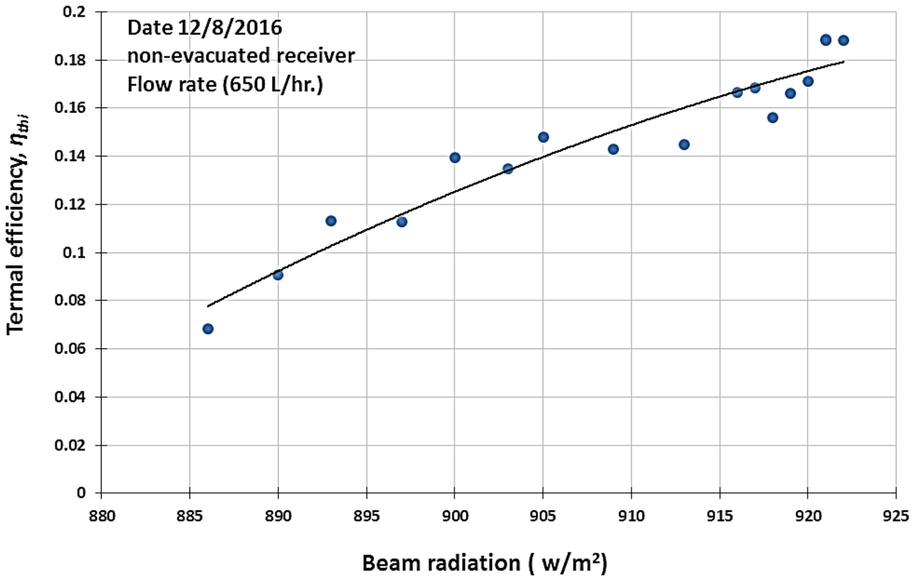


Fig. 5. Variation of thermal efficiency with solar beam radiation at different days for evacuated and non-evacuated receiver.

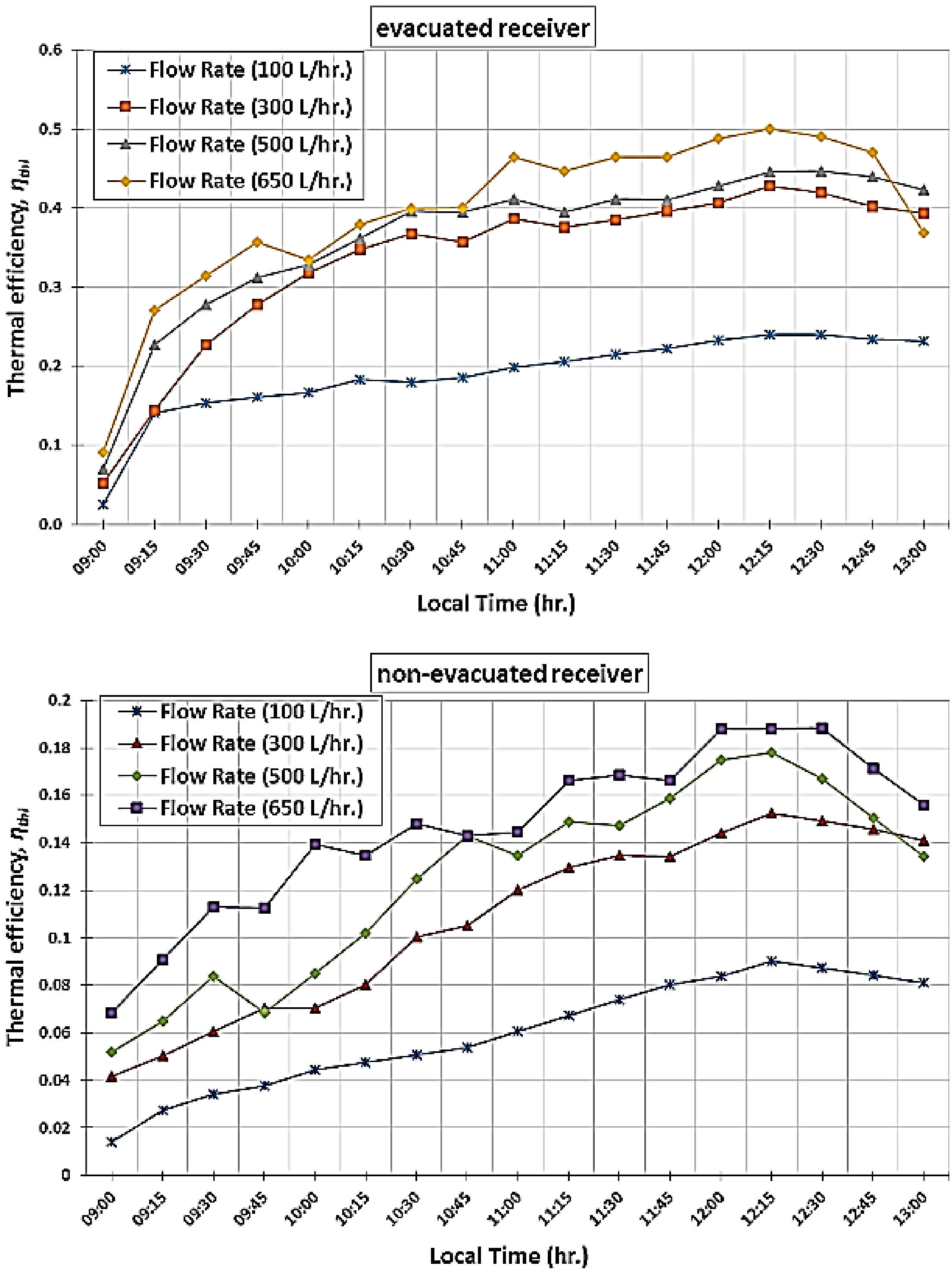


Fig. 6. Comparison between Thermal Efficiency for Different Days at Different Flow Rates and Different Receiver.

6.3. Thermal Collector Efficiency

The performance curve of the PTC of the present work derived from a series of test days conducted at different flow rates that are pass in evacuated and non-evacuated glass receivers in two case.

Equation (5) plots as a straight line on a graph of efficiency versus the heat loss parameter $\Delta T/Ib$.The performance curve of the PTC of the present work derived from a series of test days conducted at different flow rates that are pass in evacuated and non-evacuated glass receivers in two case.

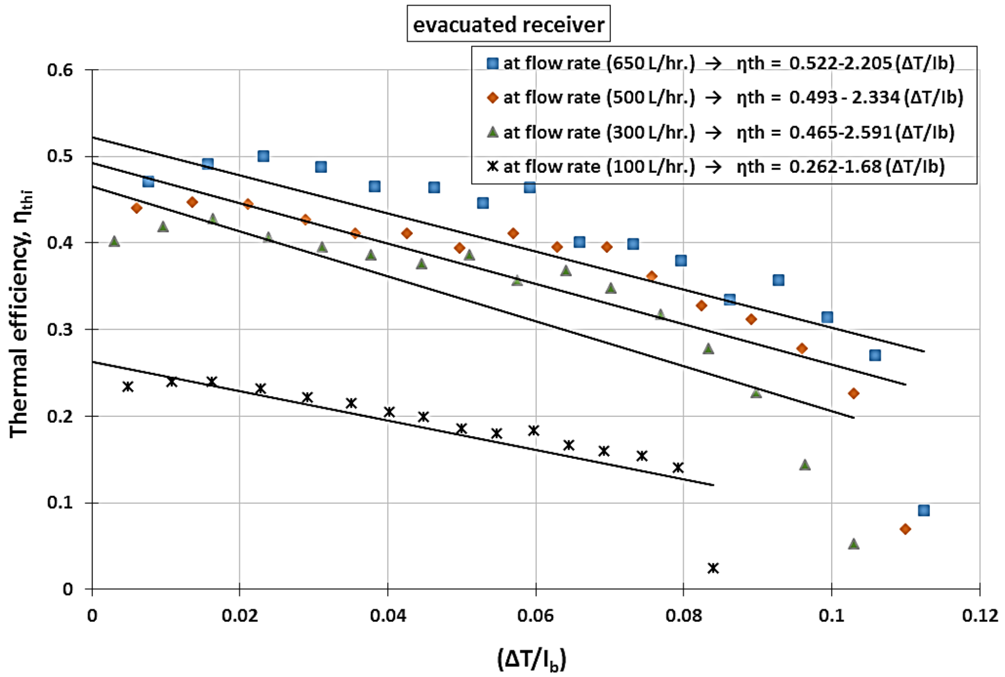
The efficiency curves for both cases are shown in Fig.7. The points show the thermal instantaneous efficiency and a straight line of best fit can be drawn between those points to obtain the thermal efficiencies for the solar concentrators. The peak values for the thermal collector efficiency close to 50% and 18.8% were obtained for the evacuated and non-evacuated glass receiver, respectively. It is noted clearly, that the collector efficiency is at high flow rate in both cases. This phenomenon can be attributed to the fact that higher heat gained and absorbed at higher feed water flow rate. By increasing the feed water flow rate the heat removal factor will be increase, thus by increasing the heat removal factor the collector efficiency increases too. Moreover, the thermal efficiency using evacuated receiver increasing steadily compared with non- evacuated glass receiver. Thus, thermal efficiency indicate a beneficial effect when the receiver is evacuated. The values of the thermal efficiency η_{th} , the heat removal factor F_R, and the overall heat loss coefficient U_L are reported in Table 3. While Table 4 shows the efficiency curves that have been reported in the literature for this type of solar collectors.

Table 3. Thermal Performance of PTC for This Work.

Flow rate (L/hr.)	Receiver type	Thermal efficiency equation	F_R	U_L (W/m^2 k)
100	Evacuated	$\eta_{th} = 0.262 - 1.68\ (\Delta T/I_b)$	0.47	16.5
	N-Evacuated	$\eta_{th} = 0.098 - 1.116\ (\Delta T/I_b)$	0.18	29.3
300	Evacuated	$\eta_{th} = 0.465 - 2.591\ (\Delta T/I_b)$	0.84	14.34
	N-Evacuated	$\eta_{th} = 0.168 - 1.70\ (\Delta T/I_b)$	0.30	26
500	Evacuated	$\eta_{th} = 0.493 - 2.334\ (\Delta T/I_b)$	0.89	12.1
	N-Evacuated	$\eta_{th} = 0.187 - 1.59\ (\Delta T/I_b)$	0.34	21.8
650	Evacuated	$\eta_{th} = 0.522 - 2.205\ (\Delta T/I_b)$	0.95	10.8
	N-Evacuated	$\eta_{th} = 0.198 - 1.28\ (\Delta T/I_b)$	0.36	16.6

Table 4. Thermal Efficiency for Different Types of PTC.

Efficiency equation	Refs.
$\eta_{th} = 0.642 - 0.441\ (\Delta T/I_b)$	(S A Kalogirou et al. 1994)
$\eta_{th} = 0.69 - 0.390\ (\Delta T/I_b)$	(Arasu and Sornakumar 2006; 2007)
$\eta_{th} = 0.5430 - 0.189\ (\Delta T/I_b)$	(Hau and Soberanis 2011)
$\eta_{th} = 0.5688 - 2.0494\ (\Delta T/I_b)$	(Venegas-Reyes et al. 2012)
$\eta_{th} = 0.5214 - 0.1006\ (\Delta T/I_b)$	(Yilmaz et al. 2015)



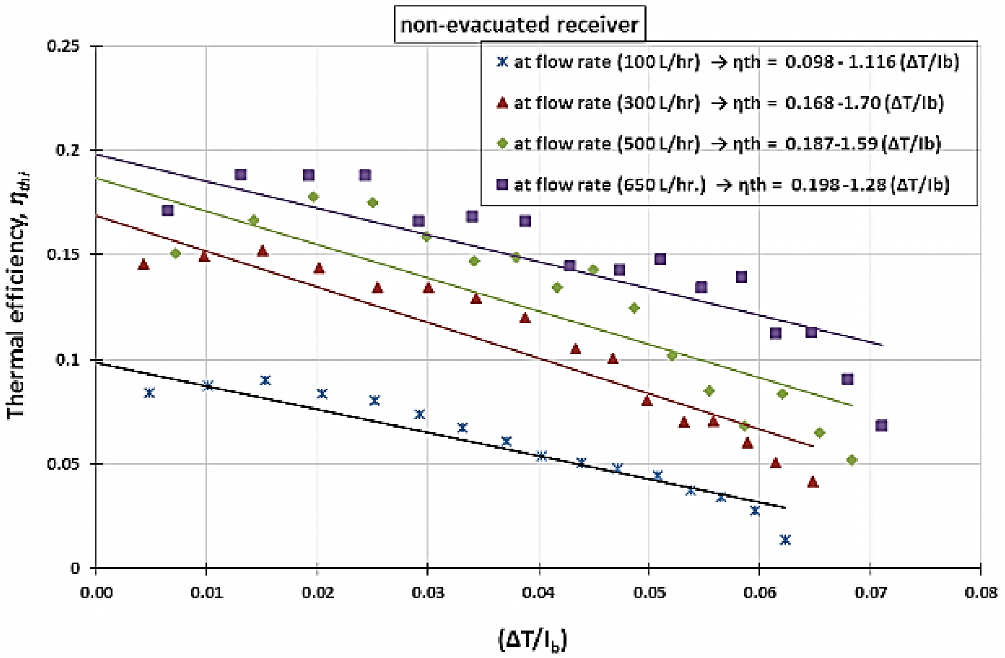


Fig. 7. Thermal Efficiency Data and Fit Curves for Different Days at Different Flow Rates and Different Receiver.

7. CONCLUSIONS

The PTC array was evaluated in two different forms. In the first test, it is set the evacuated glass receives and the system operate in four different flow rate for four days where the operation of the system took place from 9:00 to 13:00 h. In the second test The PTC arry is set the non-evacuated glass receives and the system operate in other four days at same different flow rate. The thermal performance of PTC was evaluated according to the Standard ASHRAE 93-1986 (RA 91) and the efficiency curve for the PTC was estimated. A peak efficiencies close to (50%, 18.8%) were obtained for solar collectors with (evacuated and non-evacuated glass receiver respectively at higher flow rate. The collector efficiency equation obtained in the present work compares well with the other reported literature The final results establish the technical feasibility of using PTC for applications requiring thermal energy at temperatures up to 150 ºC.

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