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Experimental Investigation Of Thermal Performance And Climatological Parameters For Trough Parabolic Collector With Manual Tracking System

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ABSTRACT: The experimental and theoretical studies are evaluate the thermal performance of three parabolic trough collectors with manual tracking system connected in parallel. The collectors are designed and manufactured utilizing the existing Iraqi technologies and available local materials. The sun tracking system was assembled using mechanical components that were procured from the Iraqi market. The receiver plate is made from galvanized material and is covered with aluminium foil of thickness 2 mm. The absorber tube is fabricated from stainless steel material, which is coated with selective black paint that can absorb solar radiation with internal and external diameters of 30 mm and 33mm, respectively. Numerical analysis was used in the simulation to determine the performance of the thermal model in order to study the influence of convective heat transfer resulting from the effect of fluid flow, falling and reflected solar radiation on the absorber and focusing on the receiving tube. A computer program was used to calculate the performance equation of the collector. The experimental results revealed that the data of tested collector is lower than that of a typical collector. However, average collection efficiency of this collector is about 43% which is fairly acceptable within the designs of parabolic trough collectors.

KEYWORDS: Heat Transfer; Collector; Parabolic; Solar radiation; Collector efficiency; Tracking system

INTRODUCTION

The subject of solar energy investment in different applications and methods of concentration of solar radiation for various types of solar collectors is one of the important topics that led researchers and international companies specialized in solar energy to conduct many theoretical and practical studies in their research. This research deals with the use of solar energy and its investment in many applications that serve the human being. The work has been divided between theoretical and practical studies, but the practical studies have received the biggest part of them. And through the review of these researches and studies, it was found that most of them are interested in showing the effect of mass flow rate of fluids used in solar collectors and some of them studied the effect of using evacuated tubes, while others studied the effect of performance coefficients on thermal efficiency and other design and operational determinants, which affects directly on the thermal performance of different types of solar collectors. Since this research includes a theoretical and experimental study of the performance of the parabolic trough collector, it is necessary to search for similar researches and reviewing the various studies for the purpose of comparison.

Misa [1] et al. gave an insight into the design of concentrating solar power (CSP) systems. The basic design of several types of CSP system was presented alongside their advantages and disadvantages. These advantages and disadvantages are based on their application and construction details and the paper shows how to select the most convenient CSP system. After presenting these types of CSP systems, an example of a new type of design was explained that presents a combination of several other solar concentrators. The experimental study to calculate the heat transfer coefficient on the outer surface of the absorber tube which is used for concentrating collectors and plays a major role in calculating the efficiency of the performance of the solar collectors studied by Balbir and Fauziah [2]. They established a mathematical correlation by creating a dimensionless factor as a function of the temperature instead of the dynamic viscosity. Also, the influence of the diameter of the absorber tube on the flow velocity at temperature degrees of 0 to 360°C at a constant mass flow rate was calculated based on this empirical correlation.

Uri [3] implemented an experiment to estimate the performance of two parabolic trough collectors connected in parallel. These collectors have two absorber tubes surrounded by a glass tube which allows sunlight to pass and minimizes the thermal losses from the metal tube to the atmosphere. The oil was used as a heat transfer fluid that heats water to obtain steam which is used for generating electricity. The purpose of the study was to verify practically the theoretically calculations that had already performed by Natal et al. and the results were very close. Also, Ahmed and Mohamed [4] designed and tested experimentally parabolic trough collector with automatic tracking system for water desalination in arid places in Saudi Arabia. The area of the absorber is 5.40 m2 with rim angle of 75o.The fabricated PTC and its tracking system were tested outdoors on the roof of the Mechanical Engineering Department, King Saud University, Riyadh. The results revealed that the thermal performance is very low as compared to the typical collector because of the high thermal losses resulting from non-use of evacuated tubes and due to the lack of precision in tracking process. The average collector efficiency was 40% and it is somewhat accepTable.

Brooks [5] studied experimentally the thermal performance of two types of parabolic trough collectors using water as working fluid. The study was for two types of concentrating collectors, one of which contains a glass tube that encapsulates the absorber tube while the other does not contain the glass tube. It was found that the thermal efficiency of the collector which has the evacuated tubes is higher than the collector without the evacuated tubes at low temperature degrees. Star Lab Radiometer device was used to measure the amount of solar radiation. Also, it was concluded that the amount of thermal losses was affected by the wind speed over the solar collector as well as by humidity and temperature. The effective method in developing the electric technology produced by solar energy in China was stdied by Liu et al. [6]. They constructed parabolic trough collectors for thermal generation, where the performance was studied using industrial oil (HTF) as heat transfer fluid at different mass flow rates. They found that the efficiency of the parabolic solar collector was found to be limited between 40% and 60%. They also demonstrated the effect of heat losses on the efficiency of the collector and their amount was 220W/m on the absorber tube when the temperature difference between the tube and the surrounding is about 180 °C, approximately about 10% of the total amount of solar energy on the absorber tube. Also, Govindaraj et.al. [7] investigated experimentally in university of Anna, south India to evaluate the performance of parabolic trough collectors with tracking system using (Therminol 55) as working fluid. The absorber tube was painted with black color to increase the absorption of the tube to the sun and reduce the amount of reflected radiation. The researchers used a glass cover of type (Borosilicate Glass) and the total collector area was (7.5 m2) with mass flow rate (0.1 kg/sec).The results revealed that the collector efficiency mainly based on the amount of direct solar radiation falling on the receiver and the amount of heat gained. They also found that the optimum collector efficiency was obtained at 12:00 o'clock and the heat losses from the storage tank is larger than the heat gain after 14:00 o'clock and this reduces the temperature of the working fluid so it does not require to use the storage tank after the hour 14:00.

Tadahmun [8] studied experimentally and theoretically the thermal efficiency of a parabolic trough solar collector using water as working as working fluid. The dimensions of the collector were (1.9 m length and1 m width) and the internal and external diameter of the absorber tube was 0.026 m and 0.03 m, respectively. The study was achieved during summer and winter in the city of Tikrit, Iraq. The theoretical study was completed using (Fortran 90) program and the Specifications and dimensions of the solar collector were entered into the program to calculate theoretical thermal efficiency. The resulting data showed that the experimental thermal efficiency for the collector was lower than the theoretical efficiency about (7% -15%). In addition, the increase in mass flow lead to increase the thermal efficiency of the collector. The experimental study for the parabolic trough collector with tracking system using (Synthetic Oil) as working fluid, because of its ability to transfer heat and suitability for high temperatures was studied by Baha et al. [9]. The collector was designed and manufactured using Iraqi technologies and locally available materials with a total area of (5.4 m2). The receiver was fabricated from carbon steel and was coated with a reflected mirror with thickness of (5 cm). A storage tank with a capacity of (50 Liters) was used in their research. Practical experiments were carried out under the climatic conditions of Baghdad during the months of October and November. During these experiments, the maximum outlet temperature of the oil was (150°C) and the oil temperature within the tank increased from(30° C) to (136°C) within four hours of operation.The experimental results showed that the system efficiency was (42%) and it is somewhat accepTable.

Nizar and Ali [10] studied the storage of solar energy and the use of it at night during cloudy weather. In this study, two methods were used to store electrical energy resulting from concentrating collectors. A battery consisting of three positive panels and has a storage capacity of around 500 amp-hour and (24) volts. The second method is to collect the heat gain from the sun using substances that collect large amounts of heat and release them when needed slowly and one such substance is ($Na_2SO_4.10H_2O$). The results showed that storage in the first method is significant in solar thermal systems and also the energy storage by the latent heat of molten salts is more efficient than storage with sensible heat and (90%) of the total energy stored in the second method is produced by the potential energy. Three factors that affect the heat gain from salt depletion, which is the primary salt temperature, the geometric shape of the salt container, its surface area, and the latent heat value of the salt used. Simulated numerically the heat transfer of parabolic trough solar receiver under different operating conditions was studied by Muhammad [11]. He studied and analyzed the heat transfer losses to know the performance of the solar collectors. Numerical analysis methods were used to solve the governing equations. He concluded that these types of concentrating collectors are considered some of the best collectors for heat transfer losses, which makes their performance well under different conditions. Performance Improvement of the Parabolic Trough Solar Collector Using Different Types of Fluids with Numerical Simulation was studied by Saad et al. [15]. Solar concentrators are an important facility to utilize the solar energy. There are many kinds of solar concentrators. In this work an experimental has been implemented to improve the thermal performance of Parabolic Trough Solar Collector (PTSC) using three different fluids as a working fluid. The experimental tests have been carried out in electro-mechanical engineering department at university of technology in Baghdad city during October 2017 and daytime between (9am -15pm) hours. Using (CuO + distilled water) as a working fluid increases the average of the output temperatures by 10.4%, the average of useful heat gains increases by 11% and the average of the collector efficiencies increases by15%.

This work aims to conduct an experimental and theoretical study and test the performance of a solar collector of parabolic type without automatic tracking system and rely on manual tracking and the possibility of generating electricity by taking advantage of the concentrated solar radiation available in our country. It provides a scientific and realistic view of solar energy. The values of the solar flux, ambient temperature and wind velocity were obtained from a port log system for all test days and from 10:00 am to 2:00 pm. The tests were carried out on Day 20 of each month for different flow rates and different temperatures for the water entering the absorber tube. On the practical side, the thermal efficiency of the solar collector was calculated at a different mass flow at 0.03 kg/s and 0.07 kg/s.

MATHEMATICAL MODELING

Solar Collector Mechanism

The solar collector, in fact, is a special type of heat exchanger that converts the energy of solar radiation into heat. In the solar collector, energy travels from the receiver to the fluid, where the ideal PTC can be used for applications that require energy at medium or high temperatures, possibly above (300 °C) above ambient environmental temperature [12].

Assumptions

The assumptions that were adopted for calculating the performance of the PTC according to the **Lamprecht** model [13] are:

1- The fluid is single-phase.

2- Neglecting the change in the ambient temperature of the absorber tube.

3- Assuming that the fluid pressure is stabilized inside the tube.

4- Neglecting heat transfer by conduction along the tube.

5- Assumption of forced convection from the absorber tube to surrounding.

6- During the theoretical simulation of the model, the average variables for weather conditions (wind speed, solar radiation, air temperature) are read simultaneously and used as inputs to the mathematical model.

The performance Factor Calculation of a parabolic Trough Collectors [14]

The efficiency of the collector is calculated from the following equation:

$$\eta = \frac{Q_u}{IA_a} \qquad \text{……………………………………..……....….(1)}$$

The useful energy is calculated from the following equation:

$$Q_u = A_a F_r \left[S - \frac{A_{abso}}{A_a} U_L \left(T_{w,i} - T_a \right) \right] \qquad \text{……..………….……..(2)}$$

Absorbed solar energy by the tube can be calculated from the following equation:

$$S = I\,\tau\,\alpha\,\rho\,\gamma \times \cos\,\theta \qquad \text{……………...…….……......…....(3)}$$

If the glass tube is not used, the overall thermal loss coefficient is calculated as follows:

$$U_L = h_w + h_{r,abs-sky} \qquad \text{………...……….…………....(4)}$$

The convective heat transfer coefficient resulting from wind speed on the outer surface of the absorber tube is calculated from the following equation:

$$h_w = 5.7 + 3.8V \qquad \text{……...………….……..……….……...(5)}$$

The heat transfer by radiation between the absorber tube and the surrounding is calculated as follows:

$$h_{r,abs-sky} = \varepsilon_{abs} \sigma (T_{abs} + T_{sky}) \left(T_{abs}^{\ 2} + T_{sky}^{\ 2} \right) \text{…………….......(6)}$$

The temperature of the sky can be calculated from the following equation:

$$T_{sky} = 0.055\,Ta^{1.5} \qquad \text{…………………………………..…...(7)}$$

To calculate the average temperature of the absorbent tube, we use the following equation:

$$T_{abs} = T_{w,m} + \frac{\dot{m} c_p \left(T_{w,o} - T_{w,i} \right)}{h_{c,i} A_{absi}} \qquad \text{………………......…..........(8)}$$

The average water temperature is calculated from the following equation:

$$T_{w,m} = T_{w,i} + \frac{Qu}{A_{gi} U_L F_r} \left(1 - \frac{F_r}{F'} \right) \text{……....…......………........(9)}$$

The water temperature at exit is calculated from the following equation:

$$T_{w,o} = T_{w,i} + \frac{Q_u}{\dot{m} c_p} \qquad \text{………………………........................(10)}$$

The heat removal factor is calculated from the following equation:

$$F_r = \frac{\dot{m}c_p}{A_{absi}U_L}\left[1-\exp\left(-\frac{A_{absi}U_L F'}{\dot{m}c_p}\right)\right] \ldots\ldots\ldots\ldots\ldots\ldots \text{(11)}$$

While the efficiency coefficient of the collector is calculated from the following equation:

$$F' = \frac{1/U_L}{\frac{1}{U_L} + \frac{D_{abso}}{h_{c,i}D_{absi}} + \frac{D_{abso}\ln\left(D_{abso}/D_{absi}\right)}{2k_{abs}}} \ldots\ldots\ldots\ldots \text{(12)}$$

The heat transfer coefficient inside the absorber tube is calculated from the following equation [14]:

$$h_{c,i} = \frac{k_w}{D_{absi}}\left[3.6 + \frac{0.0668\left(D_{absi}/L\right)\mathrm{Re}_w\,\mathrm{Pr}_w}{1+0.04\left[\left(\frac{D_{absi}}{L}\right)\mathrm{Re}_w\,\mathrm{Pr}_w\right]^{2/3}}\right] \ldots\ldots\ldots\ldots \text{(13)}$$

$$\mathrm{Re}_w = \frac{4\dot{m}}{\pi\mu_w D_{absi}} \ldots\ldots\ldots\ldots\ldots\ldots \text{(14)}$$

Specifications of solar collectors

The specifications of solar collector that used in the present work is shown in Table (1).

Table 1. Characteristics of the receiver

L = 11 m	W = 80 cm	γ= 0.995	ρ= 0.85	$\tau\alpha$= 0.99
D_{abso}=0.03 m	D_{absi}=0.028 m	k_{abs}=14 W/m°C	ε_{abs}= 0.9	

Proposed Design Method

To determine the curve of the parabolic collector section with high accuracy for easy design, especially that any deviation in the bow section of the receiver will lead to the deviation of the solar radiation and reflected rays toward the absorber tube and to avoid the scattering and ensuring the concentration of radiation towards the absorber tube, the parabolic equation is programmed with the Excel as shown in Figure (1). The coordinates of the arc section of the parabola were determined besides to the focus position and the angle of the edge and in order to execute the arc section, AutoCAD was used to draw the engineering shape as shown in Figure (2).

The determination of the curve of the parabola requires input of the values of the width and depth of the receiver and the number of points at which the curve is drawn in order to find the values of the rim angle, the position of the focus and the coordinate points for the receiver. To calculate the rim angle and the location of the focus of the receiver, a mathematical equation was used as shown in the following:

$$y = \frac{D}{4W^2}X^2 \ldots\ldots\ldots\ldots\ldots\ldots \text{(15)}$$

$$f = \frac{W^2}{16d} \ldots\ldots\ldots\ldots\ldots\ldots \text{(16)}$$

Where the equation (2-15) show the relationship between the width and depth of the receiver part, while equation (2-16) use to find the focus point. The rim angle can be calculated from the following equation:

$$Cos\phi_R = \frac{2f}{\sqrt{4W^2 + (d-f)^2}} - 1 \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(17)$$

Equation (2-15) shows that the selection of the rim angle (90°) with the width of the receiver (80 cm), the location of the focus is equal to (20 cm).

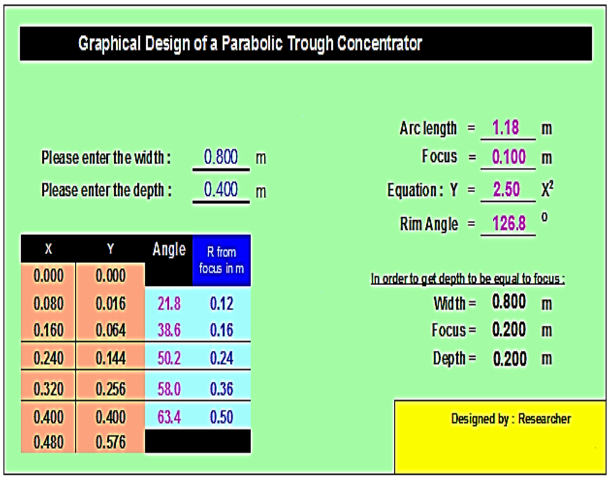

Figure 1. The main interface for the design of the (PCTS) curve using the Excel program.

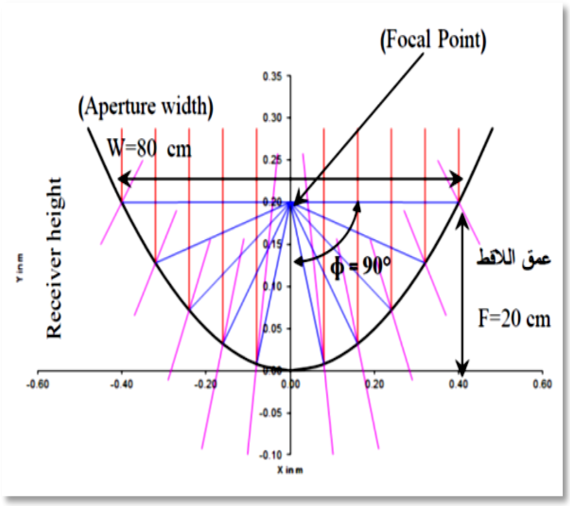

Figure 2. Schematic diagram of the receiver curve.

EXPERIMENTAL WORK

General Specifications of Solar Collectors

The collector system consist of eight main parts are: metal support frame of the PTC, receivers, absorber tubes, flow meter, control valves, thermocouples and data acquisition system as shown in Figure (3). The metal frame with dimensions (3 m × 2.8 m) was made from iron of square cross-section with light weight for easy installation in desired locations and fixed with joints and screw shafts that allow changing the inclination angle according to latitude angle. The receiver of collector was fabricated from galvanized iron, designed to provide a suiTable focal distance where it was formed by special rolling devices and according to the design dimensions in order to ensure the reflection of the sun rays to the focal line. A layer of aluminum foil was installed on the concave part of the collector to reflect the solar radiation on the focal line of the absorber tube. The absorber tube was made from stainless steel metal with length and internal diameter of (10 m) and (32 mm), respectively. It is installed by joints fixed on the iron structure by screws and bolts, which provides great ease in installation and disassembly. The tube was painted with a non-shiny black dye to increase the absorption of the tube and was insulated in the distance between the collectors to reduce thermal loss by convection. Two vents were made near the inlet and outlet section of the tube to fix the thermocouples by special welding. The flow meter was used to measure the volumetric flow rate of the fluid inside the absorber tube and the range of flow meter is (0.6 – 6 liter/min). Their accuracy was verified by conducting experimental readings by calculating the amounts of fluid discharged during the time unit and for different flow quantities.

Two thermocouples are used during the experiment are K-Type, range (-50 °C to 400 °C). They were immersed in the flow to measure the inlet and outlet temperatures of the fluid in the absorber tube. The thermocouples are fixed on the specified place with screws, while all thermocouples are connected with a digital reader data acquisition. The thermocouples are calibrated before use. Data Acquisition system is an interface system that was used to convert the thermocouples reading to temperature and record it directly to the computer. The interface system type is (LabJack - model U6) from LabJack Corporation - USA, the thermocouples are connected to two external terminal boards type (CB37) that both are connected to Mux board Multiplexer which in turn was connected to the main interface system (U6).A software (LJLog UD v 1.07) was used to connect the system to the PC as shown in Figure (4).

Experimental Setup and Procedure

The experimental setup that was employed to test the fabricated parabolic trough collector is shown schematically in Figure (5). It consists of the constructed parabolic trough collector, storage tank of a capacity 200 liter, a centrifugal pump which was used for circulating working fluid with maximum mass flow rate of 0.25 kg/s. The water circuit in the current experiment is a closed one. The storage reservoir was filled from main water supply. A pump circulates water from the storage reservoir through the absorber tube of the solar collector back to the storage reservoir. The inlet and outlet water temperatures of the absorber tube, ambient temperature, mass flow rate and intensity of solar radiation are continuously measured during the experiment.

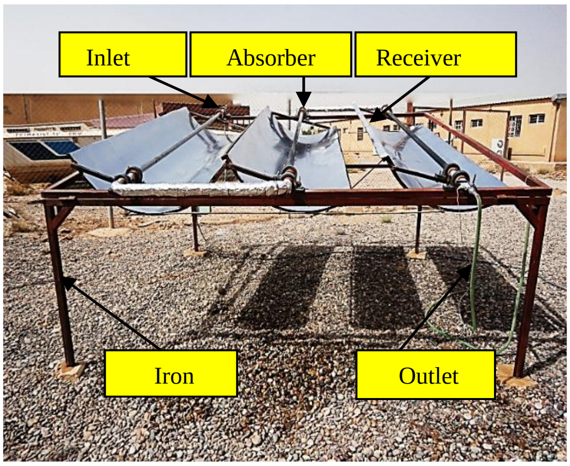

Figure 3. A photograph of the solar energy system.

Figure 4. The front view of the thermal control system program.

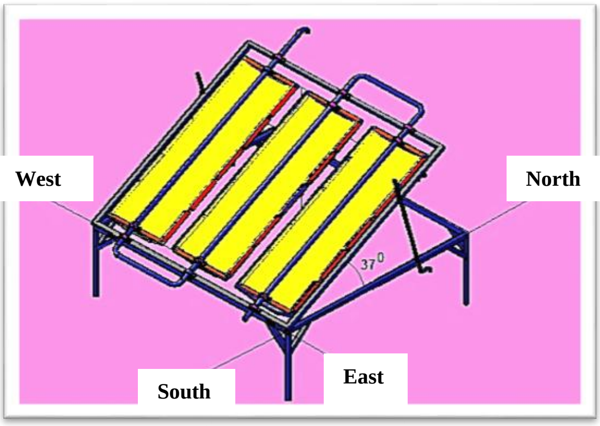

Figure 5. A schematic diagram of the experimental setup at different inclination angles (20°-90°).

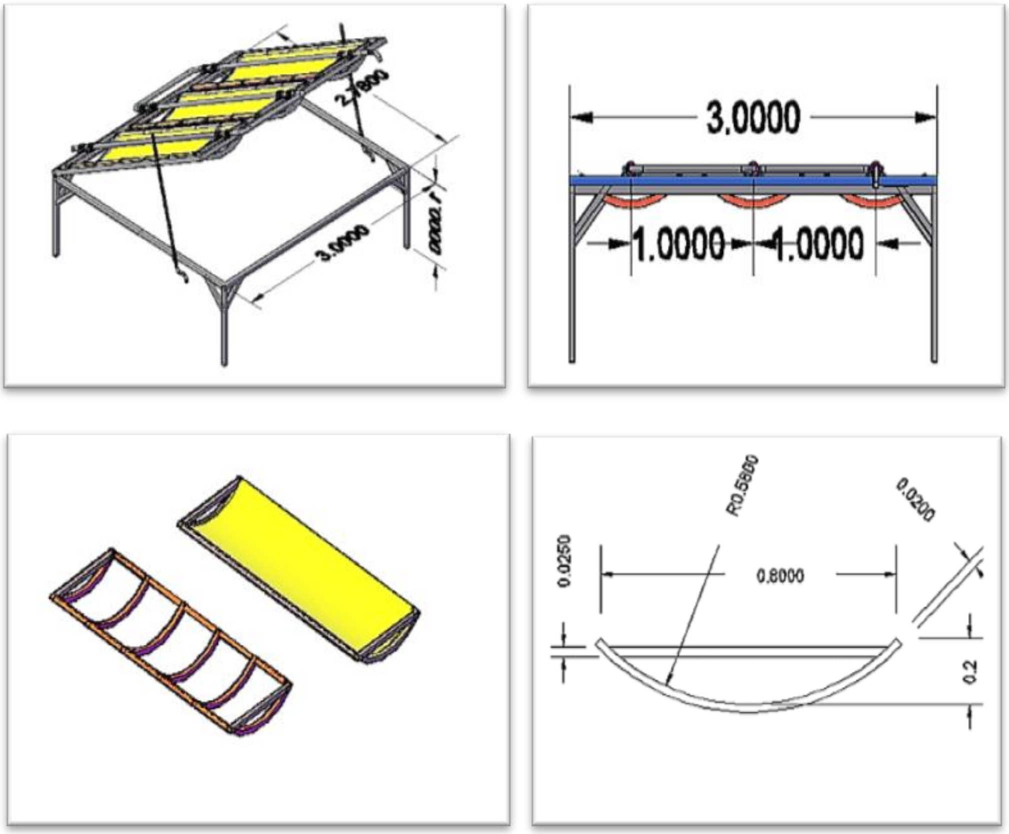

Figure 6. The detailed design and layout of parabolic solar collector with all its parts.

RESULTS AND DISCUSSION

In this paragraph, the theoretically and experimentally obtained results will be discussed. The first part will review and discuss the results of the theoretical part. A computer program was built using Fortran 90 for solving the theoretical equations of the solar collector and the calculating of solar radiation theoretically. The second part will discuss the results of the experimental part of the research for the same test days where the temperature of the ambient, inlet and outlet of the solar collector were recorded. The values of solar radiation, relative humidity and wind speed were also recorded for the test days by the devices mentioned in the experimental side of the research, and comparing the experimental results in terms of different weather conditions and operational variables of the solar collector as well as comparing the theoretical results with the experimental results.

Validation of the Experimental Work

This comparison is established for determining the compatibility between the theoretical and experimental results, as shown in Tables (2) and (3). The results showed that the thermal efficiency increases when the mass flow rate of the water entering the solar collector increases and this is compacTable with the experimental results. Figure (7) and (8) demonstrate the comparison between the theoretical and experimental results of the thermal efficiency values for mass flow rate 0.03 kg/s in Jan. for the day 20/1/2018 and in May for the day 20/5/2018, respectively. It is clear that the theoretical data is higher than the experimental ones and both are higher in May than in January. In addition, the theoretical data is approximately constant but the experimental one is improved until mid-day then decreases again.

Figure (9) and (10) show a comparison between the theoretical and experimental results of the solar radiation values on January 20/1/2018 and on May 20/5/2018, where there is a large difference between the values. This high error ratio belongs to the assumptions that have been developed to simplify the solution of the equations that were used in the theoretical side of the research, where theoretical values of solar radiation which directly affect the values of efficiency were used. This is contrary to the reality in the winter season. There is a clear fluctuation in the values of solar radiation due to the presence of clouds that lead to the dispersion of direct solar radiation and change the rate of its value during the test period. In summer, the results of solar radiation were very close due to the convergence of realistic weather conditions in summer with the conditions taken into consideration in the theoretical calculation.

Effect of Solar radiation and Climatic Conditions on Thermal Efficiency

Tables (4) and (5) show a sample of experimental results that were obtained on January of 20/1/2018 and May of 20/5/2018 with a mass flow rate of 0.07 kg/s. These Tables show that the highest solar radiation value obtained was (823 W/m^2) and at 12:10 am, where the solar radiation decreases with time according to the sine function as shown in Figure (11). The observed results show that the values of solar radiation and ambient temperature in summer is higher than the values in winter, as a result, the fluid temperature will increase and this leads to an increase of the thermal efficiency because of the lack of heat losses from the absorber tube due to the high ambient temperature.

Figure (12): shows the variation temperature difference of the absorber tube and its influence on the thermal efficiency. The result shows that the thermal efficiency increases when temperature difference of the absorber tube increases at mass flow rate 0.07 kg/s in winter and summer.

Effect of mass flow rates on Thermal Efficiency

The change in mass flow rate and its effect on the thermal efficiency values of the solar collectors and also its effect on the temperature of the water inside the solar collector were also examined. Tests were carried out for winter and summer at similar weather conditions. The thermal efficiency of the solar collector was increased by increasing the flow rates of water entering the absorber tube as shown in (13). The reason for the increase in heat transfer is due to the increased absorption of thermal energy by the water flowing through the absorber tube as a result of the increase in water velocity, where the highest value of thermal efficiency was recorded at the highest density of solar radiation.

CONCLUDING REMARKS

In the present work, a parabolic trough collector (PTC) with manual tracking system have been designed, manufactured and tested experimentally and theoretically. From this study it can be concluded that:

1. The collected efficiency from the (PTC) that was locally manufactured is less than that of the international standard.

2. It is expected to obtain better performance by adding glass envelope to the collector receiver to reduce thermal losses, and by using automatic tracking system.

3. The experimental thermal efficiency of the collector is less than the theoretical thermal efficiency.

4.There is a significant change in the efficiency when the water mass flow rate is increased.

5. The thermal efficiency of collector in January is more than the thermal efficiency of the same collector in May.

6. Increasing the direct solar radiation leads to an augmentation in the useful energy as a result of increasing the thermal efficiency.

7. Raising the water temperature degree inside the absorber tube leads to increasing the thermal losses and decreasing the efficiency of the collector.

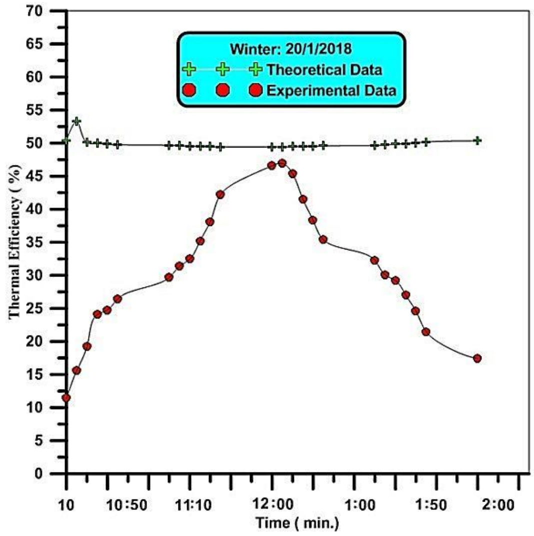

Figure 7. Comparison between theoretical and experimental thermal efficiency in winter, for m· = 0.03 kg/s.

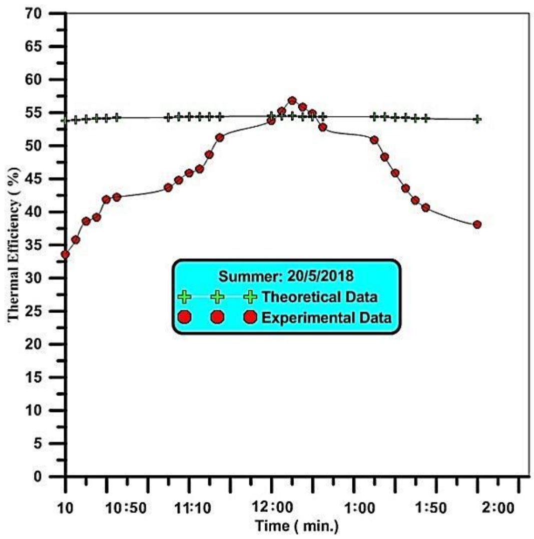

Figure 8. Comparison between theoretical and experimental thermal efficiency on May, for m· = 0.03 kg/s.

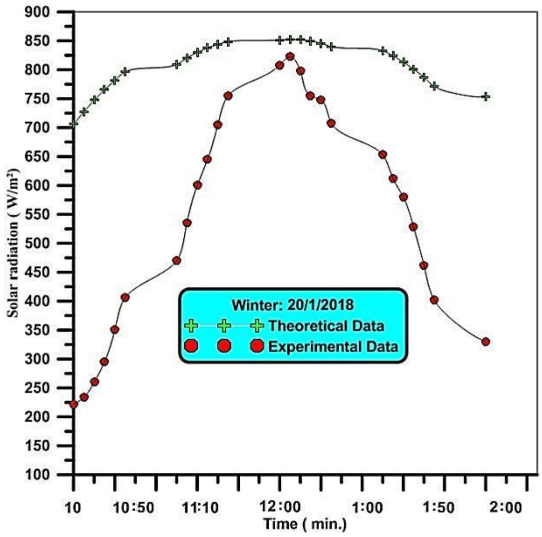

Figure 9. Comparison between theoretical and experimental solar radiation in winter on 20/1/2018.

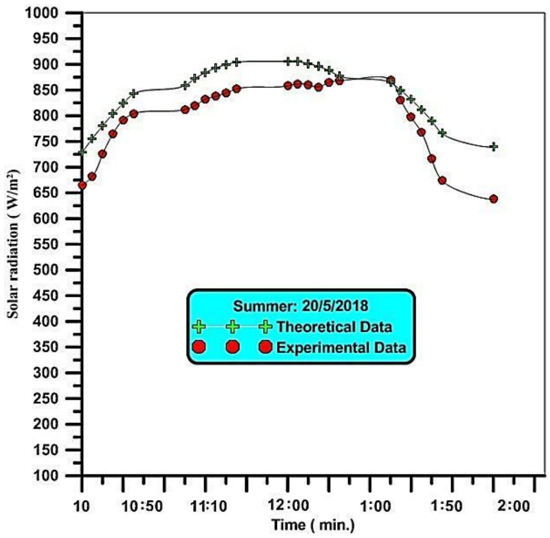

Figure 10. Comparison between theoretical and experimental solar radiation on May at m· = 0.03 kg/s

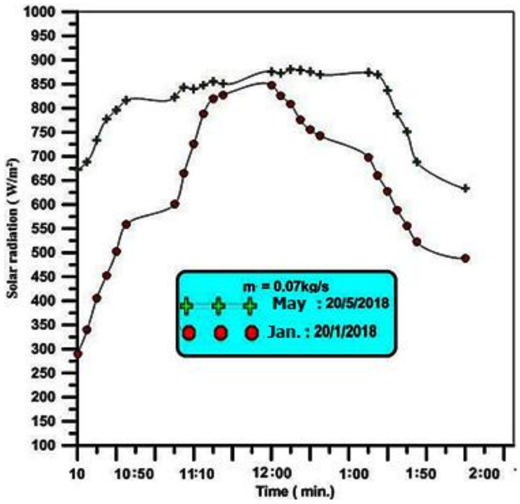

Figure 11. Comparison between the experimental solar radiation in Jan. and May at m· = 0.07 kg/s.

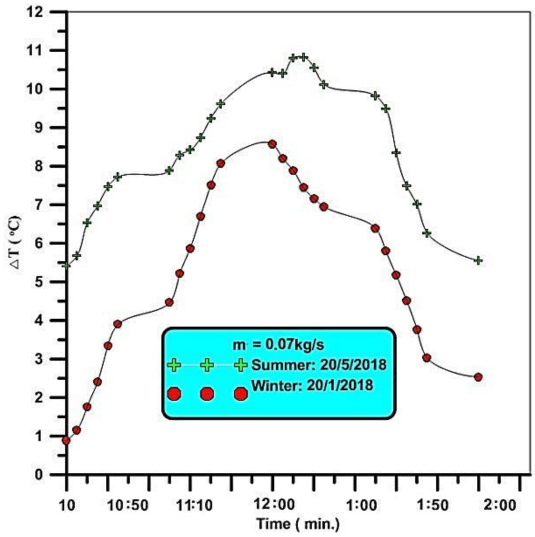

Figure 12. Variation of absorber tube temperature difference in winter and summer at m·=0.07 kg/s.

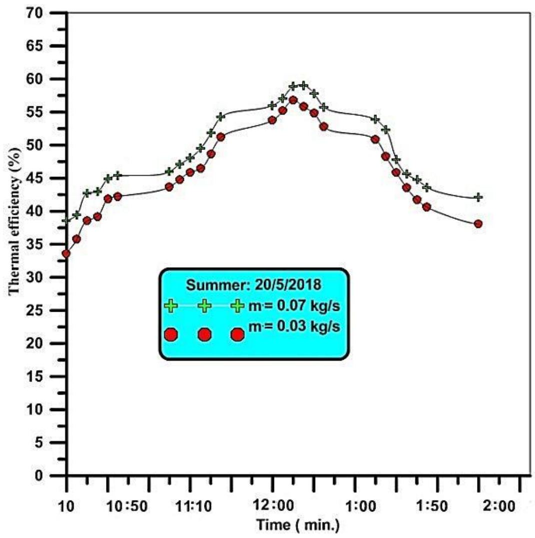

Figure 13. Effect of mass flow rates variation on thermal efficiency in summer on 20/5/2018

Table 2. Theoretical and experimental results of thermal efficiency in the winter for the day 20/1/1018.

Test Time(s)	Theoretical results for m·=0.03 kg/s	Experimental data for m·=0.03 kg/s	Theoretical results for m·=0.07 kg/s	Experimental data for m·=0.07 kg/s
10:00	50.379	11.44	56.423	14.78
10:10	53.230	15.58	56.335	16.3
10:20	50.094	19.2	56.252	20.84
10:30	49.972	24.06	56.175	25.5
10:40	49.862	24.78	56.105	31.89
10:50	49.765	26.47	56.04	33.56

11:00	49.680	29.68	55.983	35.67
11:10	49.608	31.35	55.932	37.6
11:20	49.549	32.46	55.888	38.82
11:30	49.502	35.21	55.851	40.77
11:40	49.468	38.15	55.821	43.89
11:50	49.447	42.24	55.798	46.7
12:00	49.438	46.57	55.783	48.46
12:10	49.442	46.94	55.774	47.58
12:20	49.458	45.38	55.773	46.8
12:30	49.487	41.53	55.779	46
12:40	49.529	38.29	55.792	45.48
12:50	49.583	35.36	55.813	44.84
01:00	49.650	32.29	55.84	43.9
01:10	49.730	30.07	55.875	42.11
01:20	49.822	29.24	55.916	39.56
01:30	49.926	27.05	55.965	36.84
01:40	50.044	24.6	56.02	32.55
01:50	50.174	21.46	56.082	27.85
02:00	50.318	17.44	56.15	25.02

Table 3. Theoretical and experimental results of thermal efficiency on May for the day 20/5/2018.

Test Time (s)	**Theoretical results for m·=0.03 kg/s**	**Experimental data for m·=0.03 kg/s**	**Theoretical results for m·=0.07 kg/s**	**Experimental data for m·=0.07 kg/s**
10:00	53.785	33.65	59.213	38.58
10:10	53.901	35.76	59.067	39.48
10:20	54.001	38.56	58.938	42.68
10:30	54.087	39.22	58.824	43.00
10:40	54.161	41.84	58.725	44.92
10:50	54.225	42.26	58.639	45.33

11:00	54.280	43.69	58.566	45.99
11:10	54.325	44.82	58.505	47.12
11:20	54.363	45.90	58.455	48.04
11:30	54.394	46.44	58.416	49.46
11:40	54.417	48.72	58.387	51.82
11:50	54.434	51.20	58.370	54.25
12:00	54.445	53.76	58.363	56.00
12:10	54.449	55.20	58.366	57.11
12:20	54.447	56.78	58.380	58.86
12:30	54.439	55.84	58.404	59.04
12:40	54.424	54.84	58.440	57.84
12:50	54.403	52.74	58.486	55.74
01:00	54.375	50.84	58.543	53.84
01:10	54.339	48.33	58.612	52.33
01:20	54.296	45.83	58.694	47.83
01:30	54.245	43.58	58.788	45.58
01:40	54.185	41.73	58.896	44.73
01:50	54.114	40.62	59.019	43.62
02:00	54.032	38.05	59.159	42.05

Table 4. Experimental measurements on winter 20/1/2018, at mass flow of water (0.07) kg/s.

Test Time(s)	**(T_{fi}) (°C)**	**(T_{fo}) (°C)**	**T_{amb} (°C)**	**G_{DN} (W/m^2)**	**Δ T (°C)**	**Hum. (%)**	**Wind Speed m/s**	**Efficiency (%)**
10:00	16.6	17.56	9.5	290	0.89	71	3.0	14.78
10:10	17.4	18.55	9.9	340	1.15	71	2.8	16.30
10:20	18.2	19.96	10	406	1.76	69	2.1	20.84
10:30	20.8	23.20	11	453	2.40	66	2.5	25.50
10:40	21.4	24.74	12.2	502	3.34	60	2.2	31.89

10:50	21.7	25.60	12.4	558	3.90	62	3.5	33.56
11:00	21.9	26.36	12.6	600	4.46	63	2.5	35.67
11:10	22.4	27.61	12.7	665	5.21	64	2.7	37.60
11:20	22.5	28.37	12.8	725	5.87	62	2.8	38.82
11:30	22.6	29.30	12.8	788	6.70	60	2.2	40.77
11:40	22.6	30.11	12.8	820	7.51	63	2.5	43.89
11:50	22.4	30.47	13.3	828	8.07	59	2.4	46.70
12:00	22.6	31.17	13.6	848	8.57	58	3.4	48.46
12:10	22.7	30.90	13.6	826	8.20	56	3.3	47.58
12:20	22.7	30.59	13.7	808	7.89	55	2.4	46.80
12:30	22.7	30.14	14.0	775	7.44	53	2.6	46.00
12:40	22.7	29.86	14.0	755	7.16	53	2.6	45.48
12:50	22.7	29.65	14.4	743	6.95	55	2.5	44.84
01:00	22.8	29.19	14.5	698	6.39	48	2.7	43.90
01:10	22.8	28.60	14.7	660	5.80	47	2.7	42.11
01:20	22.8	27.98	14.7	628	5.18	47	2.9	39.56
01:30	22.8	27.32	14.9	588	4.52	41	2.7	36.84
01:40	22.6	26.37	15.2	556	3.77	38	2.5	32.55
01:50	22.5	25.53	15.2	522	3.03	38	2.5	27.85
02:00	22.4	24.94	15.5	488	2.54	38	2.6	25.02

Table 5. Experimental measurements on May of 20/5/2018, at mass flow of water (0.07) kg/s.

Test Time(s)	**(T_{fi}) (°C)**	**(T_{fo}) (°C)**	**T_{amb} (°C)**	**G_{DN} (W/m^2)**	**Δ T (°C)**	**Hum. (%)**	**Wind Speed m/s**	**Efficiency (%)**
10:00	21.4	26.81	28.7	672	5.41	15	1.6	38.58
10:10	22.1	27.77	28.7	689	5.67	15	2.9	39.48
10:20	22.5	29.03	28.8	733	6.53	15	2.8	42.68
10:30	22.8	29.77	28.9	777	6.97	14	2.9	43.00

10:40	23.4	30.86	29.0	796	7.46	14	2.7	44.92
10:50	23.7	31.42	29.3	816	7.72	14	2.7	45.33
11:00	24.0	31.89	29.4	822	7.89	14	1.0	45.99
11:10	24.5	32.79	29.5	843	8.29	14	2.2	47.12
11:20	25.3	33.72	29.6	840	8.42	14	2.2	48.04
11:30	25.7	34.44	29.7	847	8.74	13	2.7	49.46
11:40	25.6	34.84	29.9	855	9.24	13	2.5	51.82
11:50	25.8	35.42	30.0	850	9.62	14	2.4	54.25
12:00	26.0	36.24	30.2	876	10.42	13	1.1	56.00
12:10	26.2	36.60	30.2	872	10.40	13	2.9	57.11
12:20	26.1	36.91	30.4	880	10.81	13	2.9	58.86
12:30	26.2	37.03	30.6	879	10.83	14	3.0	59.04
12:40	26.0	36.56	31.0	875	10.56	14	3.2	57.84
12:50	25.8	35.92	30.8	870	10.12	14	3.0	55.74
01:00	25.8	35.62	30.4	874	9.82	14	1.4	53.84
01:10	25.7	35.19	30.0	869	9.49	14	2.5	52.33
01:20	25.7	34.04	30.0	836	8.34	12	2.4	47.83
01:30	25.6	33.09	29.6	788	7.49	12	2.7	45.58
01:40	25.8	32.80	29.4	750	7.00	12	2.1	44.73
01:50	25.8	32.07	28.8	689	6.27	12	2.4	43.62
02:00	25.8	31.36	28.4	634	5.56	12	2.2	42.05

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NOMENCLATURE

Symb	Title
A_a	Aperture area, (m^2)
A_r	Receiver area, (m^2)
C_p	Water specific heat capacity (kJ/kg°C)
D	Absorber tube diameter, (m)
F'	Collector efficiency factor
Fr	Heat removal factor
hc	Heat transfer coefficient by convection, (W/m^2°C)
hr	Heat transfer coefficient by radiation, (W/m^2°C)
I	Solar radiation (W/m2)
hw	Heat transfer coefficient due to wind speed, (W/m^2°C)
L	Length of the absorber tube, (m)
$\dot{m}$	Mass flow rate, (kg/s)
Qu	Useful power, (W)
S	Absorbed solar energy, (W/m^2)
A_{abso}	External area of the absorber tube, (m^2)
A_{absi}	Internal area of the absorber tube, (m^2)
$T_{w,i}$	Water inlet temperature, (°C)
U_L	Overall heat loss coefficient, (W/m^2°C)
T_a	Ambient temperature, (°C)
hr,abs $-sky$	Heat transfer by radiation between absorber tube and surrounding
$h_{c,i}$	Heat transfer coefficient inside the absorber tube, (W/m^2°C)
k_{abs}	Thermal conductivity for the absorber tube, (W/m^2°C)
k_w	Thermal conductivity for water, (W/m^2°C)
D_{absi}	Internal diameter of the absorber tube, (m)

Re	Reynolds number
R_{ew}	Reynolds number for water
Nu	Nusselt number
Pr	Prandtle number
Pr_w	Prandtle number for water
Tc	Tube temperature, (°C)
T_{fi}	Fluid inlet temperature, , (°C)
T_{fo}	Fluid outlet temperature, , (°C)
T_f	Fluid temperature inside the tube, (°C)
$T_{w,m}$	Water mean temperature, (°C)
$T_{w,o}$	Water outlet temperature, (°C)
V	Wind Speed, (m/s)
W	Aperture Width, (m)

Greek Symbols

Symbol	Title
α	Tube absorptivity
γ	Reflective rays factor
τ	Transmittance
ε	Emissivity
η	Collector thermal efficiency
ϕ	Latitude angle
ρ	Reflectivity of the receiver

Subscript

Symbol	Title
a	Perimeter
abs	absorber
i	inner
m	mean

o	outer
sky	sky
w	water
F	Fluid