Investigation of gap losses in a modified compound parabolic concentrating collector with evacuated tube receiver

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Abstract. Compound parabolic concentrating (CPC) collectors paired with evacuated tube receivers have great potential to supply solar thermal energy for numerous applications operating in the medium temperature range. Optical losses resulting from the gap between inner absorber tube and cusp of reflectors badly affect the performance of such collectors. In this paper, a modified design and optical performance of a CPC collector with evacuated tube receiver is presented. Effect of reflectors truncation on the collector’s parameters including aperture width, concentration ratio and energy collection is also evaluated. Ray tracing simulation is performed to assess the instantaneous and daily energy collection. Optical performance of a cusp type CPC is compared with that of a modified CPC with w-shaped cavity at the bottom of reflectors to evaluate gap losses. Optical power density and daily average energy collection by cusp type CPC was 26% higher than CPC with w-shaped cavity due to relatively larger aperture size. CPC with w-shaped cavity was 11% more efficient than CPC with cusp type reflectors.

1. Introduction

Solar thermal energy at medium temperature can be obtained by converging solar radiation on smaller area using concentrating type collectors. Conventional concentrating collectors such as parabolic trough, parabolic dish or central tower receiver systems need accurate tracking mechanisms and large-scale installations for efficient heat collection [1]. Moreover, these collectors are imaging type and only intercept direct radiations. Compound parabolic concentrators (CPCs) are non-imaging devices which can deliver solar thermal energy in the medium temperature range (90-250 °C) without active tracking mechanisms. Ability of CPC collectors to collect diffuse radiations provide additional advantage especially in tropical regions where percentage of diffuse radiations is relatively high [2, 3]. Many researchers have designed and evaluated the performance of CPC collectors for various low-to-medium temperature applications such as industrial process heat [4], solar heating and cooling [5], water desalination, waste water treatment and purification [6], methanol reforming and hydrogen production [7], building integrated water heating systems [8] and photovoltaic/thermal hybrid systems [9].

A CPC is combination of two parabolas such that incident radiations falling on the entry aperture of the reflectors are directed to receiver placed at the exit aperture. Ideally, all solar radiations falling on the entry aperture at incidence angles between ±θi (called acceptance half angle) are directed to the receiver placed at exit aperture. The maximum achievable optical concentration ratio (C) for an ideal CPC is determined by equation (1) [10].
The geometric concentration ($C_g$) of a CPC is the ratio of aperture area to the receiver area. For a 2-D CPC with equal length of reflectors and receiver, it can be defined as ratio of aperture width to the receiver perimeter as given in equation (2).

$$C_g = \frac{A_{apr}}{A_{abs}} = \frac{W_{apr}}{2\pi r_o}$$

Potential application of CPC for solar energy collection was first presented by Roland Winston [11]. Extensive calculations carried out by Winston et al. [12] and Rabl et al. [13, 14] laid the foundation for future research related to CPCs. Many researchers have presented various designs of CPCs for improved optical and thermal performance. Derrick et al. [15] compared different designs of concentrators with tubular absorbers and calculated annual energy collection for east-west (E-W) and north-south (N-S) orientations. However, the research study did not consider thermal losses in the performance evaluation.

Integration of evacuated tube receiver (ETR) with CPC improved the performance of these collectors by reducing thermal losses from the receiver. However, large gap between inner absorber tube of ETR and reflector’s cusp result in optical losses which badly affect the optical performance. In this paper, a modified design of CPC with a w-shaped cavity at the bottom is presented and compared with standard cusp type reflectors. The effect of design modification on collector parameters and optical performance is evaluated using Monte Carlo ray tracing simulations.

2. Methodology

A modified design of CPC with evacuated tube receiver is presented in which a w-shaped cavity is made at the bottom of reflectors to accommodate the envelope glass tube and minimize the optical gap losses resulting from large opening between inner absorber tube of the ETR and cusp of the concentrators. Reflectors height was truncated to save material and manufacturing cost with minor decrease in aperture width and concentration ratio. Different truncation levels were considered and their effect on the geometric parameters and energy collection was evaluated. Optical analysis of the newly designed CPC was carried out using Monte Carlo ray tracing simulations in TracePro 7.8.1 software. Instantaneous power density at the receiver of both designs is compared and daily average energy collection during the effective operating time is also analysed.

2.1. Geometric design of CPC

The size of a CPC collector depends on receiver size and acceptance angle which in turn defines the desired concentration ratio. The CPC profile with extended cusp type reflectors and evacuated tube receiver is shown in figure 1. Any point C on the reflector can be defined by considering angle $\varphi$ (between lines from the origin O to E and O to D) and distance $\rho(\varphi)$ (line CE between point C and tangent at point E on the periphery of the absorber tube). The profile curve of a CPC with evacuated tube receiver is expressed by equation (3) as presented by [16].

$$\begin{align*}
  x &= r \times \sin \varphi - \rho(\varphi) \times \cos \varphi \\
  y &= -r \times \cos \varphi - \rho(\varphi) \times \sin \varphi
\end{align*}$$

For the extended cusp design incorporating size of envelope glass tube, the distance ‘$\rho(\varphi)$’ can be determined by using string method as given by [17].
where $\phi = \cos^{-1}(r/R)$ and $\gamma = \sqrt{R^2 - r^2} - \phi$

The lower part in reflector profile ($\phi \leq \varphi \leq \frac{1}{2}\pi + \theta_a$) is involute and upper part ($\frac{1}{2}\pi + \theta_a < \varphi \leq \frac{3}{2}\pi - \theta_a$) is parabolic.

**Figure 1.** Profile of a 2-D CPC with evacuated tube receiver.

It is noteworthy that tubular receiver is in contact with the concentrator at cusp in an ideal CPC collector. However, considering the practical constraints small gap ($g$) between absorber and reflector was provided to accommodate glass tube. Some additional space between glass tube and cusp of reflector was also desired to avoid conduction heat loss. Therefore, profile of the concentrator was generated for the ETR with absorber radius ($r$) and glass tube radius ($R$).

### 2.2. Reflectors modifications

In order to minimise the effect of opening between inner absorber tube and reflectors in the form of gap losses, a w-shaped cavity was made at the bottom of the concentrators. For the modified design, following equation is used to determine the distance $\rho(\varphi)$.

$$
\rho = r \begin{cases} 
\varphi - \gamma & \text{for } 2\phi \leq \varphi \leq \frac{1}{2}\pi + \theta_a \\
\frac{1}{2}\pi + \theta_a + \varphi - 2\gamma - \cos(\varphi - \theta_a) & \text{for } \frac{1}{2}\pi + \theta_a < \varphi \leq \frac{3}{2}\pi - \theta_a 
\end{cases}
$$

where $\gamma = 2\phi - ((R + g)^2 - r^2)^{3/2}/r$ and $\phi = \cos^{-1}((r/(R+g))$. The design of w-shaped cavity made at the bottom of CPC reflectors is shown in figure 2.
The design of a CPC reflector depends on receiver size and acceptance angle which defines the desired concentration ratio. Figure 3 shows variation of reflector width and height as well as CR for different acceptance angles for the selected receiver. In the present design, 30° acceptance half angle is considered which corresponds to 4 hours of operating time of the full height CPC collector. The effective operating time can be increased by truncation of reflectors which enable direct radiation to reach the receiver beyond acceptance angle.

The reflectors’ height of an ideal CPC is very large which leads to high material and manufacturing cost. However, top portions of a CPC become almost parallel to CPC axis which contribute very less in the radiations concentration. Therefore, upper portions of reflectors are truncated to save cost of CPC. As a result, view field of the absorber is also increased and thus more direct and diffuse radiations, outside the acceptance half angle, could reach the receiver.

2.3. Effect of reflectors truncation
Since the upper portions of a CPC reflectors contribute very less in the concentration of incident radiations, therefore, upper sides of the reflectors were truncated to considerably reduce the material and manufacturing cost with minor decrease in CR. The effect of different truncation levels on width, height, width/height ratio, CR and effective acceptance angle for direct radiations in both types of the CPC troughs is shown in figure 4. Solid lines indicate the variation in width, height, width/height, CR and effective acceptance angle (for direct radiations only) in case of cusp type reflectors while dashed lines demonstrate the effect of truncation on corresponding parameters of cavity type CPC.
width/height ratio first decrease slowly and then steeply after about 50% truncation which shows that variation in aperture width is more than height at higher truncation levels. Effective acceptance angle for direct radiations also increases by truncating reflectors which in turn improves the overall effective operating time of the collector. Concentration ratio decreases slightly by increasing the truncation level as shown in figure 4(b).

**Figure 4.** Effect of reflectors truncation on (a) width, height and width/height, (b) CR and effective acceptance angle for beam radiations.

The upper sides of the original height were truncated by 40% with only about 4.6% corresponding decrease in the aperture width and CR. The vertical height of the truncated reflectors was 0.205 m with 0.344 m corresponding aperture width for cusp type CPC. In case of cavity reflector, the truncated height and aperture width were 0.160 m and 0.252 m respectively. The length of reflectors was 2.5 m in both designs. Construction details of the designed CPC troughs with full and truncated heights are shown in table 1.

**Table 1.** Construction parameters of CPC.

| Parameter                  | Unit | Original | Modified | Original | Modified |
|----------------------------|------|----------|----------|----------|----------|
| Reflector size             | M    | H = 0.341| H = 0.205| H = 0.266| H = 0.160|
|                           |      | W = 0.360| W = 0.344| W = 0.264| W = 0.252|
| Aperture area              | (m^2)| 0.90     | 0.86     | 0.66     | 0.63     |
| Concentration ratio (CR)   |      | 2.86     | 2.74     | 2.10     | 2.01     |
| Acceptance half angle (θ_a)| degree| 30       | 30+20*   | 30       | 30+20*   |
| Absorber Tube              | M    | L = 2.5  | L = 2.5  | L = 2.5  | L = 2.5  |
|                           |      | d = 0.04 | d = 0.04 | d = 0.04 | d = 0.04 |
| Glass Tube                 | M    | L = 2.42 | L = 2.42 | L = 2.42 | L = 2.42 |
|                           |      | D = 0.75 | D = 0.75 | D = 0.75 | D = 0.75 |

*increase in acceptance angle is only for direct radiations

2.4. Ray Tracing Simulation
Monte Carlo ray tracing method was used to plot ray paths and evaluate optical performance of the designed collectors. Geometric models of the CPC developed in Solidworks 2016 were imported into the ray tracing software TracePro 7.8.1. Material and surface properties for the collector components
were applied. Radiations source was defined, and parallel radiations were considered since the source was taken at long distance from the collector. Collector location (4.385N and 100.979E) was set and orientation was adjusted in north-south direction.

Table 2. Properties of CPC components for optical ray tracing.

| Component     | Material            | Reflectivity | Absorptivity | Transmissivity |
|---------------|---------------------|--------------|--------------|----------------|
| Reflector     | Aluminium           | 0.92         | 0.08         | -              |
| Glass Tube    | Borosilicate glass  | -            | 0.002        | 0.98           |
| Absorber      | AlN coated Stainless Steel | - | 0.98 | - |

3. Results and discussion

3.1. Ray path diagrams

Ray paths of solar radiations were obtained for different incidence angles (0°, 20°, 30°, 35°, 45° and 55°) at aperture planes of both cusp and cavity type reflectors as shown in figure 5 and figure 6 respectively. It is evident from figure 5(a) that the maximum radiations were concentrated at lower side of the absorber tube for normal incidence of solar radiations. When the radiations source (the sun) moved away from the zenith, the angle of incidence increased and concentration region shifted upward until the incidence angle approached acceptance angle of the CPC where the radiations were tangent to the absorber tube following edge ray principle as shown in figure 5(c). When the incidence angle further increased beyond the acceptance angle, only direct radiations could reach the absorber tube as shown in figure 5(d-f) which were made possible due to truncation of reflectors height. This additional advantage of increased view field partially compensates for the reduction in CR due to truncation.

![Ray paths in CPC](image)

Figure 5. Ray paths of absorbed radiations in CPC with cusp reflector at different incident angles (a) 0°, (b) 20°, (c) 30°, (d) 35°, (e) 45° and (f) 55°.

The w-shaped cavity formed at the bottom of the reflectors made room for accommodating the envelope glass tube. In this way, the effect of gap between the reflectors and absorbers was reduced and some of the radiations which were previously passing through the gap and escaping to the environment were reflected back to the absorber surface. In this way optical gap losses were reduced and almost constant power was available at the absorber for incidence angles within the range of acceptance angle. Direct radiations were also intercepted beyond acceptance angle due to reflectors truncation as shown in figure 6(d-f).
3.2. Optical analysis

The ray tracing simulations were carried out to evaluate the optical performance of both designs. The power density available at the outer surface of the absorber of both cusp and cavity reflectors is shown in figure 7. The maximum power density (about 500 W/m²) was achieved at incidence angle close to acceptance angle which dropped to about 400 W/m² at noon time as shown in figure 7(a). Further increase in incidence angle beyond acceptance half angle resulted in sharp decrease of the available power due to limitation of radiations concentration beyond the acceptance half angle. However, direct radiations could reach the absorber until incidence angle reached the value of $\theta_t$ (angle between the optical axis and edge ray of truncated reflector). In case of cusp type reflectors, the optical gap losses were highest (about 100 W/m²) at noon time. These gap losses were significantly abridged by using cavity type reflectors as shown in figure 7(b).

![Figure 6. Ray paths of absorbed raditions in CPC with cavity at different incident angles (a) 0°, (b) 20°, (c) 30°, (d) 35°, (e) 45° and (f) 55°.]

![Figure 7. Instantaneous power density on receiver with (a) cusp reflectors, and (b) cavity reflectors.]

The optical efficiency defined by ratio of power available at the absorber surface to incident at aperture plan was also determined for both designs. Similar trends were observed for optical efficiency in case of cusp as well as cavity type reflectors for different truncation levels as shown in figure 8. Even though, the total optical power was comparatively lower in case of cavity type CPC due to smaller aperture area, the available power density was almost uniform during the concentration time zone of the collector. Cavity type CPC was found about 5% more efficient than cusp type reflectors.
Figure 8. Optical efficiency of CPC with (a) cusp, and (b) cavity reflectors.

Comparison of daily average energy collection during operating time of the collectors showed that full height CPC with cusp type reflectors achieved 9.23 MJ which was 30% more than cavity type CPC. Similarly, 40% truncated CPC with cusp type reflectors intercepted about 9.00 MJ which was 26.8% higher than corresponding value for cavity type reflectors as shown in figure 9. It is noteworthy here that even though average daily energy capture by cusp type reflectors was higher due to larger aperture area, the optical efficiency of cavity type CPC was almost 7% higher than cusp type reflectors for different truncation levels. The reason can be attributed to reduced gap losses due to w-shaped cavity at the bottom which trapped large amount of the radiations passing through the space between absorber and envelop glass tube and re-direct to the absorber tube.

Figure 9. Comparison of daily average energy collection and optical efficiency of CPC with cusp and cavity reflectors.

4. Conclusion
In this paper, design and optical performance of a CPC paired with evacuated tube receiver is presented. Two variants of reflectors i.e. extended cusp type and w-shaped cavity type were considered. Acceptance half angle was selected to be 30° which corresponds to 4 hours of operating time of the full height CPC trough. Truncation level of the concentrators was selected to be 40% to save material and manufacturing cost with only about 4.6% decrease in CR. Ray tracing analysis of both collectors showed that about 26% gap losses occurred in case of cusp type reflectors which were abridged by using w-shaped cavity at the bottom of the reflectors. Comparative analysis of daily
average energy capture revealed that full height CPC with cusp type reflectors achieved 9.23 MJ which was 30% more than cavity type reflectors. Similarly, 40% truncated CPC with cusp type reflectors intercepted about 9.00 MJ which was 26% higher than corresponding value of cavity type CPC. The optical efficiency of cavity type CPC was almost 7% higher than cusp type reflectors for different truncation levels.

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