DESIGN, FABRICATION AND PERFORMANCE EVALUATION OF A LOW-COST PARABOLIC TROUGH COLLECTOR WITH COPPER RECEIVER

Amit Kumar Pandey, Dr. Ajeet Kumar Rai, Vivek Sachan

MED, SSET, Sam Higginbottom Institute of Agriculture Technology and Sciences, Allahabad (U.P.), India

ABSTRACT

In the present work, an attempt has been made to design, fabricate & evaluate the performance of Parabolic Trough Collector (PTC) to produce hot water. The Supporting stand of concentrator is made of mild steel & reflector is made of acrylic sheet with a rim angle of 45° and aperture area of 2.14 m² and with a concentration ratio of 12.59. The receiver pipe is made of pure copper. The thermal performance of the PTC was determined according to ASHRAE 93-1986 (RA 91). The maximum instantaneous thermal efficiency of 52.35% is obtained. The total cost of the parabolic trough collector is calculated as Rs 7,000.

INTRODUCTION

Parabolic Trough Concentrator (PTC) is a solar concentrator technology that converts solar beam radiation into thermal energy. A cylindrical parabolic trough is a conventional optical imaging device used as a solar concentrator. It consists of a cylindrical parabolic reflector and a metal tube receiver at its focal plane. The receiver is blackened at the outside surface covered by concentrator and rotated about one axis to track the sun’s diurnal motion. The heat transfer fluid flows through the absorber tube, gets heated and thus carries heat.

Such concentrators have been in use for many years. The aperture diameter, rim angle and absorber size and shape may be used to define the concentrator. The absorber tube may be made of mild steel or copper and is coated with a heat resistant black paint. Selective coatings may be used for better performance. Depending on the temperature requirement different heat transfer liquids may be used. Reflectors may be of anodized, aluminium Mylar or curved silvered glass. Since it is difficult to curve a very large, mirror strips are sometimes used in the shape of parabolic cylinder. The reflecting part is fixed on a light weight structure. The concentration ratio for a cylindrical absorber varies from 5 to 30.
The major energy losses from a concentrator-receiver assembly for normal incidence are losses during reflection from reflecting surface and convection loss from the receiver to surrounding. Efforts are made to use high reflecting materials and to reduce convection. Twisted types are used in the absorber tube to cause large heat transfer from the absorber to working fluid.

A cylindrical parabolic trough may be oriented in any of the three directions: East-west, north-south or polar. The first two orientations although simple to assemble, have higher incidence angle cosine losses. The polar configuration intercepts more solar radiation per unit area as compared to other modes and thus gives the best performance.

**DESIGN CONSIDERATIONS**

The Parabolic Trough Solar Concentrator, we present here, has the following innovative characteristics: low cost of manufacturing materials, light and strong structure, and easy construction. In order to reduce the construction expenses, two commercially available Acrylic Mirror Sheets of the size (0.92 m * 1.22 m) and 1 mm thickness were used. They were placed longitudinally; this in turn determined the size of the PTC. An Acrylic Mirror Sheet is chosen, since it reflects 80% of sunlight. As part of the design of the PTC, the Mirror Sheets are not cut or rolled; the Mirror Sheets are installed on the structure without modification, the parabolic profile is given by the shape of the ribs and the weight of the sheets as they rest on said ribs.

**Design Parameters of PTC**

In order to determine the dimensions of the PTC, the following parameters were considered: a rim angle of 45° ($\phi_r = 45^\circ$) and the width of the acrylic sheet $S = 1.22$ m. Based on these two parameters, it is possible to determine the aperture of the parabola, $W_a$:

$$W_a = \frac{2S \tan \left(\frac{\phi_r}{2}\right)}{\left(\sec \left(\frac{\phi_r}{2}\right) + \tan \left(\frac{\phi_r}{2}\right) + \ln \left(\sec \left(\frac{\phi_r}{2}\right) + \tan \left(\frac{\phi_r}{2}\right)\right)\right)}$$

And, focal length, $f$:

$$f = \frac{W_a}{4 \tan \left(\frac{\phi_r}{2}\right)}$$

On the other hand, the geometric concentration ratio (C) for a tubular receiver is given by:

$$C = \frac{W_a}{\pi D_o}$$

Where, $W_a$ is the width of the collector and $D_o$ is the outer diameter of the receiver. For the manufacture of the receiver, a commercially available copper tube with outer diameter ($D_o$) of 0.03 m is used. Table 1 gives a summary of the PTC key features.
Table 1: Specifications of PTC

<table>
<thead>
<tr>
<th>Specification</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rim Angle ($\phi_r$)</td>
<td>45°</td>
</tr>
<tr>
<td>Focal Length (f)</td>
<td>0.0051 m</td>
</tr>
<tr>
<td>Aperture Width ($W_a$)</td>
<td>1.1861 m</td>
</tr>
<tr>
<td>Diameter of Receiver Tube ($D_o$)</td>
<td>0.03 m</td>
</tr>
<tr>
<td>Length of Parabola (L)</td>
<td>1.82 m</td>
</tr>
<tr>
<td>Effective Aperture Area ($A_a$)</td>
<td>2.09 m²</td>
</tr>
<tr>
<td>Concentration Ratio (C)</td>
<td>12.59</td>
</tr>
<tr>
<td>Reflectivity of collector ($\rho$)</td>
<td>0.9</td>
</tr>
<tr>
<td>Absorptivity of receiver tube ($\alpha$)</td>
<td>0.8</td>
</tr>
<tr>
<td>Transitivity of receiver tube ($\tau$)</td>
<td>0.8</td>
</tr>
<tr>
<td>Intercept Factor ($\gamma$)</td>
<td>0.92</td>
</tr>
</tbody>
</table>

Therefore, the sacrifice in optical efficiency is small, while the increment in concentration ratio and aperture area is significant. This allows savings in reflective materials cost.

Fabrication of PTC

The PTC is constructed in a very simple manner. It consists of a parabolic trough, a receiver, and a support structure. The detailed description of each part is given below:

1. Parabolic Trough

The proposed trough collector consists of low-cost Acrylic Mirror Sheet of 1 mm thickness, which has undergone a careful deformation process that was necessary to bring it to parabolic shape. The material is easily available and can be given requisite shape. For the easy manoeuvrability of the collector system, the aperture width of the trough is taken 1.18m and its focal length is 0.0051 m. The aperture area of the reflecting surface is 2.14 m². To maintain the parabolic shape intact, cross-ribs made of cast iron are provided on the back surface. The trough collector is then mounted on stand made of cast iron. The specific mirror sheet is economic, light and has a high reflectivity coefficient of 0.80. The environmental stability of the reflective surface was monitored for 12 months.

2. Receiver

The purpose of the designed parabolic trough collector was to heat water at atmospheric pressure and temperature. The desired process was carried out in the receiver placed concentrically along the focal line of the collector. Out of many shapes thought of, from circular to square, circular section was finalized. The reason being easy availability and less area coverage to avoid shading on the reflector. The circular pipe made of Copper (Cu) is used for the purpose. Copper makes a good conductor of heat because of its free electrons that can quickly pass on the energy that is applied to it. The size of the Receiver was decided based on two factors viz. (i) Local availability of channel section, and (ii) Concentration ratio desired. The final Receiver dimensions are taken as outer diameter 0.03m and length 2.13m.

3. Collector Support Structure

For collector’s stability and accuracy, a rigid supporting structure is designed and made with rigid iron strips. The structure frame is supported to the rotation axis of the parabolic reflecting...
surface. It is used for the rotation of the horizontal axis for daily tracking of the sun. For test purpose and cost reduction, the unit is designed for easy manual tracking.

EXPERIMENTAL SETUP

The experimental setup of the parabolic trough solar collector consists of a collector, a storage tank of capacity 30 litres, and a receiver pipe of length 2.13 m with two valves at both ends. The water supply tank is located above the receiver’s pipe level to allow the heating fluid to flow naturally without pumping system. The storage tank is filled from main water supply. The water inlet and outlet temperature of the absorber tube, the ambient temperature, the reflector temperature, the temperatures at inlet/outlet/middle surface of the receiver, the solar radiation intensity and the wind velocity are continually measured during the experiment. The outdoor experimentation was carried out in the month of March and April 2014. The testing system is oriented North-South to capture maximum insolation as shown in figure 1.

Fig. 1: Experimental Setup of parabolic trough concentrator

PERFORMANCE OF PARABOLIC TROUGH COLLECTOR

The purpose of the performance analysis is to develop an empirical mathematical model that characterizes the performance of the solar field under different operating conditions for the system under study. The parameters that will be used to estimate the performance are the solar field efficiency and the useful heat output from the solar field.

Optical Efficiency

The optical efficiency $\eta_o$ is defined as the amount of radiation absorbed by the absorber tube divided by the amount of direct normal radiation incident on the aperture area. The optical efficiency when the incident radiation is normal to the aperture ($\theta = 0^\circ$) is given as:

$$\eta_o = \rho (\tau \alpha) \gamma$$

Thermal Efficiency

For solar collectors in general, the collector overall efficiency $\eta_c$ is defined as the ratio between the useful output $Q_u$ [W] delivered by the collector to the global irradiance $I$ [W/m²] incident on the collector aperture area $A_a$ [m²]
\[ \eta_c = \frac{Q_u}{A_a \cdot I_b} \]

For a concentrating collector, the useful output \( Q_u \) can be expressed as:

\[ Q_u = m \cdot C_p \cdot (T_o - T_i) = A_a \cdot I_b \cdot \eta_a - A_{abs} \cdot U_l \cdot (T_{abs} - T_a) \]

RESULTS AND DISCUSSION

Numbers of observations were taken on the system in the month of March & April 2014 in the campus of SHIATS, Allahabad, Uttar Pradesh, India. Datas are plotted for a particular day.

Fig. 2: Variation of solar intensity with time

Figure 2 shows the variation of solar intensity with time. As it is expected, the maximum intensity of 1020 W/m\(^2\) is obtained at mid noon.

Fig. 3: Variation of wind speed with time
Figure 3 shows the variation of wind speed with time, which is moderate except in the evening time. System is capable of offering good resistance to wind.

Figure 4 shows the variation of water inlet into the receiver pipe, water outlet from the receiver pipe and ambient temperatures with time of the day. It is clear from figure 2 and 4 that, due to better solar intensity in the forenoon, water outlet temperature from the receiver pipe is higher than in the afternoon. The blue line shows the water inlet temperature to the receiver from an overhead tank, which is getting heated throughout the day and because of this the blue line, has a tendency to move up in the graph. Till around 11 ‘o’ clock water temperature in the tank is at atmospheric temperature and so, green line and blue line are closer to each other.

Figure 5 shows the variation of temperature difference between inlet and outlet temperatures with time of the day. As it is clear from figure, the maximum temperature difference of 47°C was obtained at 11:00 Hours.
Figure 6: Variation of thermal efficiency with time

Figure 6 shows the variation of instantaneous thermal efficiency of the system with time of the day. As it is clear from the figure, a maximum instantaneous thermal efficiency of 52.35% is obtained at around 3:30 Hours.

Cost analysis of the system is also performed and it is obtained as Rs 7,000. Payback period is also calculated and it is less than 2 years.

CONCLUSION

From the collected data, figures, graphs and tables, in relation with the analysis and discussions, this research investigation can be concluded that, the fabricated PTC is quite efficient. As the construction is very simple with locally available low cost materials, it could be manufactured in any workshop. The maximum water temperature obtained from the PTC was 80°C and a maximum temperature difference from the inlet was 47°C. Due to its low cost and simple technology, it is affordable by the middle and lower middle class people of India.

NOMENCLATURE

\( \eta_0 \) = optical efficiency  \hspace{1cm} \rho = \text{Reflectivity}  \\
\( \tau \) = Transitivity  \hspace{1cm} \alpha = \text{Emissivity}  \\
\( \gamma \) = Intercept Factor  \hspace{1cm} \eta_c = \text{Thermal Efficiency}  \\
Q_u = \text{Useful Heat Output}  \hspace{1cm} m = \text{Mass Flow Rate}  \\
C_p = \text{Specific Heat of Water}  \hspace{1cm} T_o = \text{Outlet Temperature}  \\
T_i = \text{Inlet Temperature}  \hspace{1cm} A_a = \text{Aperture Area}  \\
I_b = \text{Incident Solar Radiation}  \hspace{1cm} A_{abs} = \text{Absorber Area}  \\
U_l = \text{Overall Heat Transfer Coefficient}  \hspace{1cm} T_{abs} = \text{Absorber Temperature}  \\
T_a = \text{Ambient Temperature}

REFERENCES


