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Manufacturing of a parabolic trough concentrating collector test rig and a "LASER-Screen" technique for measuring actual focal length and light interceptance of the collector

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Abstract

A portable parabolic trough-concentrating solar collector test rig was designed, and fabricated using locally available materials and technique. A trough made of any materials and the energy collection element of any geometry with maximum aperture area of 80×100cm^2 and 2.5×100cm^2 respectively can be fitted readily in the support structure of the rig. A two-axis manual tracking system allows the rig to track the sun daily from east to west for every 5° interval, and seasonally from 50°North to 80°South for every 15°. In addition to this, actual focal length and light interceptance were investigated applying customised "LASER-Screen" technique. An average light interceptance of the rig for a 2.5 cm diameter absorber tube was measured to be 85.9%. The focal length of the 100 cm long test rig was found to be 18.167±1.35cm. The test rig will facilitate to investigate the energy potential in Chittagong region of Bangladesh.

Keywords: Parabolic trough concentrating collector; concentrating solar power; parabolic profile accuracy; slope error measurement; LASER-Screen technique.

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1. Introduction

Rapid depletion of fossil fuels, global warming and ecological imbalance are driving society to use green and renewable alternatives like solar energy. Efficient harnessing of this vast energy sources has the potential to fulfil the world's energy demand [1–3]. A significant amount of research has already been undertaken to develop technologies for harnessing this abundant energy source [4–15]. Concentrating solar power technologies including the PTCC, parabolic dish, linear Fresnel reflector and heliostat field are competitive candidates to the conventional sources in terms of carbon emissions though the investment cost is still higher [16].

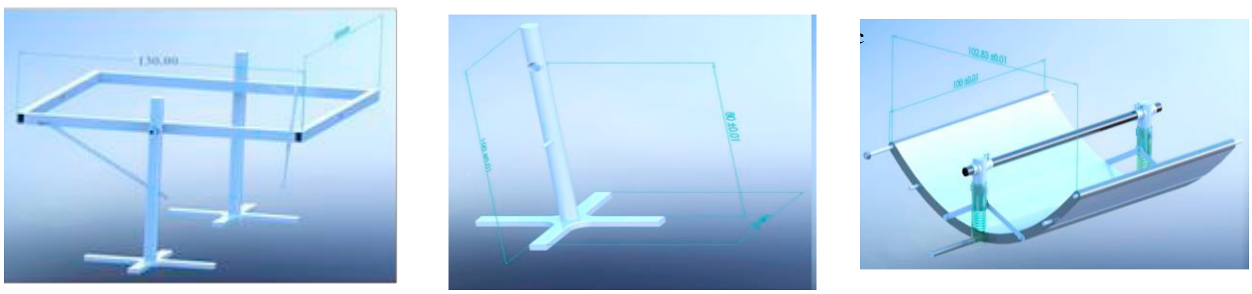
A PTCC can be used for collecting thermal energy using a parabolic trough collector (PTC) [12,17–19], electrical energy using a concentrating photovoltaic collector (TCPV) with passive cooling system [20,21] or combined thermal and electrical energy using a concentrating photovoltaic/thermal collector (TCPVT) with an active cooling system [22–23]. Usually a PTCC is fabricated placing an energy collection element (ECE) along the focal line of a parabolic trough mirror. While the geometry of the ECE of a PTC collector is generally tubular [17,25], that of the CPV collector is flat and rectangular with a heat sink [20,21] and CPVT collectors are either flat rectangular [23], hollow inverted triangular [26–28] or tubular [25] with a heat transfer fluid passage. The overall energy performance of a PTCC relies directly on the optical performance of the collector, which is affected by many optical factors [29] including profile accuracy of the mirror.

In this paper, design and fabrication of a portable PTCC test rig with multiple functionality using locally available materials and technique is discussed. In addition to this, a customized "LASER-Screen" technique is introduced to measure the actual focal length and light interceptance of the collector.

2. Design and fabrication

2.1 Design parameters

The width and height of the trough supporting frame were 130cm (see (Fig. 1(a)) that can be rotate 360° for sun tracking. Therefore the height of the support stand was chosen 100 cm (see (Fig. 1(b)). The CAD design of the collector is shown in Fig. 1(c). The cross-sectional areas of the frames were chosen 1.5 × 1.5 inch^2 arbitrarily to bear the collector dynamic load, tracking mechanism and fatigue wind load quite satisfactorily. Trough supporting frame is connected with the supporting stand by means of journal bearings at 80 cm height from the ground.



(a) (b) (c)

Fig. 1. (a) trough supporting frame; (b) support stand; (c) the trough and ECE arrangement

The Frame also hold the tracking mechanism. MS square bar with dimensions 1.5″ × 1.5″ is used to making the supporting frame. The parabolic trough as shown in Fig. 1(c) is the most important part of the whole model. To designing it and making the concentrator all the parameter regarding the parabola was taken into account. We made all the calculation while fabricating the model. According to calculation a parabola was drawn, and 3 flat MS bars will bend according to this shape. After that MS sheet was placed upon the bar and riveted with it. Then it was placed into the supporting frame with a central load carrying road and connect with it by journal mechanism.

Concentrator also hold the receiver tube and tube holder mechanism. Receiver tube holder is attached with the trough rigidly. The tube holder able to change its height to gain off focal position. Tube holder was designed such a way, so it can hold various size shape and cross-sectional receiver tube.

2.2 Fabrication of parabolic trough

The prototyping was carried out in the workshop at Chittagong University of Engineering and Technology, Bangladesh. Mild steel (MS) square bars of 1.5 cm^2, flat bars of 1.5 cm width and 2 mm thickness, and sheet of 100 cm^2 were collected from the local markets. The complete test rig was fabricated (see Fig. 2. (a)) as per the design shown in Fig. 2(b).Two pieces of MS flat bars were rolled repeatedly until the desired parabolic shape was achieved, and then heat treatment was done to reduce spring back action. These two flat bars were bolted with four more flat bars. The sheet metal was bolted on this frame and fabricated a parabolic mirror of aperture area 80×100 cm^2. Two pieces of perforated MS flat bars as can be seen in the figure were used to track the sun daily. Similar arrangement was used for seasonal tracking, which is not seen in the figure. The base of the support stand was welded. The rest of the joints of the test rig were made temporary using nuts and bolts to make it easy to disassemble and portable.

(a) (b)

Fig. 2. (a) Prototype; (b) CAD model of the collector.

3. Tracking performance of the test rig

3.1 Daily solar tracking capability of the test rig

Essentially, the collector has the capability to rotate 360° with respect to its vertex. Three positions of the test rig at the morning, noon and evening are shown in Fig. 3.

(a) (b) (c)

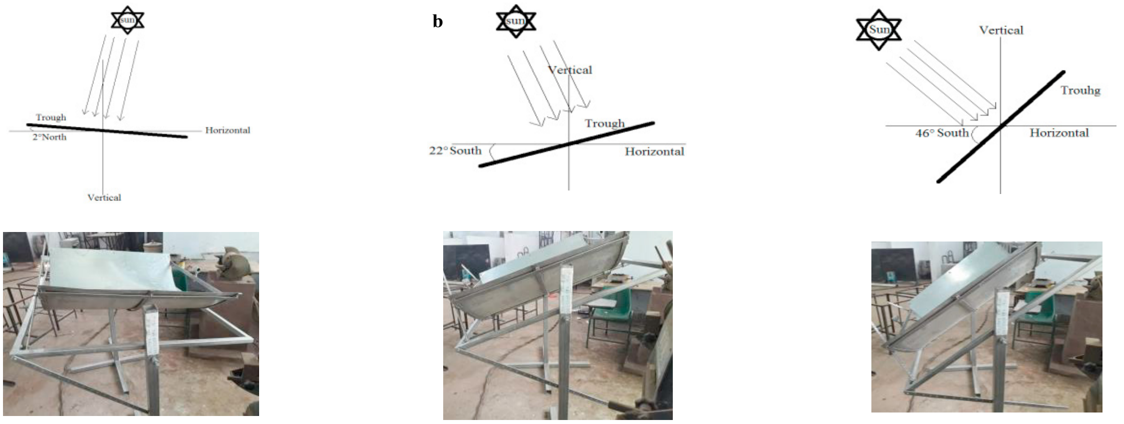
Fig. 3. (a) The collector facing the morning sun at 90°East; (b) The trough inclination is 0° at the noon; (c) Trough inclination in the evening 90°West from zenith.

3.2 Seasonal solar tracking capabilities of the test rig

Chittagong is situated in 22°20′51″ North and 91°48′44″ East coordinates. The movement of the sun throughout the year can be categorized into three major time durations [22]:

i. Winter: Throughout the day the sun appears at an orbit 46º inclined from the vertical towards the South;
ii. Spring: The sun orbit remains around 22º from the vertical.
iii. Summer: At summer the inclination is the lowest. Its 2º toward the North.
iv. Autumn: It the same as the winter with a negligible fluctuation.

Seasonal solar tracking capability of the test rig is demonstrated in Fig. 4.



(a) (b) (c)

Fig. 4. Sesonal variation of solar azimuth angle at chittagong region; (a) 2°North in the summer; (b) 22°South in the autmn and spring; (d) 46°South in winter.

4. Trough profile accuracy measurement using "LASER-Screen" technique

One of the main influences on the overall performance of a parabolic-trough concentrator is the optical quality of the concentrator field, which is determined by the reflectivity of the mirrors, the absorptivity of the receiver, and, in particular, the geometric precision of the reflector shape. Deviations from the optimum parabolic shape lead to optical losses on account of reflected rays that pass the absorber tube. These deviations are quantified in the local surface slope error, which gives the angular deviation of the surface normal at a given point on the mirror from the ideal surface normal.

4.1 Profile error measurement of the trough

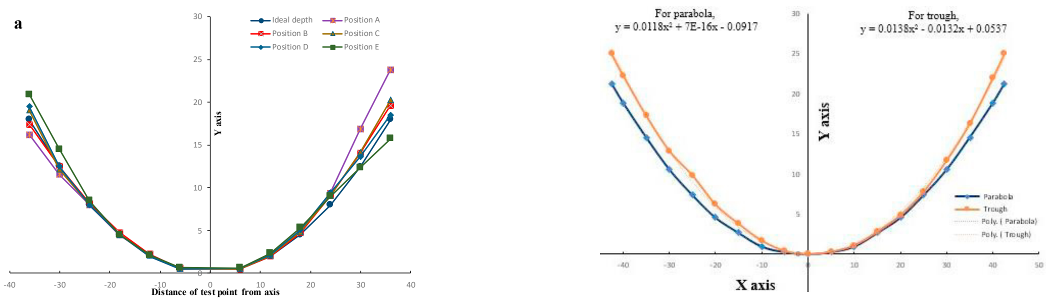
In the parabolic trough concentrator, the perpendicularly incident ray intersects in the focal point of the parabola after reflection. A technique was investigated where laser ray was used as the incident ray and a flat board as screen will be positioned through the focal point along the axis of symmetry of the trough where reflected rays will be intersected. In the flat board a straight line was drawn though the theoretical focal points and the position of the reflected rays was marked. From the marking of the reflected rays the deviation between the actual focal line and theoretical was calculated. At first, laser rays should incident on different points of the parabolic slope, which should intersect in the focal point after reflection. If there is error in the slope, the reflected ray from the point does not coincide with the focal point.

The "LASER-Screen" technique is explained in Fig. 5. At first some points were taken on the parabolic concentrator A, A', B, B', C, C', D, D', E, E' shown in Fig. 5(a). Every corresponding points act as individual parabola like AA', BB',CC',DD' , EE'. The distances a_1, a_2, a_3 ,a_4, and corresponding focal lengths can be determined experimentally. These experimental focal lengths were compared with theoretical focal lengths, which was calculated from the equation of parabola, $a = X^2/(4f)$. Determine the corresponding distance of the points A, A',B,B',C,C',D,D' from the parabolic axis $-x_1$, x_1, $-x_2$, x_2, $-x_3$, x_3, $-x_4$, x_4, $-x_5$, x_5 respectively. After plotting the data ($-x_i$, a_i), (x_i, a_i) the parabolic slope can be determined. From Fig. 5(b), the flat plate is situated vertically with the X axis along the focal plane of the parabola. The laser lite holder holds the laser lite and can travel through the Z axis. For the implementation of the method the required design arrangement is shown in Fig. 5(c).

Fig. 5. Profile error measurement (a) depth of parabola at different test point; (b) experimental setup; (c) theoretical background of slope error measurement.

4.2 Results and discussion

As the parabolic solar concentrator is 1 meter long, readings were taken at five positions of the parabola A, B, C, D, E, F about Y axis shown in Fig. 6(a). Along a slope at twelve positions readings are taken. The test points are 6cm apart from each other. The laser lite holder was travelled along the axis of the parabolic axis. From the reflected rays on the flat plate along the parabolic axis the Laser ray measured focal points were measured. L.L.M (Laser Ray Measured) depth of the parabola can be measured from equation 3. S.M (Scale Measured) depth was measured to compare with L.L.M depth. The ideal VS L.R.M (Laser Ray Measured) profile and ideal VS S.M (Scale Measured) profile at all five positions (position A, position B, position C, position D and position E) is shown in Fig. 6(a) and Fig. 6(b) respectively. From the figure the actual profile of the parabolic concentrator at all five positions are found. The figure explains the scale measured profile from which the error in the laser ray measurement can be easily determined. Theoretical and actual equations of parabolic profile of the trough was measured as shown in Fig. 6(b).



(a) (b)

Fig. 6. (a) ideal VS laser ray measured slope at all tested positions; (b) ideal parabola VS actual trough profile equations measured by curve fitting technique.

The error in laser ray measured data compared to scale measured value in different test points are shown in Fig. 7. Average overall error of the L.R.M. technique is 9.2% compare to the scale measured value.

By analyzing the Fig. 6 and Fig. 7, it can be said that the examined parabolic concentrator has some slope error and the deviation from the ideal profile is around 23%. It is also noticed from the results that the alignment of parabolic concentrator during set up was not symmetrical along the optical axis and it deviates at the left side from the axis. To find the accuracy of this laser ray measurement technique, direct scale measured profile is also evaluated. By comparing the scale measured profile, it is found that the error in laser ray measurement technique is 9.2% which represents that the accuracy of this technique is around 90.8%.

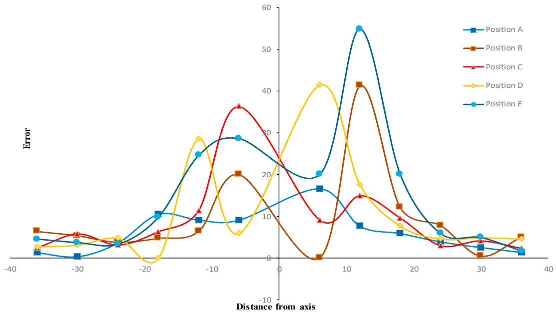


Fig. 7. Errors between L.R.M. and S.M. Values in different test points.

4.3 Mean deviation of focal point

The focal point distribution at five different position shown in Fig. 5(a) was obtained experimentally and theoretically. Mean or average deviation (see equation (1)) of these focal point can be calculated. In this case the diameter of the receiver tube is considered 2.5cm. The mean deviation and percentage of rays miss the receiver tube were calculated using equations (1) and (2) respectively.

$$\text{Mean deviation at any position} = \frac{\sum \text{Deviation of all points}}{\text{Total number of points}} \quad (1)$$

$$\%\ \text{of rays miss the receiver tube} = \frac{\sum \text{Number of rays miss the receiver tube}}{\text{Total number of rays}} \times 100 \quad (2)$$

For position A, B, C, D and E, see Fig. 7(a), mean deviation of the focal length was found to be 1.48461, 1.16153, 1.2, 1.16153 and 1.68461 cm respectively. Percent of the rays miss the receiver tube as per equation (2) was found to be 23.08 %, 7.69 %, 0 %, 7.69 % and 30.77 % respectively for the five position. Final average mean deviation and average percent of rays miss the receiver tube for all position was found 1.35512 cm and 14.10 % respectively. Hence, Average light interceptance by the tubular receiver of 2.5 cm diameter was found to be 85.9 %.

5. Conclusion

This paper discussed on design and fabrication of a parabolic trough concentrating solar collector test rig, and analyses of profile accuracy of the trough mirror. The prototype has two axis intermittent tracking system. It can hold any parabolic mirror with aperture area of 80cm×100cm. The parabolic mirror and the receiver tube of the trough is readily changeable. It could be able to track the sun daily as well as seasonally. After analyzing different trough profile different parameters are found below:

- While, the theoretical focal length of the trough was calculated to be 18.167 cm, the actual focal length of the trough was found to be 18.167±1.35 cm.
- Average light interceptance by the receiver was found to be 85.9%.

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