Performance Assessment of Parabolic Trough Collector (PTC) by Using Three Passes Receiver for Preheating the Fuel Oil Under Iraq Climate for Different Mass Flow Rates

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Abstract-- An alternative design receiver of parabolic trough collector (PTC) has been discussed in the present study. The three passes design (3p) receiver made from copper and coated with selective black paint was studied and optimized experimentally. Mass flow rates were varied alongside number of days. The proposed design was compared with the PTC equipped with smooth receiver (SM). The aforementioned variations resulted in the experiments performed in September 2018. The 17th, 18th, 19th, and 20th, were chosen for the PTC with smooth receiver, while 25th, 26th, 27th, and 28th were for the receiver with three passes. The solar irradiances for these days were similar. The heat transfer fluid (HTF) was fuel oil. Mass flow rates of 2, 2.5, 3, 3.5 LPM were observed alongside change in number of days for the experiment. The results show that the PTC with three passes receiver achieved higher average thermal efficiency and average useful energy than the PTC with smooth receiver.

Index Terms— PTC, Three passes receiver, fuel oil, mass flow rate, Efficiency

I. INTRODUCTION

There are high demands for parabolic trough collector (PTC) in industrials. It has an advantage of lesser pressure drop and higher heat transfer rate. The most important part of the PTC equipment is the heat collection element (HCE) called the receiver or absorber tube. Many researchers have studied and analyzed this part of the PTC. The use of twisted tape, discs, three passes, and wire coil in the receiver part was reported to have increased the external surface of the receivers or produce turbulence increase in the flow and can improve the transfer of heat. In addition, previous investigations on design parameters such as glass envelope, annulus spaces between absorber glass and tube cover (GC), tracking system, rim angle, absorber tube and mirror reflector were reported in the current study. Furthermore, the main parameter affecting the PTC thermal performance is the working fluid alongside diverse operating temperature [1]. It is essential to design an accurate working fluid selection pattern for solar systems due to the operating conditions and temperature. Key findings of previous researches are outlined as follows:

Edenburn had performed a theoretical evaluation for the analysis of performance in cylindrical parabolic collector. The study equally compared theoretical with experimental results. The researcher considered the analysis of performance, radiation transfer, the irradiation exchange, conductive and fatalities of convective, and transferred energy to fluid of a working going via the tube of receptor; the collector was able to completely trace the movement of the sun [2].

Many authors had performed experiment analyses using PTC as electric generator. Gang et al. suggested a modern technique for solar electric thermal generation haven decreased the temperature based on (substance parabolic concentrator) SPC and (Organic Rankine Cycle) ORC. Results of this study indicated better focusing efficiency and thermal collection[3,4]. In addition, it was also revealed that solar energy was sufficient for heating and electrical purposes experimentally.

Researchers conducted analysis on solar collectors and found improved efficiency[5,6]. Kalogirou proves that utilization of solar thermal power in power plants may save about (24%) of coal consumption [7]. The level of the steady thermal efficiency and temperature of solar energy systems in industrial applications should be 60–80 °C as clarified by several researchers [8,9].The consumption of available electricity decreases by the adoption of solar energy in industrial applications such as cooking, cleaning, degreasing or drying, and decontamination refinement. The majority routes of industry need a temperature below 300 °C [10].

Solar PTC is able to yield temperatures above 300 °C. It can serve as a supplier for heat required in industrial processes [11,12 and13]. Thermal efficiency of the absorbers was numerically analyzed and validated with experimental result by numerous researchers [14,15 and 16].

Eiamsa-ard and his group had experimentally assessed Nusselt number (Nu), thermal enhancement of a twisted single tape, co-twisted (twin-counter) tapes and co-swirled (counter) tapes in PTC receivers. All results revealed that thermal enhancement, friction factor of Nusselt number, improved when twist ratio was reduced [17]. Venegas-Reyes et al. calculated PTC thermal performance in accordance with the (ASHRAE), with Air Conditioning Engineers 93–1986 (RA 91). Arthurs predicted an unprecedented theoretical as well as practical model of PTC with a 45°rim angle [18]. Zhang et al. had done
identification of PTC receiver experimentally using U-type double glazing vacuum. To enhance thermal efficiency, they applied water to working fluid [19]. The experimental and numerical heat loss analysis in the receptor tube was completed by Yaghoubi et al. The researchers found that the heat loss in jacket tube was less than heat loss in vacuum tube [20].

Jaramillo et al. [21] also investigated the effect of twisted tape in an inactive mode for heat transfer growth in a PTC. The authors performed both experimental and numerical studies. They recommended that twisted tape improved transfer of heat when the twist ratio was around 1 at lower number of Reynolds. Enhancing the heat transfer in a PTC experimentally was the focus of Jafar and Sivaraman’s study [22]. The authors used twisted tapes and nail twisted tape. The performance of twisted tapes was better in the laminar flow resulting in an increase in the transfer of heat.

The experimental study performed by Reddy et al. [23] examined six different PTC configurations of receiver. The rates of flow increased from about 100 L/h to 1000 L/h. The maximum efficiency was 69.42%, 69.26% and 68.51% in the rate of flow to 1000 L/h and under heat flux of 900 W/m² for, APDR, IBPDR and BPDR, in a respective order. Jafar and Sivarman proved that the (APDR) porous disc receiver was the best option for the receiver configurations. Mohammed et al. had conducted an experimental study on the smooth receiver PTC under Iraq climate with the fuel oil as working fluid. The results showed that the efficiency of the PTC increased alongside the mass flow rate [1].

Recently many researchers have shown interest in the Nano technology in order to enhance the performance of the PTC. An experimental investigation implemented by Waghole et al. [24] studied and screened the effect of silver nanofluids pressure drop of a PTC and on the thermal performance with twisted tape. The absorber tube including inserts had better Nusselt number compared to the plain absorber. This resulted in an increase in the rate of heat transfer due to mixing enhancement of fluid. This study performed experimental characterizations on heat transfer enhancement of PTC with three passes receiver at various mass flow rates and measured with smooth receiver PTC. The heat transfer fluid was used fuel oil in the Iraqi (cement, electricity) plants.

II. METHODOLOGY OF EXPERIMENTAL

The parabolic trough collector (PTC) was mounted in the city of Najaf, at the alternative Energy Research Centre, Al-Furat Al-Awsat Technical University of, Iraq. The modus operandi of the PTC is as described in the following section.

A. Principal Work of the PTC

The PTC is one of the solar energy technology designed to trap solar radiation and concentrate it onto the receiver placed in the focal line. The receiver is one of the important parts of the PTC. The receiver adopted in this work was made of copper with three passes and coated with selective black paint, Figure 1 illustrate PTC photos.

B. PTC installation and description

In the current study, a PTC was designed and produced/implemented. The parabola width was 1.5 m. The PTC length was 3 m and the focal distance of PTC was 0.375 m [1]. The receiver of the PTC was modified to three passes. The length of the three passes receiver measures 9 m after modification. The inner diameter was 0.02 m. Hence, the heat transfer fluid (fuel oil) passes through the receiver and subjected to the concentrated solar radiation which reflects from the reflector in order to raise the temperature of fuel oil. The modified receiver was made from copper with a selective black coating. The concentration ratio for the present work was 7.64 [25,26]. The PTC parameters are summarized in Table 1 [1]. The parabola for the PTC can be calculated as a function of the (x,y) values of the width as captured in Kalogirou [26]:

\[ y = \frac{x^2}{4F} \]  (1)

The Steps taken in fabricating this apparatus can be summarized as follows;

The first step was to fabricate the frame of the PTC. The frame consists of 8 ribs. The distance between each rib is 0.375 m. The ribs were manufactured by the automatic (CNC machine) from a galvanized iron frame (Figure 2), these ribs were then connected to the starter motor by the screw rod forming a rotation axis allowing permitting the tracking to the sun path. The second step was more subtle than the previous, because the reflector film is weak (Figure 3). is the reflector was then attached to the reflector frame. This reflector sheets were made of hard stainless steel of 1 mm in thickness with the reflectivity 0.83. The last step was the thermal pipe installation, consisting of flexible rubber pipes with good thermal insulation.
C. Devices of experiment
This experiment was conducted in (alternative Energy Research Centre) located in Najaf City (Middle of Iraq: 29°5′-37°22′N, 38°45′-48°45′E). The PTC was trucked to east-west direction rotating around the axis of horizontal north-south in order to trap higher percentage of the energy from the sun. The experimental devices consist of the system of fluid heating found by PTC and other devices to conduct the experiment such as thermal piping circuit, flow meter and the K type thermocouple, pyrheliometers CHP! Kipp and Zonen. All data measured were recorded at an interval of 5 minutes using the CR5000 data logger.

\[ F - C_U [T - m] - C_U m - T = 0 \]

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\[ \text{(1,27) } \]

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\[ \text{The power and cement plants whose was } \]

\[ \text{at an interval of 5 minutes using the CR5000 data logger.} \]

\[ \text{CHP1 Kipp and Zonen. All data measured were recorded} \]

\[ \text{flow meter and the K type thermocouple, pyrheliometers} \]

\[ \text{c system of fluid heating found by PTC and other devices to} \]

\[ \text{from the sun. The experimental devices consist of the} \]

\[ \text{north to east (29°} \]

\[ \text{Research Centre) located in Najaf City (Middle of Iraq:} \]

\[ \text{This experiment was conducted} \]

\[ \text{C.} \]

\[ \text{Thickness inner tube (mm)} \]

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Length (mm)</td>
<td>3000</td>
</tr>
<tr>
<td>Aperture (mm)</td>
<td>1500</td>
</tr>
<tr>
<td>Focal distance (mm)</td>
<td>375</td>
</tr>
<tr>
<td>Aperture area (m2)</td>
<td>4.4</td>
</tr>
<tr>
<td>Concentrating ratio</td>
<td>7.64</td>
</tr>
<tr>
<td>Rim angle (°)</td>
<td>90</td>
</tr>
<tr>
<td>Reflected surface</td>
<td>0.93</td>
</tr>
<tr>
<td>Reflectivity</td>
<td></td>
</tr>
<tr>
<td>Type of receiver</td>
<td>Three passes tube-copper coated tube</td>
</tr>
<tr>
<td>Inner diameter receiver (mm)</td>
<td>18.5</td>
</tr>
<tr>
<td>Thickness inner tube (mm)</td>
<td>20</td>
</tr>
<tr>
<td>Length of receiver (mm)</td>
<td>9000</td>
</tr>
<tr>
<td>Absorbtivity</td>
<td>0.93</td>
</tr>
<tr>
<td>Emittance</td>
<td>0.08</td>
</tr>
</tbody>
</table>

Table I
Parameters of the PTC [1].

\[ \text{III. THERMAL ANALYSIS OF THE PTC} \]

This section presents the thermal analysis of the PTC. The experimental useful heat gain from the PTC can be calculated by [25]:

\[ Q_{ue} = \dot{m} C_{pf} (T_o - T_{in}) \]

(2)

The instantaneous efficiency \( \eta \) of a PTC was defined as the useful energy gained divided by the incident radiation of the aperture area of the PTC. From experimental results, the instantaneous efficiency was evaluated using the equation:

\[ \eta = \frac{Q_{ue}}{I A_o} = \frac{\dot{m} C_{pf} (T_o - T_{in})}{L A_o} \]

(3)

Comprehensive investigative for the receiver was done In order to found the theoretical useful energy supplied from the PTC using thermodynamics and heat transfer relations. The theoretical useful energy was given by[25]:

\[ Q_{uth} = F_R [\eta_v - \frac{U_l}{C} (T_o - T_{in})] \]

(4)

Where, UL is the overall collector heat loss coefficient. The heat removal factor FR is defined as:

\[ F_R = \frac{\dot{m} C_{pf}}{A_o U_l} \left[ 1 - \text{Exp} \left( - \frac{U_l P' A_o}{\dot{m} C_{pf}} \right) \right] \]

(5)

D. Fuel Oil
The fuel oil was selected as the heat transfer fluid in the present work. The justification for the use of fuel oil was in the interest of the power and cement plants whose was the used fuel oil in the Middle East. This fluid passed through the three passes receiver to gain heat from the sun via the concerted solar radiation. This process was designed to reduce the viscosity of the fuel oil. Several parameters of fuel oil such as, availability and cost among other advantages made this fuel oil the main fuel for these aforementioned plants in the Middle East. The properties of fuel oil were specified and tested in the Oil and Petrochemical Research Center / Materials Department / Ministry of Science and Technology of Iraq [1,27] The results are summarized in Table 2. The results are summarized in Table 2.

The heat transfer fluid (fuel oil) was stored in three tanks linked and well insulated with glass wool against thermal effect. The combined volume of the storage tanks was 3000 liters. The HTF flow was achieved by a (specification) pump. The solar tracking process was manual and uniaxial.

![Fig. 2. The metal frame is made of galvanized iron[1].](image)

![Fig. 3. Attachment of the reflector and the receiver to the metal frame[1].](image)

Table II
Properties of Fuel oil [1]

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Data</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density (15 °C)</td>
<td>0.949</td>
<td>g/ml</td>
</tr>
<tr>
<td>Flash point</td>
<td>97</td>
<td>°C</td>
</tr>
<tr>
<td>SP. Gravity (15 °C)</td>
<td>0.6943</td>
<td>-</td>
</tr>
<tr>
<td>Viscosity (40 °C)</td>
<td>243.07</td>
<td>C.st</td>
</tr>
<tr>
<td>Viscosity (100 °C)</td>
<td>17.80</td>
<td>C.st</td>
</tr>
<tr>
<td>Specific heat</td>
<td>1897.3</td>
<td>J/kg.K</td>
</tr>
</tbody>
</table>
Where, $F'_{\text{ratio}}$ is the collector efficiency factor and reads as it is written as it follows:

$$F'_{\text{ratio}} = \frac{1}{U_i} + \frac{D_o}{h_{\text{HTF}}D_i} + \frac{D_o}{2K}\ln\frac{D_o}{D_i}$$  \hspace{1cm} (6)

Where, $h_{\text{HTF}}$ is the HTF convection heat transfer coefficient is given by:

$$h_{\text{HTF}} = \frac{N_{\text{uf}} K_f}{D_i}$$  \hspace{1cm} (7)

Where, $N_{\text{uf}}$ is the Nusselt number.

For laminar flow, we use a Nusselt number value of 4.36 [25]. The general behaviour of the thermal performance of the PTC is represented by:

$$\eta = F_R \left[ \eta - U_i \left( \frac{T_o - T_{\text{in}}}{C} \right) \right] = a + bT^*$$  \hspace{1cm} (8)

With

$$T^* = \frac{(T_o - T_{\text{in}})}{I}$$  \hspace{1cm} (9)

$$a = (F_R \eta_C)$$  \hspace{1cm} (10)

$$b = -\left(\frac{F_R U_L}{C}\right)$$  \hspace{1cm} (11)

### IV. RESULTS AND DISCUSSION

#### A- TEST METHODOLOGY OF THE PTC

The experiment was performed according to ASHRAE 93–1986 standard [28] to get give room for comparison of the performance with other collectors. The test methodology is described in the following results.

#### 1- THERMAL PERFORMANCE

Numerous experimental tests were carried out in compliance with the ASHRAE 93–1986 standard [28] to evaluate the thermal performance of the PTC. The mass flow rates of the fuel oil was changed four times [2, 2.5, 3, 3.5 LPM], according to the days of experimental. PTC was operated under a steady irradiation and fluid flow rate. The thermal efficiency for the PTC in the operating conditions are shown in Figure 4. This was obtained by plotting $\eta$ against $T^*$ (Eq. 8) and comparing with smooth receiver [1]. The efficiency is a linear function of $T^*$. The slope “$a$” and the intercept “$b$” is given by Eq. (10) and Eq. (11), respectively. The slope and intercept are an instantaneous function and were taken as constants for a collector. The collector thermal efficiency of three passes receiver was at a mass flow rate of 2.5 LPM and expressed as:

$$\eta = 0.373 - 1.627^*$$  \hspace{1cm} (11)

![Fig. 4. The thermal efficiency for the PTC (smooth, three passes) receiver in the operating conditions at mass flow rate 2.5 LPM.](image)

The efficiency curve shows that the slope of the three passes receiver was higher than the slope of the smooth receiver. In addition, the three passes receiver length become 6 m higher than the smooth receiver which lead to increase in the PTC heat losses.

This result presented in both cases of this study did not deploy the glass jacket which usually causes high PTC heat losses to the surroundings. PTC is steady with respect to HTF temperature. The collector efficiency was 49%. The collector efficiency is in agreement with the results found in the literature. Table 3 shows the comparison of the straight line thermal efficiency obtained in present PTC with other researchers who used PTC. From the present result, it was observed that the difference between the intercept can be improved on by changing the optical performance, concentration ratios of the collectors tested and the properties of the receivers used as collectors.

<table>
<thead>
<tr>
<th>Research</th>
<th>Concentration ratio</th>
<th>The straight line thermal efficiency</th>
</tr>
</thead>
<tbody>
<tr>
<td>Murphy and May [29]</td>
<td>16.42</td>
<td>$\eta = 0.66 - 0.233T^*$</td>
</tr>
<tr>
<td>Valan Arasu and Sornakumar [30]</td>
<td>19.89</td>
<td>$\eta = 0.69 - 0.39T^*$</td>
</tr>
<tr>
<td>Kalogirou [31]</td>
<td>21.2</td>
<td>$\eta = 0.638 - 0.387T^*$</td>
</tr>
<tr>
<td>Rosado Hau and Escalante Soberanis [32]</td>
<td>38.84</td>
<td>$\eta = 0.505 - 0.189T^*$</td>
</tr>
<tr>
<td>Jaramillo et al. [PTC90] [33]</td>
<td>13.3</td>
<td>$\eta = 0.612 - 2.302T^*$</td>
</tr>
<tr>
<td>Jaramillo et al. [PTC45] [33]</td>
<td>14.9</td>
<td>$\eta = 0.351 - 2.117T^*$</td>
</tr>
<tr>
<td>Venegas-Reyes et al. [18]</td>
<td>14.87</td>
<td>$\eta = 0.560 - 2.046T^*$</td>
</tr>
<tr>
<td>Coccia et al. [34]</td>
<td>9.25</td>
<td>$\eta = 0.658 - 0.683T^*$</td>
</tr>
<tr>
<td>Chafi et al. [35]</td>
<td>11.77</td>
<td>$\eta = 0.551 - 0.316T^*$</td>
</tr>
<tr>
<td>Mohammed [1]</td>
<td>23.56</td>
<td>$\eta = 0.405 - 0.518T^*$</td>
</tr>
<tr>
<td>Present work</td>
<td>7.64</td>
<td>$\eta = 0.373 - 1.627^*$</td>
</tr>
</tbody>
</table>

Table III: Comparison of collector thermal efficiency.
2- INCIDENCE ANGLE MODIFIER

One more parameter to describe the collector performance is the incidence angle modifier. The incidence angle modifier is given by [25,28]:

\[ K_\theta = \frac{n(T_{in} = T_o)}{F_R(\eta)} \]  

(12)

Figure 5 indicates the variation of the incidence angle modifier with the angle of incidence. It is clear that the incidence angle modifier decline accelerates with the angle of incidence. A curve fitting was employed to the results to obtain a second order polynomial equation of \( K_\theta \) as a function of the incidence angle. The coefficient of determination \( (R^2) \) for curve fitting was 0.985. The resulting equation can be written as:

\[ K_\theta = -0.0002\theta^2 - 0.0005\theta + 1.0039 \]  

(13)

B- EXPERIMENTAL PERFORMANCE INVESTIGATION OF PTC AT DIFFERENT MASS FLOW RATES

An experimental study has been carried out to record the evolution of the HTF temperature of fuel oil and the useful heat gained as well as the thermal efficiency. All data were taken from 8:00 h to 16:00 h with different flow rates of fuel oil, which were (2, 2.5, 3, and 3.5) LPM. The experiment was conducted to the effect of wind velocity, ambient temperature and solar irradiation. The analyses of PTC performance were carried out at four typical sunny days of September 25th, 26th, 27th, 28th, 2018 for eight hours per day. The HTF supplied from the tank passed through receiver for continues storage into another tank.

In all, four tanks were prepared. The capacity for each of the tank was 1000 L. Three tanks were fill by the HTF and the last one was empty to ensure smooth circulation of the HTF after get heated. The results of a thermal test of the PTC for sunny days are analyzed and discussed. The variation of inlet and outlet fluid temperatures, useful heat gained, beam radiation and efficiency of the collector are showed in Figures. 6 – 16.

The variation of the incidence angle modifier with angle of incidence at 2.5 LPM.

![Graph showing the variation of incidence angle modifier with angle of incidence](image)

Fig. 5. Shows the variation of the incidence angle modifier with the angle of incidence.

Figure 6 [1] shows the variation of the inlet fuel oil temperature in the PTC with smooth receiver at four typical days (17\(^{th}\), 18\(^{th}\), 19\(^{th}\), 20\(^{th}\) 2018). The average of inlet temperatures per day was about (33, 35, 34.7, and 33.1 °C). It varies from (30.9 to 33.5 °C), (31.8 to 37.5 °C), (32.5 to 35.8 °C) and (32.1 to 33.7 °C) during days of experimental (17\(^{th}\), 18\(^{th}\), 19\(^{th}\), 20\(^{th}\)) respectively.

Figure 7 shows the variation of the inlet fuel oil temperature in the PTC with three passes receiver at four distinctive days (25\(^{th}\), 26\(^{th}\), 27\(^{th}\), 28\(^{th}\) 2018). The averages of inlet temperatures were about (31.6, 31.2, 30.6, and 32.7 °C). It varies from (30.4 to 33 °C), (30.1 to 33.1 °C), (30 to 32.6 °C) and (29 to 36.6 °C) during days of experimental (25\(^{th}\), 26\(^{th}\), 27\(^{th}\), 28\(^{th}\), 2018) respectively.

Figure 8 [1] shows the outlet HTF temperatures for all experimental days where PTC has the smooth receiver rises progressively with time and reach a peak at noon and then decreased as showed in figures. The maximum outlet HTF temperatures obtained by the PTC for all experiment days were 52.7°C, 52°C, 50.5°C and 46.3°C respectively. The maximum HTF temperature differences reach 19.2 °C, 17.2 °C, 14.9 °C and 13 °C in all aforementioned days. The result show that hat when the mass flow rate increases the difference in temperature decreases.

Figure 9 shows the outlet HTF temperatures for all experimental days. When PTC had the three passes receiver, progressively rise alongside the time was observed. It was maintained until it reached a peak at noon and then decreased as showed in figures. The maximum outlet HTF temperatures obtained by the PTC for all experiment days were 57°C, 51.9°C, 47.9°C and 48.9°C respectively. The maximum HTF temperature differences reach 25.2 °C, 20.7°C/17.6°C and 15.8 °C in all aforementioned days. It is clear that when the mass flow rate increases, the difference in temperature decreases.

The variation in solar radiation and useful heat gained with time is shown in Figures 10, 11, 12 and 13 respectively. In the first day of the experiment it was observed that the variation of beam radiation was between 373 W/m\(^2\), the morning and 250 W/m\(^2\) in the afternoon. The maximum value of beam radiation was recorded around noon (814 W/m\(^2\)). Second day of the experiment, the variation of beam radiation varies between 375 W/m\(^2\) in the morning and 257W/m\(^2\) in the afternoon. The maximum value of beam radiation was about (808 W/m\(^2\)). On third day, the variation of beam radiation changed between 353 W/m\(^2\) in the morning and 258W/m\(^2\) in the afternoon. The maximum value of beam radiation occurred around noon (775W/m\(^2\)). On the fourth day the beam radiation varies between 365W/m\(^2\) in the morning and 230W/m\(^2\) in the afternoon. The maximum value of beam radiation recorded was around noon (781 W/m\(^2\)).

To evaluate the useful heat gain, Eq. (2) has been drawn with respect to the time for all cases, following the HTF temperature differences between the outlet and inlet of the PTC. The evolution of the useful heat gain at the beginning of the experiment increased and reached a peak of 1486.07 W, 1525.9 W, 1556.09 W and 1637.9 W, respectively. All days were selected to perform the experiment around noon when the solar radiation was at maximum value of 789 W/m\(^2\), 794 W/m\(^2\), 772 W/m\(^2\) and 766 W/m\(^2\). It was equally observed that the increase in the flow of HTF lead to a higher useful heat energy. After noon the sun begins to
retreat and the solar radiation begins to decrease which leads to reduction in the useful heat gain. This is due to the fact that the useful heat gain is strongly influenced by the incident beam radiation and therefore follows its variation.

Figure 14 a, b, c, d, illustrates the maximum temperature difference in both cases (smooth, three passes receiver). From figure 14, it was observed that the PTC with three passes receiver had higher temperature difference than the PTC equipped with smooth receiver. In the case of the three passes, the temperature difference were 25.2 °C, 20.7°C, 17.6°C and 15.8 °C on the 25th, 26th, 27th, 28th days of September, 2018. On the other hand, for the smooth receiver were 19.2 °C, 17.2 °C, 14.9 °C and 13 °C on 17th, 18th, 19th and 20th days of September 2018. The mass flow rates of (HTF) vary for both cases as 2, 2.5, 3, 3.5 LPM for the typical days selected.

Fig. 6. Inlet temperature for PTC with SMOOTH RECEIVER(sm) at different mass flow rates.

Fig. 7. Inlet temperature for PTC with THREE PASSES RECEIVER (3p) at 2LPM different mass flow rates.

Fig. 8. Outlet temperatures for PTC with SMOOTH RECEIVER(sm) at different mass flow rates.

Fig. 9. Outlet temperatures for PTC with THREE PASSES RECEIVER (3p) at 2LPM different mass flow rates.

Fig. 10. The variation of beam radiation and useful energy at 2LPM.
Figure 11 a, b, c, d have showed the efficiency of PTC as a function of time during the all sunny days according to Eq. (2) and Eq. (3). For both cases, (three passes, smooth) receiver was at different mass flow rates. From figure 15, it is clear that the efficiency of PTC at the beginning of the experiment increased until it reached a maximum value. At noon maximum values were 55, 56, 59, 62% on 25th, 26th, 27th, 28th days in September 2018 for three passes receiver. The efficiencies in case of the smooth receiver were 48, 51, 54 and 57% on 17th, 18th, 19th, 20th days of September 2018. Then, PTC instantaneous efficiency started to decrease until the end of the experiment for both cases. It was clear that when the mass flow rate increased the efficiency of PTC increased and the temperature difference decreased as shown in Figure 16.
Fig. 14c. The comparison between the temperatures difference 3 LPM in typical sunny days at numerous mass flow rates.

Fig. 14d. The comparison between the temperatures difference 3.5 LPM in typical sunny days at numerous mass flow rates.

Fig. 15a. The PTC instantaneous thermal efficiency 2LPM.

Fig. 15b. The PTC instantaneous thermal efficiency 2.5LPM.

Fig. 15c. The PTC instantaneous thermal efficiency 3LPM.

Fig. 15d. The PTC instantaneous thermal efficiency 3.5LPM.
V. CONCLUSIONS

A PTC was installed in the city of Najaf at the Alternative Energy Research Centre in the Technical Institute of Najaf, Al-Furat Al-Awsat Technical University, Iraq. The performance of a PTC was analyzed in detail under different operating conditions. The calculations of thermal efficiency, incidence angle modifier have been studied in the present work in addition to the temperatures or heat fluxes. The collector thermal efficiency curve of the PTC shows a good agreement with published data. These performance tests were done according to the ASHRAE 93 – 1986 standard. The experimental tests were done on typical sunny days of September 2018 using the PTC equipped with three passes receiver. When compared with the PTC, it has a smooth receiver under, approximately, the same solar radiation in the different days. A glass jacket was excluded in both cases. The heat transfer fluid was fuel oil in both cases. The mass flow rates varied as 2, 2.5, 3 and 3.5 LPM. The results after enhancement of the receiver show that:

- At 2LPM flow of fuel oil in the PTC with three passes receiver achieved an average thermal efficiency of 40% and average useful heat gain was 890.99. While, the PTC with smooth receiver has an average thermal efficiency of 34 %. The average useful heat gain was 667.13 W.
- In the next day of experiment mass flow rate of fuel oil was 2.5LPM the average thermal efficiency of PTC with three passes receiver reached 42% and an average useful heat gain was 952.29W. While the PTC with smooth receiver recorded an average thermal efficiency of 36%) and the average useful heat gain was 758.55 W respectively.
- The mass flow rate of fuel oil changed to 3LPM in the third day of experiment, the PTC with three passes receiver achieved an average thermal efficiency of 45 % and average useful heat gain of 945.12 W. The PTC with smooth receiver had an average thermal efficiency 40% and the average useful heat gain was 800.93 W respectively.
- During the final day, the mass flow rate of fuel oil was set 3.5LPM, the PTC with three passes receiver recorded an average thermal efficiency of 47% and average useful heat gain of 1006.63 W. The PTC with smooth receiver had an average thermal efficiency of 44 % and the average useful heat gain was 821.86 W respectively.

<table>
<thead>
<tr>
<th>NOMENCLATURE</th>
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<tbody>
<tr>
<td>Aa</td>
<td>Aperture area [m2]</td>
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<td>Aab</td>
<td>Absorber outer surface area [m2]</td>
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<tr>
<td>C</td>
<td>Concentration ratio</td>
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<td>Cpf</td>
<td>Fluid specific heat capacity [J/kg K]</td>
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<td>Di</td>
<td>Inner diameter of absorber tube [m]</td>
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<td>Do</td>
<td>Outer diameter of absorber tube [m]</td>
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<td>F</td>
<td>Focal distance [m]</td>
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<td>FR</td>
<td>Heat removal factor</td>
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<tr>
<td>F’</td>
<td>Collector efficiency factor</td>
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<td>hft</td>
<td>Convection heat transfer coefficient of the HTF [W/m2 K]</td>
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<td>Direct normal irradiance [W/m2]</td>
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<td>kf</td>
<td>Thermal conductivity of the fluid [W/m K]</td>
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<td>Kθ</td>
<td>Incidence angle modifier</td>
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<td>Collector length [m]</td>
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<td>m</td>
<td>Mass flow rate [kg/s]</td>
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<td>Nuf</td>
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<td>3p</td>
<td>Three passes receiver</td>
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<td>Sm</td>
<td>Smooth receiver</td>
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REFERENCES


