Performance Testing of A Parabolic Trough Collector Array

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Abstract

Parabolic Trough Solar Collectors (PTSCs) are concentrating collectors which are widely used to supply thermal energy at temperatures higher than those non-imaging collectors. In this study, an experimental investigation for testing the performance of a PTSC array (10.2 m² total aperture area) at moderate temperatures is presented. The tests were performed using the outdoor measurements to evaluate the useful heat gain and the instantaneous thermal efficiency. In the performance analysis of the PTSC array, the effects of collector inlet temperature, ambient conditions, and the variation in mass flow rate of the working fluid (Renolin therm 320) were investigated. The steady-state and dynamic tests were carried out in a summer season of Gaziantep. The peak thermal efficiency for the PTSC array was estimated as 57% while the optical efficiency is at the level of 56%. Moreover, the efficiency tests were performed in a temperature range from 50°C to 200°C, and mass flow rate of 0.1 kg/s to 0.5 kg/s, respectively. The performance tests show that the obtained characteristic curve of the tested collector is considerably favorable for Industrial Process Heat (IPH) applications requiring thermal energy need lower than 200°C.

Keywords: Solar energy, parabolic trough collector, performance testing
Symbols

\( A_a \) aperture area, m\(^2\)

\( c_p \) specific heat capacity, J/kg°C

\( I \) total radiation, W/m\(^2\)

\( I_b \) beam radiation, W/m\(^2\)

\( I_d \) diffuse radiation, W/m\(^2\)

\( m \) mass flowrate, kg/s

\( \dot{Q}_u \) useful energy gain, W

\( \eta_{PTC} \) efficiency of parabolic trough collector

\( T_a \) ambient temperature, °C

\( T_{ex} \) exit temperature, °C

\( T_{in} \) inlet temperature, °C

Subscript

\( HTF \) heat transfer fluid

Abbreviation

HTF Heat Transfer Fluid

PTSC Parabolic Trough Solar Collector
1. Introduction

Concentrating collectors are widely used for many applications to supply thermal energy at temperatures higher than those nonimaging collectors. Not only this feature but also having relatively high thermal efficiency makes them to be convenient for thermal systems. Such typical characteristics put them forward to be used in industrial process heat (IPH) and concentrating solar power (CSP) applications. The type of application demonstrates the importance of collector testing throughout a design stage and its implementation. In this study, the outdoor test results of a PTSC array of Smirro300 [1] with a series of three modules have been presented for steady and dynamic cases under different operating conditions. The steady tests of the collector array have been performed under the variations of solar insolation, inlet temperature and mass flow rate. On the other hand, the dynamic tests have been applied under normal operating condition of the collector array.

2. Methodology
2.1 Experimental setup

The experimental setup for testing the collector array is presented in Figure 1. It is basically composed of PTSC array, Coiled Heat Exchanger (CHE), Brazed Plate Heat Exchanger (BPHE), Auxiliary Electric Heater (AEH), Thermal Expansion Tanks (TET) and gear pumps. The series arrangement of the PTSC array is composed of three collectors which are oriented toward north–south axis of the location. Thus it was provided for the array to track the sun from east to west. The tracking system is driven by the frequency-controlled double worm gear motor which is manipulated by the cooperation of the central control unit. In addition, the tracking motion is controlled by both fine positioning sun-seeking detector and external GPS (Global Positioning System). The working fluid used in the loops for heat transfer media was selected as thermal oil (Renolin therm 320). The flow rate change of the Heat Transfer Fluid (HTF) and the circulation of it were maintained by the frequency-controlled gear pump. In the solar field, the CHE was used to control the HTF’s temperature at the collector inlet by cooling it with water or air at high temperatures. At lower temperatures, the temperature control is managed by opening the Auxiliary Cooling Loop (ACL) which is connected to the solar field by BPHE. The energy transfer to the ACL is adjusted by the AEH that controls the set temperature by aid of a PID (Proportional Integral Derivative) controller.
The temperature and flow measurements in the experimental setup are performed by resistance temperature detectors (Pt100, Class A). The temperature dependent uncertainty of the detectors are designated by the relation of \( \pm(0.15 + 0.002T) \) °C and calibrated according to the standard of IEC751 [2]. The flow measurement for working fluid is operated by Krohne coriolis flowmeter having an accuracy of ±0.1% with a repeatability of less than 0.05% [3]. The wind speed is measured by NRG maximum #40 anemometer which has an accuracy within 0.1 m/s for the range of 5 m/s to 25 m/s [4]. The irradiance sensor is used to measure the global radiation by a high sensitive Kipp & Zonen CMP11 pyranometer with an expected uncertainty of less than 2% as daily total [5]. The direct beam radiation is accurately determined by Eq. 1 [6] both measuring total and diffuse radiation in a definite time periods.

\[
I = I_d + I_p \cos \theta_z
\]  

(1)

where \( \theta_z \) is the zenith angle of the sun defined as the angle between the line of beam radiation and horizontal surface.

Experimental test data for temperature, flow and solar radiation were gathered by the Daq (data acquisition) devices: USB-TEMP and 24-bit USB-2416 [7,8].

### 2.2 Thermal analysis

The PTSC array was tested and monitored in clear sky days at Gaziantep. The useful heat gain by the solar field and the thermal efficiency of the PTSC array were investigated. The
performance of the PTSC was evaluated using the parameters; beam radiation, and inlet and outlet temperatures of the HTF through the absorber tube for a given mass flow rate.

2.3 Performance parameters

2.4 Useful heat gain

The net energy transferred to the HTF by the solar field is related by the useful heat gain which leads the temperature change for the HTF flowing through the receiver tube of the PTSC array. The energy gained by the HTF can be calculated by using Eq. (2).

\[
\dot{Q}_u = \dot{m}_{HTF}c_{p,HTF}(T_{ex} - T_{in})
\]  

(2)

2.5 Thermal efficiency

The thermal efficiency of the PTSC array can be defined as the ratio of the useful heat transferred the HTF to the beam radiation incident on the aperture area of the array.

\[
\eta_{PTC} = \frac{\dot{Q}_u}{A_u \times I_b}
\]  

(3)

3. Results and discussion

The general test procedure is arranged to operate the PTSC system under nearly steady conditions in order to determine the useful heat gain and the thermal efficiency. Outdoor tests were performed in the midday hours when the beam radiation is high and the incidence conditions almost the same for the tests being involved.

Figure 2 shows the variation in the thermal efficiency of the PTSC array depending on the parameter of \((T_{in} - T_a)/I_b\). Tests were conducted in the clear sky days and the incident conditions of solar noon (about 12:00 solar time). The incidence angle calculated during the tests ranged from 20° to 24.5°. The mass flow rate for the HTF was chosen as 0.3 kg/s, and the inlet temperature of the HTF ranged from 100°C to 200°C. The efficiency tests were performed at medium temperature range due to the fact that the flow inside the receiver is in
laminar regime at lower temperatures. The HTF was entered the absorber pipe in turbulent regime to observe the highest thermal efficiencies at those temperatures. As it is expected that the thermal efficiency of the PTSC array is higher at lower inlet HTF temperatures since the heat loss from the receiver is lower relative to the higher temperatures. In case the inlet temperature is equal temperature with the ambient, the efficiency would become 52%. The efficiency curve changes as a function of second-degree polynomial. Increasing in the operating temperature affects the thermal efficiency in a negative way but more strongly.

\[
\eta = 0.5214 - 0.1006\Delta T/I_b - 1.341(\Delta T/I_b)^2
\]

\[R^2 = 0.972\]

Figure 2. Experimental results and regression of the thermal efficiency of Smirro300.

Figure 3 points out the variation of mass flow rate and its effect on the thermal efficiency. The efficiency tests were performed in a temperature range from 50°C to 200°C, and mass flow rate of 0.1 kg/s to 0.5 kg/s, respectively. The mass flow rate of the HTF is regulated by the frequency-controlled gear pump. The inlet temperature is provided initially as 50°C at which the mass flow rates 0.1, 0.3 and 0.5 kg/s are experienced, and then 100°C, 150°C and 200°C temperatures are managed with for the same flow rates.
Figure 3. Effect of mass flow rate on the thermal efficiency.

It is expected that the increase in the mass flow rate enhances the thermal efficiency [9]. At lower flow rates and temperatures, the regime of the flow for thermal oil is in laminar or transition region which degrades the convection heat transfer coefficient within the absorber pipe or Reynolds number hence the thermal efficiency of the collector drops as seen in Figure 3. This is interconnected to the viscosity value of the HTF which affects the Re to have values lower than 4000.

Table 1. Technical properties of Renolin therm 320.

<table>
<thead>
<tr>
<th>Temperature °C</th>
<th>Density kg/m³</th>
<th>Specific heat J/kg. °C</th>
<th>Thermal conductivity W/m. °C</th>
<th>Kinematic viscosity m²/s ×10⁻⁶</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>879</td>
<td>1864</td>
<td>0.134</td>
<td>368.39</td>
</tr>
<tr>
<td>50</td>
<td>848</td>
<td>2078</td>
<td>0.131</td>
<td>22.144</td>
</tr>
<tr>
<td>100</td>
<td>816</td>
<td>2293</td>
<td>0.127</td>
<td>5.535</td>
</tr>
<tr>
<td>150</td>
<td>783</td>
<td>2507</td>
<td>0.124</td>
<td>2.463</td>
</tr>
<tr>
<td>200</td>
<td>750</td>
<td>2721</td>
<td>0.120</td>
<td>1.416</td>
</tr>
</tbody>
</table>

As it is seen from Table 1, in case the inlet temperature increases from 50°C to 100°C, the viscosity of the HTF lowers about one-fourth relative to the 50°C. Further raising the
temperature declines the viscosity and increases the Re much more. However, the entrance region to turbulent for the PTSC array is about 100°C. The obtained thermal efficiencies between the flow rates 0.1 kg/s and 0.3 kg/s indicate the effect of flow regime openly.

The dynamic behavior of the PTSC array under ambient conditions is illustrated in Figure 4 and 5. The efficiency varies as a function of operation temperature and beam radiation. The flow rate change varies with operating temperature under constant frequency control; it is represented as a function of outlet temperature of the PTSC i.e., \( \dot{m} = 1210 - 1.065T_{out} \). The thermal efficiency decreases with time especially in higher temperatures. As the HTF temperature increases, the heat losses from the receiver increase. Thus, the slope of the temperature curve is started to decline. In other words, the thermal efficiency of the PTSC begins to fall with increasing of the operating temperature as seen Figure 5. The thermal efficiency strongly depends on incident beam radiation, optical efficiency of the PTSC, and operating conditions. Operating conditions such as temperature and flow regime affect predominantly the thermal efficiency [9,10]. Between 70°C and 100°C, the thermal efficiency fluctuates remarkably due to transition regime. In this temperature interval, the thermal efficiency approaches to 57%. Increasing the mass flow rate causes to develop turbulent currents within the absorber pipe so that the thermal efficiency of the PTSC rises. This is

![Figure 4. Dynamic temperature profile under ambient conditions.](image)
related to the HTF which absorbs more energy from the inner surface of the pipe. Thus the useful heat gain transferred to the fluid has increased due to lowering the thermal loss.

![Graph](image)

Figure 5. Variation in the beam radiation and thermal efficiency.

4. Conclusions

Parabolic trough solar collector is a proven technology for electricity generation but its usage in IPH applications have not been matured completely, yet. In this study, the sample performance tests of Smirro300 collector (1.14 m wide and 3.0 m long) were performed to characterize it under the climate conditions of Gaziantep. An experimental setup was installed for this task, and the necessary analyses were carried out for the future studies to be made on a small-scale IPH. Thus, all these efforts will play an important role in the related system design and the methodology to be followed experimentally. The performance tests showed that the obtained characteristic curve of the tested collector is considerably favorable for IPH applications requiring thermal energy need lower than 200°C.
5. Acknowledgement

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6. References

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4. Type 40 maximum anemometer. Available at: http://www.renewablenrgsystems.com/.