Optical performance evaluation of a 2-D and 3-D novel hyperboloid solar concentrator

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Abstract

Ray tracing is an important tool for the design of elliptical–hyperboloid concentrators (EHC). Optical efficiency for a range of parameters such as of incidence angle, concentrator height and different diameters of the receiver can be investigated through ray trace analysis. An extensive theoretical prediction of 2-D and 3-D ray tracing techniques has been adopted in the current investigation to calculate the optical efficiency of the novel EHC. An optical efficiency of 63% was found for a 2-D model of the EHC with the following dimensions: height 0.85 m, aperture length 1m, receiver diameter 0.182 m and concentration ratio of 8X. The reflectivity of the EHC is considered to be 0.94. Due to the three-dimensional nature of the EHC, the optical efficiency was improved to 78% based on 3-D ray trace geometry.

Keywords: Elliptical–hyperboloid concentrator, 3-D ray traces geometry, optical efficiency.

1. Introduction

There is a wide variety of concentrator designs. They are classified into two major optical categories: 1) Imaging optics concentrators and 2) Non-imaging optics concentrators. For imaging optic concentrator design, the image is formed on the receiver by the optical concentrators; hence it required that receiver be small enough to attain some homogeneity in the distribution of the image formed (focus). This can result therefore, in high values of concentration [1]. For non-imaging optics concentrator designs however, the receiver may be large with homogeneity of the radiation reaching the receiver since the designed is not concerned with forming an image on a focus. Non imaging optics is a field devoted to the design of optical concentrators, where light collecting systems are used instead of the imaging systems [2].

The first three dimensional (3-D) compound parabolic concentrator (CPC) has been studied using the flow line method for solar application [3], as a component originating from the field of a Lambertian emitter in the form of a 2-D truncated wedge. To complement the explanation, theoretical background references to investigation by several authors [4, 5] are made. The plane section of the hyper-parabolic concentrators is obtained from the field lines for a two-dimensional truncated wedge and constitutes a union between a hyperbola and a tilted parabola. The hyper-parabolic concentrators (HPCs) were obtained by revolution of this section (profile). When the focal length of the hyperbola of a HPC becomes the radius of the exit aperture (one of the limiting cases), the HPC transforms into the well-known compound parabolic concentrator (CPC), and the focal length of the hyperbola becomes infinite, the HPC reaches its thermodynamic limit of concentration. The concept of hyper-parabolic concentrators originated within the fields of geometric optics and solar thermal energy. Within a problem area of non-imaging optics understood as a field devoted to the design of such components, where light collecting systems are used instead of the usual image formation systems [4]. The so-called flow-line method have become one of the most productive design techniques once [6] introduced the concept of the geometric vector flux J (where flow line is the direction of J) and showed that ideal flux concentrators have shapes that do not disturb the geometric vector flux field. In present work, the optical performance of EHC concentrators will be evaluated in terms of optical efficiency and energy flux distribution on the receiver. Optical efficiency of concentrator refers to the fraction of light incident on the aperture that reaches the absorber. High angular acceptance for a wide range of incidence angles is desirable to work with the change in the position of sun over a day. Separate extensive studies have been carried out to obtain the optimum optical efficiency for this ellipsoidal – hyperboloid configuration through ray tracing simulation technique.

In this paper, an extensive theoretical prediction of 2-D and 3-D ray tracing techniques has been adopted to calculate the optical efficiency of the novel EHC, based on the investigation of effect on rays for different possibilities such as angle of inclination, variation of height of the concentrator and different diameters of receiver. The optical efficiency of the 2-D and 3-D EHCs were examined at various heights of concentrators, various diameters of the receiver but with a fixed aperture length of 1m.

2. Ray tracing Technique for Hyperboloid Concentrator

Ray tracing is a promising technique for evaluation of optical performance of solar concentrators. In present ray tracing analysis all incident rays are assumed to be parallel and carries equal amount of energy. The vector form of the reflection law of light considered in ray tracing technique is shown by (Eq.1):

$$\vec{r}_{reft} = \vec{r}_{inc} - 2(n.\vec{r}_{inc})n \qquad (1)$$

Where the direction vector of the reflected ray is $\vec{r}_{reft}$; $\vec{r}_{inc}$ is the incident direction of the incoming ray and n is the normal to the surface. Rays incident on the aperture enter to the hyperboloid concentrator and either reach the receiver or reflect back out of the concentrator. Rays can reach the receiver without any reflection or the rays can be totally internally reflected by the hyperboloid internal surface. Rays may be reflected more than once before reaching the receiver. Rays may exit the system after finite reflections within the concentrator. Fig.1 shows two dimensional hyperboloid concentrator, in which rays emitted from Z_1Z_2 toward F_1 F_2 bounces back and forth between the mirrors Z_1X_1 and Z_2X_2 and ends up on the receiver. For point S, for example, ray r_1 emitted towards point F_2 is reflected by the right-hand side mirror towards point F_1. The left-hand side mirror then reflects it towards F_1 again. After a certain number of reflections this ray reaches X_1X_2. The same happens to a ray r_2 emitted from S towards F_2. Intermediate rays between r_1 and r_2 either bounce off the mirrors and reach X_1X_2 or reach it directly without any reflection. This concentrator is called an elliptical hyperboloid concentrator and maximally concentrates onto receiver X_1X_2 all radiation entering its aperture Z_1Z_2 headed toward F_1F_2. The three dimensional of elliptical hyperboloid concentrator is presented in Fig. 2.

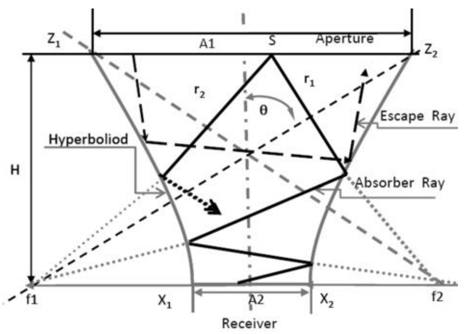


Figure 1 -2-D hyperboloid concentrator

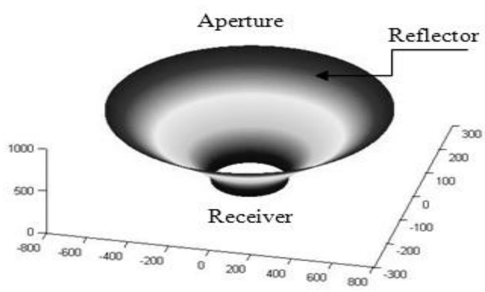


Figure 2 - 3-D elliptical hyperboloid concentrator

3. 2-D. Ray tracing of Elliptical Hyperboloid Concentrator (EHC)

A 2D ray trace simulation code of an EHC was developed in MatLab and the effects of incidence angle; height of concentrator receiver diameter on the optical efficiency of a 2-D EHC was investigated. Fig. 3 (a, b and c) indicates ray trace diagram for a 2-D EHC with different incidence angle of 0º, 30º and 50º respectively for a receiver diameter of 0.182m. It was observed that 63% of the incident rays were absorbed at incident angles of 0º, whereas 28% of the incidence rays were absorbed at 30º which reduced to only 9% when the incident angle was 50º. After a series of ray tracing simulation it was observed that 45% of the rays were absorbed when the rays were incident at an angle of 20º and the receiver diameter of 0.15m, this is shown in Fig.4. An irradiance distribution represents the energy distribution per unit area. The flux distribution of the 2-D EHC at the receiver is shown in fig.5. The intensity at the receiver was varied from minimum value of 6072 W/m^2 to a maximum value of 60726 W/m^2.

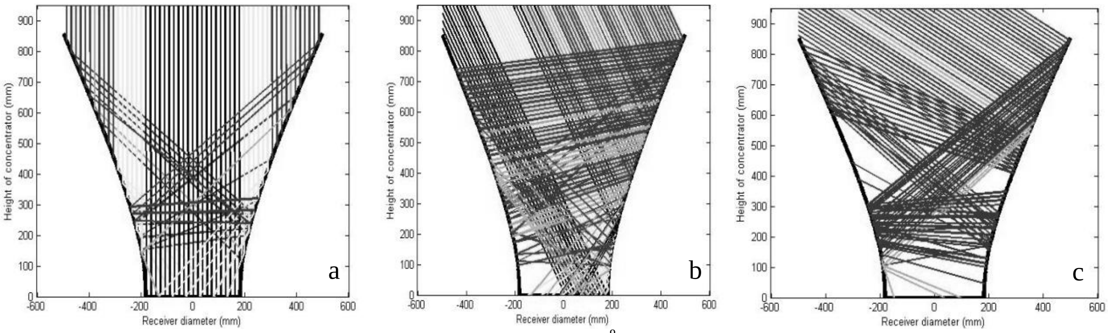


Figure 3 - (a, b and c) 2-D ray tracing with incidence 0°, 30º and 50º when receiver diameter 0.182m

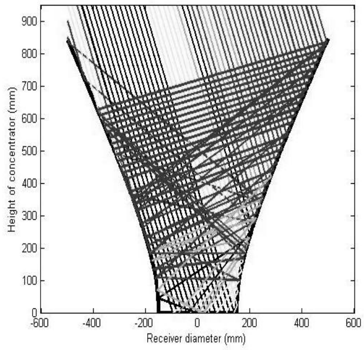
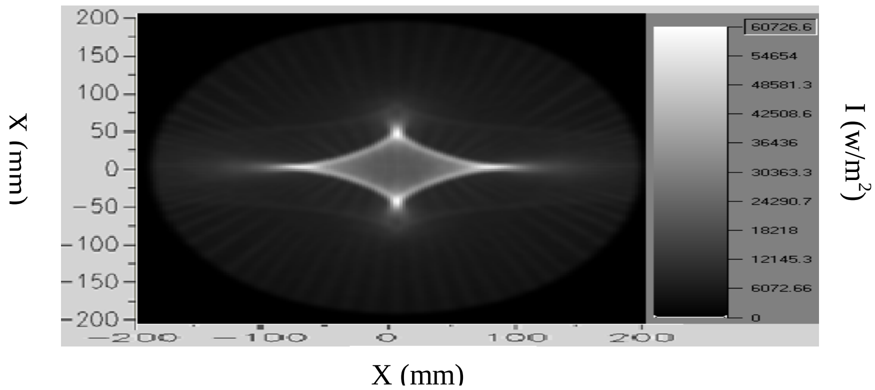


Figure 4 - 2-D ray tracing with incidence angle 20° and receiver diameter 0.15m



Figurer 5 - Flux distribution of 2-D of EHC for 0.85m

4. Optical Efficiency 2-D EHC

To obtain the optimal optical efficiency of a 2-D EHC, the effects of the variations of the incident angle within the range ± 90^o, The three different heights that examined were 0.80m; 0.85 m and 0.9 m. Optical efficiency of 78%, 63% and 60% were obtained for the concentrator heights 0.8 m, 0.85 m and 0.9 m respectively within the range ± 90^o. This result is shown in Fig. 6. For the variation of the optical efficiency with the change receiver diameter, Fig. 7 shows that the optical efficiencies of 36%, 52% and 63% were obtained for receiver diameters 0.10 m, 0.15 m and 0.182m and concentration ratio 15,10 and 8 respectively. This implies that the optical efficiency is proportional to the receiver diameter because as the receiver diameter is increased the optical efficiency increases, and this leads to reduction in concentration ratio.

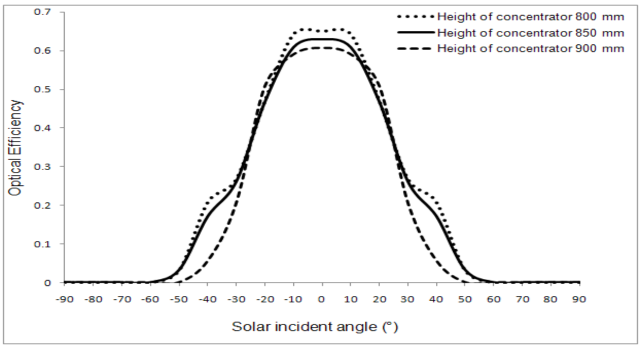


Figure 6 - Optical efficiency of 2-D for different height of concentrator and different incidence angle

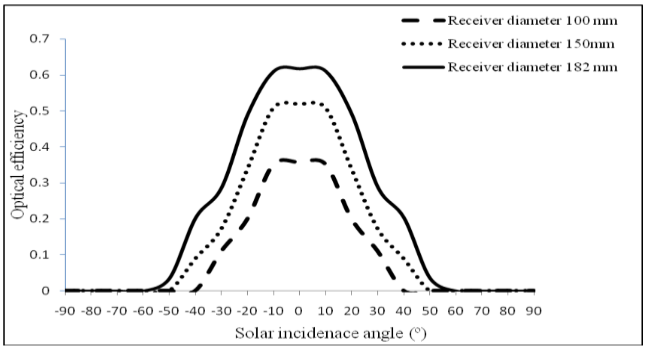


Figure 7 - Optical efficiency of 2-D for different receiver diameter and different incidence angle

5. 3-D. Ray tracing of Elliptical Hyperboloid Concentrator

With the use of the OptisWork simulation, the effects of variations of the incidence angle, height of concentrator and receiver diameter on a 3-D EHC have been examined. These variations are shown in Fig. 8 (a, b and c) with the incidence angle of 0º, 30º and 50º respectively with the receiver diameter of 0.182m. From the simulation undertaken it was observed that 78% of the rays that were incident on the aperture were observed at the receiver at incidence angle 0º and 30% of the incidence rays were observed at 30º incidence angle while 13% of the rays were observed when the incident angle was 50º. When the concentrator height was changed to 0.9m, 63% of the rays were observed at the receiver; this is shown in Fig. 9. As with the 2-D EHC the maximum luminance for a 3-D EHC is shown in Fig. 10. The four highest points in the diagram represents points of maximum energy distribution, further movement decreases the intensity of rays.

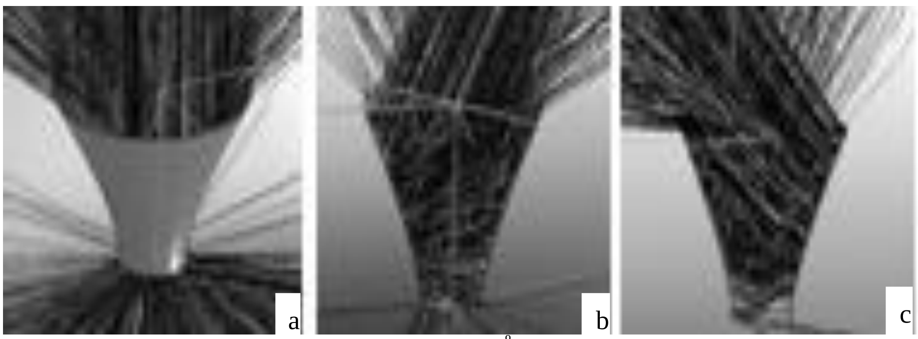


Figure 8 -(a, b and c) 3-D ray tracing with incidence 0°,30ºand 50º and receiver diameter 0.182 m and 0.85 m height

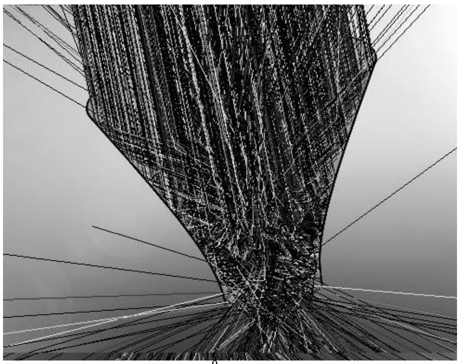


Figure 9 - 3-D ray tracing with incidence 90° and receiver diameter 0.182m and 0.9m height

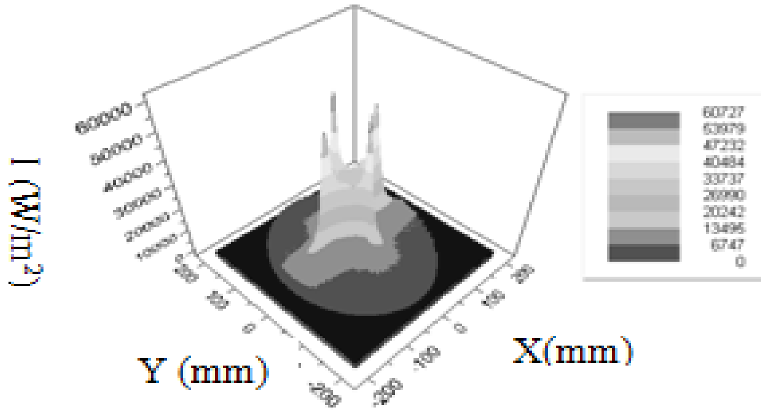


Figure 10 – Flux distribution of 3-D of EHC system for 0.85 m height

6. Optical Efficiency of a 3-D EHC

With the result from the simulation of the OptisWorks, the effects of variation of the concentrator height, for different orientation of the source within the range ± 90° on the optical efficiency of a 3-D EHC have examined. At concentrator heights 0.80m, 0.85 m and 0.9 m, the optical efficiencies obtained were 93%, 78% and 69% respectively. This is shown in Fig. 11. The effect of absorber diameter on the optical efficiency for different concentration ratio has been studied with variation of the absorber diameter of 0.1m, 0.15 m and 0.182 m the optical efficiency is 58%, 72% and 78% respectively their corresponding concentration ratio was 15, 10 and 8. Finally, as shown in Fig.12 comparing the maximum optical efficiencies of the 2-D and 3-D EHC for 0.85m height of concentrator and different incidence angle it is clearly shown that the optical efficiency for the 3-D EHC is higher then the 2-D EHC. The primary objective of using the ray tracing simulation to evaluate the optical efficiency of the 2-D EHC is to help to improve on the result that will be produced by the 3-D EHC.

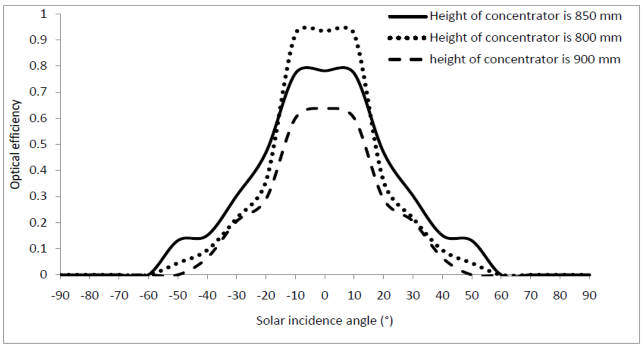


Figure11 - optical efficiency of 3-D for different height of concentrator and different incidence angle

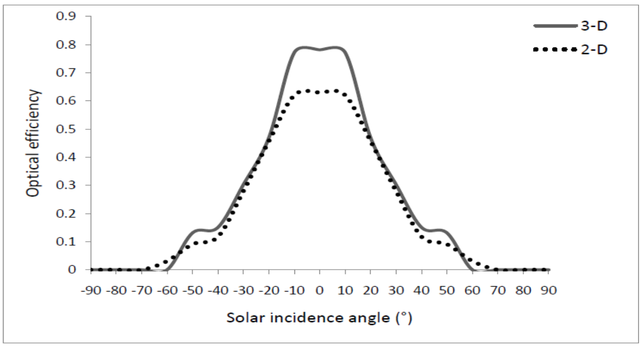


Figure 12 - optical efficiency of 2-D and 3-D for 0.85m height of concentrator and different incidence angle

7. Conclusions

A novel 3-D EHC, has been presented in this work. A ray trace modelling was performed using Matlab code to evaluate the optical efficiency of the 2-D EHC, and then the result of the 2-D EHC have been improved by using the ray tracing technique by OptisWork to determine the optimal optical efficiency of the 3-D design. Based on this study, the optical efficiency of 63% is obtained for the height of 0.850m and diameter of aperture of 1m and receiver diameter is 0.182m for the 2-D EHC. Further, extensive studies were carried with the same parameters to obtain better optical efficiency of 78% for the 3-D novel EHC. This has a great economic advantage over all existing solar concentrators which require the construction of a separate structure to support them and heavy machinery to orient them to intercept and properly reflect sunlight onto a receiver because the long axis of the ellipse produce a greater amount of absorption for a wide incidence angle. Further extensive work is still in progress to obtain, higher optical efficiency with higher concentration ratio for use in the application of water desalination system.

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8. References

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