Optimal Positioning of Reflectors to Increase Heat Interception of a Compound Parabolic Solar Collector using Taguchi Method

Diptanu Dey, Abhirup Bhattacharya, Agnimitra Das, Asmita Khan, Debalina Dhar, Gaurav Bhattacharjee and Kaushik Saha

Department of Electrical Engineering, National Institute of Technology, Agartala – 799046, Tripura, India;
ddiptanu.career@gmail.com, abhirup1296@gmail.com, lifeagni@gmail.com, khanasmita@gmail.com, hey.debalina1994@gmail.com, gauravbhattacharjee24@gmail.com, meritoriouskakka@gmail.com

Abstract
This work represents the optimization of reflector positioning of compound parabolic collectors for enhanced heat interception. The heat intercepted by a compound parabolic collector can be improved either by increasing the quantity of incident solar radiation or by absorbing a greater percentage of the available radiation. In the redesigned system, the utilization of incident heat has been increased by increasing the utilization of incident heat, instead of increasing the quantity of incident heat. We have increased the overall efficiency of the compound parabolic collector by applying Taguchi’s method, increasing the maximum concentration ratio to a value almost equal to the geometric concentration ratio and therefore achieved maximum utilizations of the available solar radiation. We have increased the heat intercepted by 23% from 3.7 KW to 3.75 KW and by applying electronic and mechanical tracking, an increase in average solar flux concentration by 10 times is observed.

Keywords: Compound Parabolic, Heat Interception, Reflector Positioning, Solar Collector, CPC

1. Introduction

Compound Parabolic Concentrator (CPC) is a type of concentrating collector which is of non-imaging type. The CPC can receive incoming radiation with large angular spread and yet can concentrate into linear receivers of small transverse width, making it highly advantageous for solar energy concentration. CPC lies in the medium temperature range of 80° – 300°. A lot of industrial applications require process heat in the range of 80° – 150°C, which can be met by employing CPC systems. It is possible to construct concentrating collectors that can function seasonally or annually with minimum tracking requirements. The concentration ratio up to 10 can be achieved in the non-tracking mode easily. Thus it leads to cost savings. It is one of the collectors which has the highest possible concentration permissible by thermodynamic limit for a given acceptance angle. The large acceptance angle of CPC results in intermittent tracking towards the sun. We have purchased a CPC from the market and have analyzed optical and thermal properties of that CPC. Now varying geometric configuration heat intercepted by the collector is observed and a study of comparison for heat interception at local solar noon by the existing CPC and redesigned CPC is done.

2. Geometry of CPC

The geometry of a CPC is shown in Figure 1(a), which consists of two parabola sections AB and CD of parabola 1 and 2 respectively. AD is the aperture area with width w, while BC is the absorber area with width b. The axes
are oriented in such a way that C is the focus of parabola 1 and B is the focus of parabola 2. The height of the collector is so chosen that tangents at A and D are parallel to the axis of the collector.

CPCs acceptance angle is the angle AED, which is obtained by joining the focus to the opposite aperture edge. The concentration ratio is given by w/b. concentration ratio for a CPC generally lies around 3–10.

### 3. Study of an Existing CPC

To start working on a compound parabolic solar collector, an existing collector needs to be studied first. We chose a random collector from the market, and it was manufactured by maharishi solar of Noida, India. The two dimensional CPC model system manufactured by at maharishi solar, Noida is designed to perform best with its length parallel to horizontal east-west direction and aperture sloping towards the south. The details of the collector have been studied thoroughly, and the results are presented below in Table 1.

The absorber axis is aligned east west for the higher yearly output.

The optical properties can be explained by the model diagram Figure 1(b). Optical angles are mentioned in the diagram. The dimensions of length are in decimetres and the angles are in degrees.

Based on the deciding factors, i.e. the value of concentration ratio and the allowed angular offset for the incident rays on the aperture plane, the intermittent tracking is recommended. Therefore, it is important to know the amount of energy reaching the target with respect to different angles of solar incidence. The analysis is done using edge-ray principle and explained in Figure 1(c).

It is required that all the rays entering into the extreme collecting angle $\theta_i$ shall emerge through the rim point P of the exit aperture.

In ideal two-dimensional CPC system, concentration ratio relationship is given as

$$C = \frac{1}{\sin \theta_a}$$  \hspace{1cm} (1)

Where $\theta_a$ = angular half-width of source (= acceptance half angle of ideal concentrator)

For a plane rotated about horizontal east-west axis with a single daily adjustment, the beam radiation is normal to the surface at noon each day.

$$\cos \theta = \sin^2 \delta + \cos^2 \delta \cos \omega$$  \hspace{1cm} (2)
The slope of this surface will be fixed for each day and will be

$$\beta = |\phi - \delta|$$

where $\beta$ = collector tilt from equatorial plane, $\phi$ = rim angle, $\delta$ = effective angular half-width of sun (or other source) as seen through imperfect mirrors.

In order to study further the properties and characteristics of concentration of the existing system, ray tracing is performed on the collector. A laser light beam is flashed on the collector at various positions in various incidence angles. The trajectory of the light beam shows the path at which the rays are concentrated in the collector. A graphical form of the rays is prepared. Following are the ray tracing results of the existing system:

Ray tracing is done for 0° incidence angle of existing design in Figure 2(a). Here all the incident rays on the reflector reach the target after one reflection.

Ray tracing is done for 10° incidence angle of existing design in Figure 2(b).

Ray tracing is done for 15° incidence angle of existing design in Figure 2(c). Here all the incident rays on the reflector reach the target except the extreme rays.

Ray tracing is done for 20° incidence angle in Figure 2(d). Here all the incident rays on the reflector reach the target except the rays on the upper mirror.

The optical efficiency is defined as ratio of the energy absorbed by the receiver to the energy incident on the aperture of collector. The optical efficiency is dependent on

| Table 1. Specifications of the existing CPC |
|-------------------------------------------|
| **CPC dimensions** | **Length (m)** | **Width (m)** | **Area (m²)** |
|---------------------|----------------|--------------|---------------|
| Reflector(w/o frame) | 2.315          | .320(4qty) | .390(2qty) | 4.77 |
| Reflector(with frame) | 2.330          | .327(4qty) | .395(2qty) | 4.89 |
| Receiver(w/o frame) | 2.270          | .400       | .910        |
| Receiver(with frame) | 2.320       | .450       | 1.040       |
| Aperture            | 2.330          | 1.100      | 2.560       |
| CPC Height          | 1.02(m)        |             |             |
| No. of tubes        | 19             |             |             |
| Outer diameter      | 12.5(m)        |             |             |
| Inner diameter      | 12(m)          |             |             |
| Acceptance angle    | 74°            |             |             |
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the optical properties of materials involved, the geometry of the collector, and the various imperfections arising from the construction of the collector. The ideal maximum optical efficiency is given by the following equation.

\[ n_o = \tau \alpha \rho \Upsilon^2 \] (4)

Where, \( \tau = 0.92 \), solar transmissivity of absorber cover, \( \alpha = 0.95 \), solar absorptivity of absorber, \( \rho = 0.94 \), solar reflectivity of reflector, \( \Upsilon = 0.96 \), fraction of total insolation accepted by the CPC.

The ideal maximum optical efficiency is found to be 79%, this is the maximum limit for optical efficiency of this system, which can be seen in Figure 3(a).

Heat intercepted by the collector is being shown in Figure 3(b) with the help of data collected for a particular day of each month along the year.

4. Redesigning the CPC

In the existing design the geometric concentration ratio is 2.36 and maximum concentration ratio is 1.66 as calculated by Equation 1. This concentration ratio is the maximum possible for the acceptance angle of \( 20^\circ \). The higher geometric ratio may ensure more aperture area, but the heat inception at the receiver area doesn’t increase accordingly. So, the aperture area must be increased in such a way that the heat inception at the receiver area is at par with the increase in aperture area. The geometric concentration ratio should be less than or equal to maximum concentration ratio set by the acceptance angle. Hence, by taguchi method, various dimensions have been tried, and the dimension yielding the maximum efficiency has been optimized. A new design is modeled at Agartala, India (23.833° N, 91.267° E) in which both the values are in agreement with each other. Following is the CPC model depicting the two dimensional view. Optical angles are mentioned in the model diagram of Figure 4(a). The dimensions of length are in decimetres and the angles are in degrees.

Following are the ray tracing results of the redesigned CPC:

Ray tracing is done for 0° incidence angle of redesigned CPC in the following Figure 4(b).

Here the rays on M₁ reach the target and contribute the flux from mid to edge portion. The rays on M₂ reach the target and flux is concentrated around the mid portion of

Figure 2. (a) Ray tracing for 0° incidence angle of existing design. (b) Ray tracing for 10° incidence angle of existing design. (c) Ray tracing for 15° incidence angle of existing design. (d) Ray tracing for 20° incidence angle of existing design.

Figure 3. (a) Optical efficiency vs. time graph. (b) Heat intercepted by the collector vs. the hours of the day around the year in graphical form.
the target. Though $M_1$ does not contribute to flux on the target, this position will not exist for long time.

Ray tracing is done for $10^\circ$ incidence angle with $10^\circ$ slope of Redesigned CPC in the following Figure 4(c).

A 23% increase in heat intercepted by collector is achieved by the new design which is being shown in Figure 4(d) with the help of data collected for a particular day of each month along the year.

The comparison graph of heat interception by the existing design with that of redesigned one is shown in Figure 4(e).

Figure 4. (a) New CPC design with geometric $C = 2.53$ and maximum $C = 2.45$. (b) Ray tracing for $0^\circ$ incidence angle of redesigned CPC. (c) Ray tracing for $10^\circ$ incidence angle with $10^\circ$ slope. (d) Hourly Solar thermal energy collected by the Improved CPC design. (e) Comparison of heat intercepted at local solar noon by the existing design and the new design.
5. Conclusion

While most of the conventional compound parabolic solar collectors focus on increasing the collector area of the device, the fact that the geometric concentration ratio should be adjusted with the maximum concentration ratio, is ignored. This leads to the decreased efficiency of the collector. Here, we have adjusted the geometric concentration ratio at par with the maximum concentration ratio, and the changed design has shown much higher heat inception. The increase in percentage of heat inception efficiency is important, because with higher efficient CPC, more devices can be installed if the available space is limited, and this will certainly increase the total heat incepted at a certain area. With the improved design, the maximum heat interception has increased significantly. During the month of May, the maximum incepted heat has gone up to 3.74 KW, whereas the previous value was 3 KW. This shows an increase of around 23% in heat inception. This also clearly shows that instead of simply increasing the aperture area for collecting more heat, it should be adjusted with the maximum concentration ratio for better efficiency. The percentage efficiency of a compound parabolic solar collector is maximum when the geometric concentration ratio is equal to or less than the maximum concentration ratio.

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