Design of non-imaging solar collectors for process heat

K. S. Reddy* and T. Srihari Vikram

Heat Transfer and Thermal Power Laboratory, Department of Mechanical Engineering,
Indian Institute of Technology Madras, Chennai, INDIA

*Corresponding Author, Email: ksreddy@iitm.ac.in

Abstract

In this article, a comprehensive optical analysis of a non-imaging elliptical hyperbolic concentrating collector has been carried out. This collector system has a wide acceptance angle so that it can be operated with no/minimum tracking based on the location of operation. Two types of receivers say flat and trapezoidal surface are considered and the flux distribution over these receivers are estimated and compared. It is found that maximum peak flux is intercepted by the trapezoidal surface receiver. The effect of concentrator geometrical parameters such as concentrator height (H_c) and concentration ratio (CR); receiver geometrical parameters such as aperture width (W_r) and receiver height (H_r) on optical performance of the collector has been studied. The optical efficiency varies between 5 – 15 % for the concentrators with height less than 1 m whose acceptance angle is about 60°, whereas for the concentrator height greater than 1m, the acceptance angle is ±45° and the optical efficiency varies between 20 – 30 % for incidence angles ±30°. The maximum flux incident on the trapezoidal surface is about 60585 W/m^2, however for flat surface, it is 40468 W/m^2. Based on the optical analysis, it can be seen that this system can be widely used for applications such as low and medium temperature applications and it requires less/no tracking with wider acceptance angle.

Keywords: Solar energy, non-imaging collector, hyperbolic concentrator, optical performance

1. Introduction

Non-imaging concentrators are widely used in low temperature solar process heating applications like water heating, air conditioning etc., For given concentration ratio, non-imaging systems provide wide acceptance angles for solar applications. Hence, these collectors require minimum or no tracking. A new type of non-imaging concentrator called elliptical hyperbolic concentrator has been developed which has wider acceptance angle and require less or no daily tracking and minor adjustment for seasonal tracking depending on the location of installation of collector. The use of hyperbolic concentrators were studied by Garcia-Botella et al. (2009). It has been concluded that the concentrators with hyperbolic profile have higher acceptance angle. Ali et al. (2009) compared the optical performance of 2-D and 3-D elliptical hyperbolic concentrator (EHC) and found that the optical efficiency of 2D and 3D system are 63% and 78% respectively. Ali et al.(2010) presented optical performance of 3D static circular and elliptical hyperboloids. Four different configurations of hyperboloids are studied based on the ray tracing techniques and flux distribution at the receiver aperture has been presented. A detailed parametric study on the elliptical hyperbolic concentrator has been performed by Ali et al.,(2013). Thermal analysis of concave cavity surface receiver of EHC was carried out by Reddy and Vikram (2015). In the present work, optical analysis of elliptical hyperbolic concentrator with two types of receivers are carried out and effect of various parameters such as concentrator height, concentration ratio, receiver height, receiver aperture on optical performance of the elliptical hyperbolic concentrator with trapezoidal/concave cavity surface receiver are studied.

2. Design of Elliptical Hyperbolic Concentrator

The elliptical hyperbolic concentrator is a non-imaging concentrator, which consists of a hyperbolic profile along the concentrator height with an elliptical aperture. This concentrator is the development of 3-D surface of revolution and falls under the category of family of surfaces called hyperboloid. The hyperboloidal surface considered in the present work is one-sheeted hyperboloid.

The equation of one-sheeted hyperboloid is given by (Gottwald, 2012):

$$\frac{x^2}{a^2}+\frac{y^2}{b^2}-\frac{z^2}{c^2}=1 \qquad \text{(eq. 1)}$$

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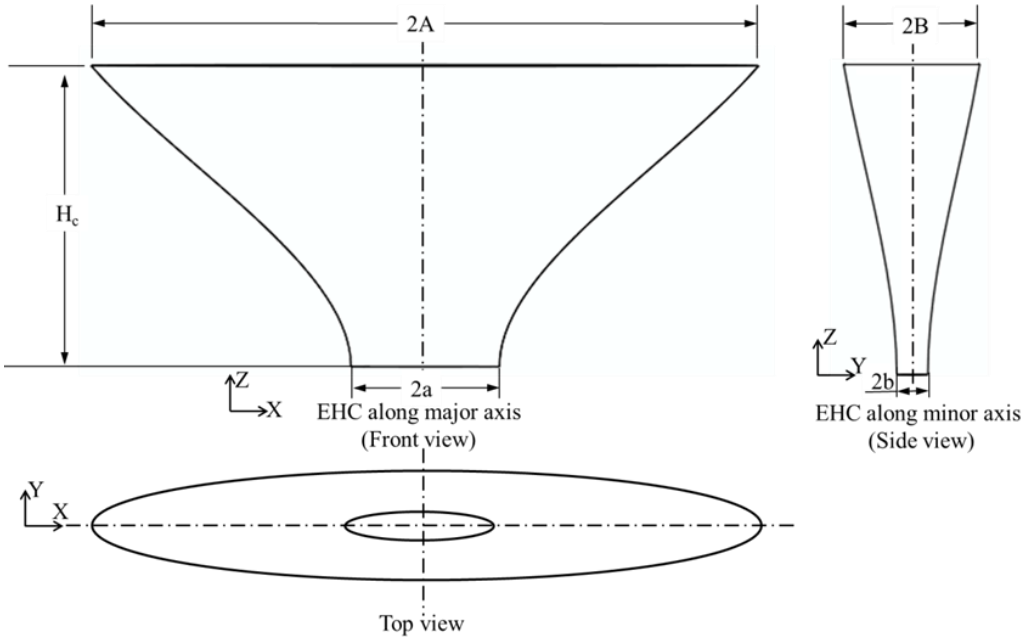
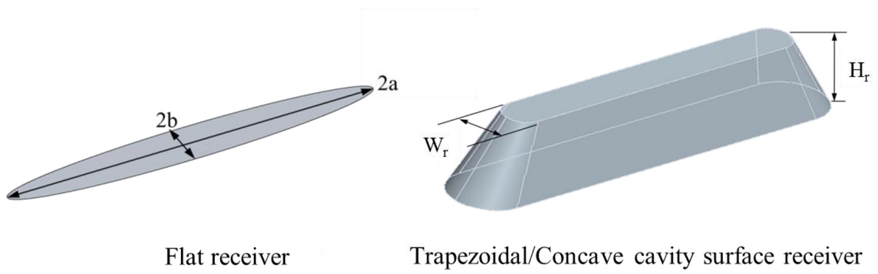
The length of the major axis and minor axis at the top aperture of the concentrator is termed as 2A and 2B whereas at bottom aperture, it is termed as 2a and 2b respectively, and Hc being the height of the concentrator. The geometrical parameters of elliptical hyperbolic concentrator are shown in Fig. 1.



(a)



(b)

Fig. 1 (a) Elliptical hyperbolic concentrator and (b) receiver showing geometrical parameters

3. Modeling of Elliptical Hyperbolic Concentrator with receiver

The equation for hyperbolic profile is obtained by rewriting the Eq. (1) for two planes X-Z and Y-Z by substituting Y = 0 and X = 0.

For hyperbolic profile along X-Z plane (major axis side), substitute y = 0 and rewriting eq. (1) in terms of z, we get,

$$z_1 = c \times \sqrt{(x/a)^2 - 1} \qquad \text{(eq. 2)}$$

Similarly, for hyperbolic profile along Y-Z plane (minor axis side) is obtained by substituting x = 0 in Eq. (1), we get,

$$z_2 = c \times \sqrt{(y/b)^2 - 1} \qquad \text{(eq. 3)}$$

The equation for elliptical profile (at top and bottom aperture) is obtained by considering different values of z, ranging from 0 to H (height of the concentrator).

$$\frac{x^2}{a^2} + \frac{y^2}{b^2} = 1 + \frac{z^2}{c^2} \qquad \text{(eq. 4)}$$

The ratio of semi major and semi minor axis (a/b) remains one of the important parameter in designing the elliptical hyperbolic concentrator. This ratio plays a role in deciding the shape of elliptic aperture. The value 1 corresponds to circular cross section of aperture, whereas 10 correspond to narrow elliptical cross section (i.e.,) lower major axis compared to minor axis. Hence a medium or average value of 5 is considered for the ratio of semi major and minor axis (a/b) in the present study. The ratio of height to aperture (H_c/a) plays a role in the amount of solar radiation entering the concentrator and reaching the receiver. An optimum ratio of H_c/a ratio is considered as 4 based on the previous studies by Ali et al., (2013). It can be seen that when the ratio of height to aperture is varied from 1 to 10, the effective concentration ratio increases or decreases depending on the incidence angle of the solar radiation. For incidence angles of 0 and 15°, the effective concentration ratio increases whereas, for 30° and 45°, the effective concentration ratio decreases beyond 4. It can be concluded that the optimum Hc/a ratio seems to be 4 and corresponding H_c/b ratio seems to be 20. The geometrical values of parameters considered for the design of elliptical hyperbolic concentrator are shown in Table 1. Based on the values provided in Table 1, the design of EHC is carried out by obtaining the equations for hyperbolic profiles along major and minor axis and elliptical apertures at bottom and top of the concentrator using Eq. (2) – (4).

Tab. 1: Geometrical specifications considered for design of EHC

Parameters	Values
Semi major axis at receiver aperture (a)	0.4 m
Ratio of semi-major to minor axis (a/b)	5
Height to aperture ratio (H_c/a)	4

The geometry of EHC is modelled using modeling software, AutoCAD 2012. The points for the profiles along the major and minor axis is calculated for different values of x and y. These coordinate points are generated and is used to model the geometry of the concentrator. The receiver converts the incident concentrated solar radiation into thermal energy with the help of fluid circulated through it. Hence the design of the receiver becomes necessary for its efficient conversion of solar radiation. The amount of solar radiation incident on the receiver depends on the concentrator and the receiver shape. In the present study, two different configurations of the receivers such as flat surface and trapezoidal surface are analyzed. The flat surface receiver has the dimensions same as the bottom aperture i.e., the shape of ellipse with major and minor axis dimensions equal to that of the bottom aperture of the concentrator. Fig. 2 shows the EHC system with receivers placed at bottom aperture of the concentrator.

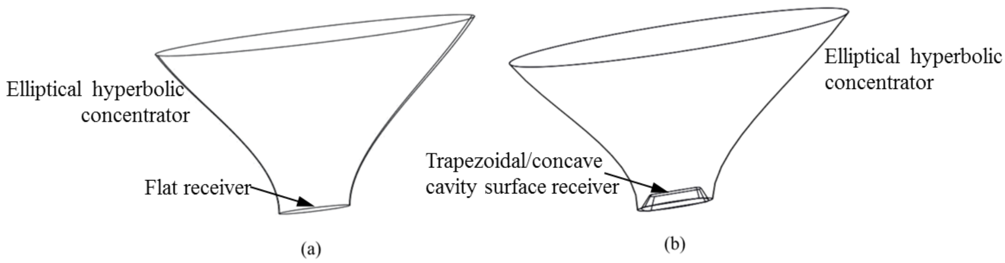


Fig. 2 EHC systems with receivers at bottom aperture (a) flat surface (b) trapezoidal surface

4. Optical ray tracing analysis

The optical ray tracing analysis is carried out to estimate the flux that is incident on the receiver and to calculate the optical efficiency of the system. ASAP (Advanced Systems Analysis Program) is an optical system-modelling software/tool based on Monte-Carlo ray tracing technique, which simulates the interaction of light with optical and mechanical structures (BRO, 2013). The geometrical model developed is imported to the ASAP software using suitable (iges or stp) format. After importing the model in ASAP, the system settings such as units, wavelengths are set. Then, the optical properties such as optical materials/coatings, refractive indices, reflectivity, and absorptivity are specified. Once the model is imported and the properties are defined, source is defined and appropriate number of rays for simulation is specified in the program. The source emitting the rays considered should have the properties of sun hence, subtended angle by the sun is specified while defining the source. After specifying the source, the ray tracing is carried out to concentrate the solar rays over the receiver through the concentrator. In the present study, the reflectivity of the concentrator is considered as 0.94. This reflectivity corresponds to the reflectivity of Reflectech sheet (DiGarcia and Jorgenson, 2010) that is used over the concentrator. The ray tracing diagram for different incidence angles are shown in Fig. 3.

The optical efficiency is given by (Kalogirou, 2009):

$$\text{Optical efficiency}, \eta_o = \frac{\text{Flux absorbed by the receiver}}{\text{Flux incident on the concentrator}} \quad \text{(eq. 5)}$$

$$= \frac{\sum_{i=1}^{N} I_i \rho_r^{\ m}}{I_o} \quad \text{(eq. 6)}$$

where, N and m corresponds to number of rays and number of reflections respectively.

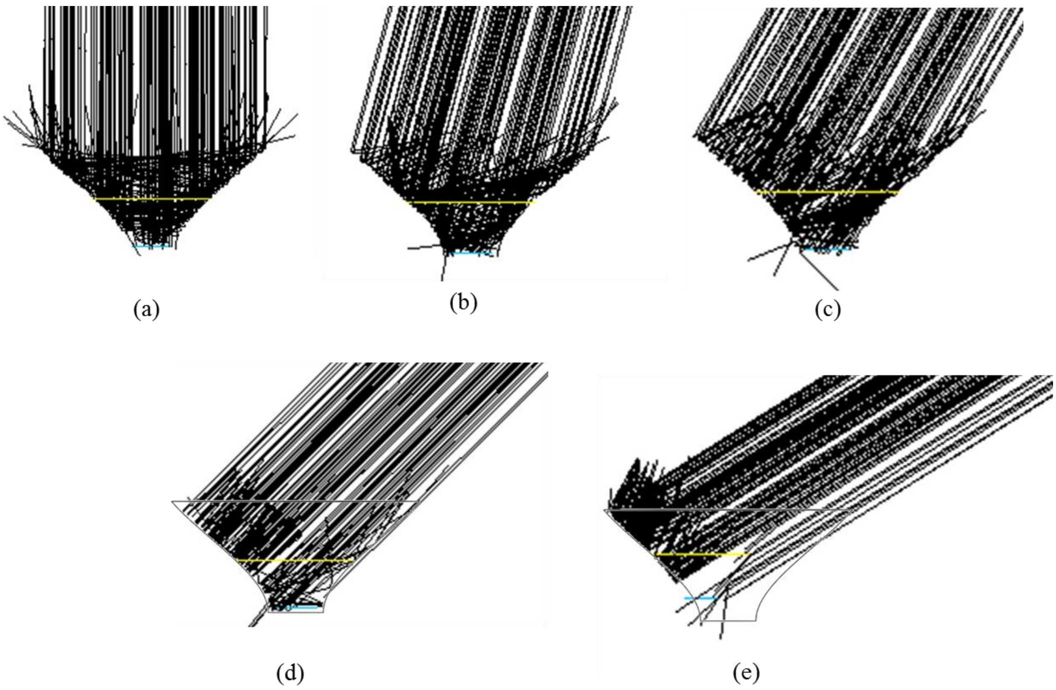


Fig.3 Ray tracing diagram for different incidence angles (a) 0º (b) 15º (c) 30º (d) 45º

The optical model/procedure needs to be validated to assure the correctness of the procedure that is followed. To validate the present optical model, the procedure is validated with optical analysis of two different geometries by Ali et al. (2010) and Abdullahi et al. (2013). Ali et al., (2013) carried out optical analysis of EHC system with flat receiver. The validation of present model with Ali et al. (2010) for Hc = 0.4 m, CR = 20, a/b = 5, a = 0.04 m was carried out. It can be seen that the variation of present model with the other model is minimum and found to have maximum deviation of 4.75%. Abdullahi et al. (2013) carried out optical ray tracing analysis of compound parabolic collector (CPC) with single and double receiver configurations. The geometry of CPC with single absorber of 11 mm radius is considered. It can be seen that the variation of optical efficiency with Abdullahi et al. (2013) is minimum.

5. Comparison of flat surface and trapezoidal surface receivers

The flux available at the bottom aperture of the elliptical hyperbolic concentrator is estimated and the receiver for EHC system has been designed based on the ray tracing analysis. The flux distribution on the receiver is important for conversion of incident solar radiation into useful heat. Hence, the receiver is designed as trapezoidal surface to intercept maximum amount of radiation that is entering the EHC system. The variation of optical efficiency for both flat and trapezoidal receiver surface is shown in Fig.4. The flux on a flat surface and trapezoidal surface for the solar incidence angle of 0° is shown in Fig.5. The optical efficiency of the flat and trapezoidal surface receiver is 27.3 % and 27.1% at normal incidence. The optical efficiency for the flat surface is slightly higher than the trapezoidal surface at the maximum of 5 % at 30° incidence angle, however at other incidence angles, the variation of optical efficiency seems to be less than 5 %. This reduction of optical efficiency might be due to the geometry of the surface as the rays might miss the surface. Although the optical efficiency of the two receivers is close enough, the variation of flux incident on the receiver seems to be large.

The maximum flux incident on the trapezoidal surface is about 60585 W/m^2, however for flat surface, it is 40468 W/m^2. From Fig. 5, it can be seen that the maximum flux over the trapezoidal surface is 1.5 times higher than that of flat surface. An average flux of about 4236 W/m^2 and 4197 W/m^2 has been observed for trapezoidal surface and flat surface. The profile represented below and right side of the flux distribution corresponds to the flux along the centre line as indicated in the flux distribution diagram. Hence, using trapezoidal surface as receiver intercepts more flux than the flat surface. Hence, the trapezoidal surface receiver is considered for further analysis.

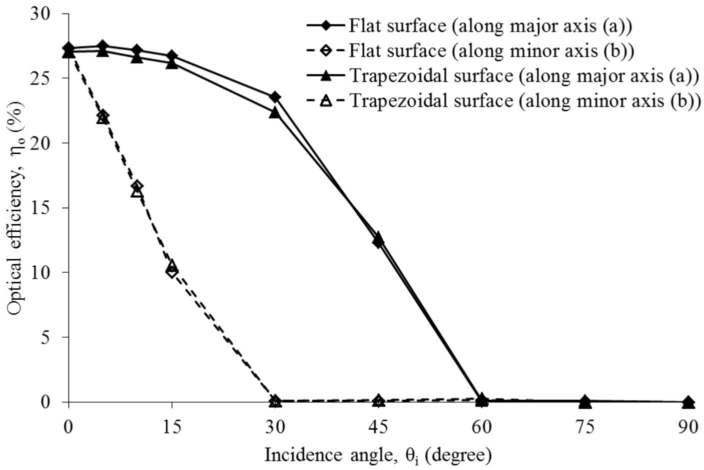
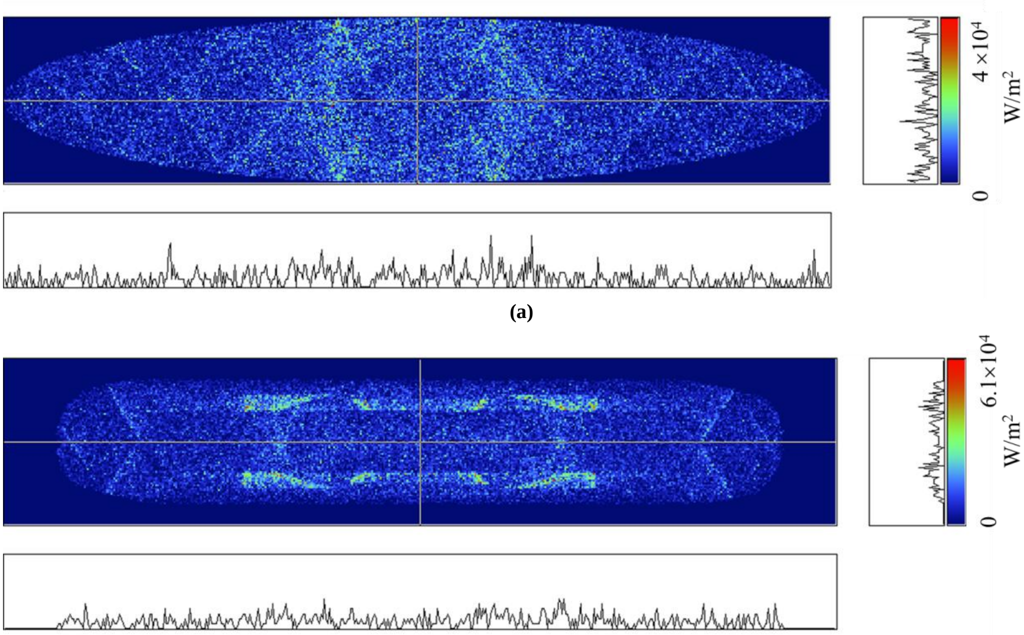


Fig. 4 Variation of optical efficiency for flat and trapezoidal surface receiver at normal incidence



(b)
Fig. 5 Flux distribution over (a) flat surface and (b) trapezoidal surface receivers

6. Optical analysis of EHC

6.1 Effect of concentrator height

The variation of optical performance for different height of concentrator (H_c) ranging from 0.4 m to 2 m is studied. The effect of concentrator height for different incidence angles on optical efficiency is shown in Fig 6. The optical efficiency increases with increase in the height of the concentrator. The height of the concentrator decides the acceptance angle of the concentrator. Higher the concentrator, lower will be acceptance angle depending on the aperture of EHC. When the concentrator height is less, for any ray to undergo multiple reflection is minimum. The optical efficiency is found to be maximum at normal incidence angle and varies for different incidence angles. The optical efficiency varies between 5 – 15 % for the concentrators with height less than 1 m whose acceptance angle is about 60°, whereas for the concentrator height greater than 1m, the acceptance angle is 45° and the optical efficiency varies between 20 – 30 % for incidence angles ± 30° and 5 – 20 % for another 15° variation in incidence angle.

The intensity of the flux incident on the receiver also depends on the concentrator height. As the concentrator height increases, the flux intensity increases. It can be observed that for the concentrator height of 0.4 m, the peak intensity of the flux incident on the receiver is 2.5×10^4 W/m^2, whereas for concentrator height of 2 m, peak intensity is 6.9×10^4 W/m^2 Fig. 7 shows the flux distribution over trapezoidal surface receiver at different incidence angles along major axis.

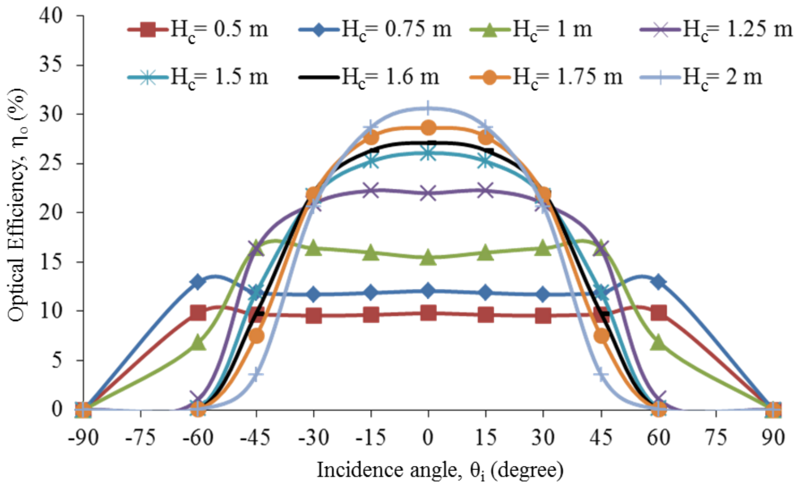
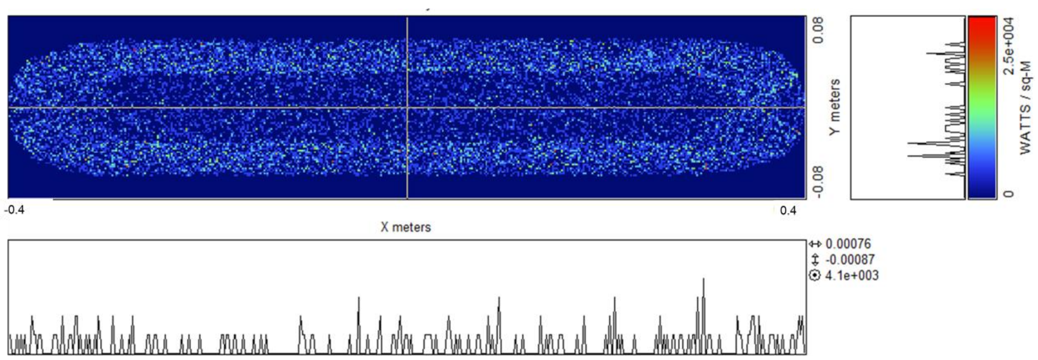
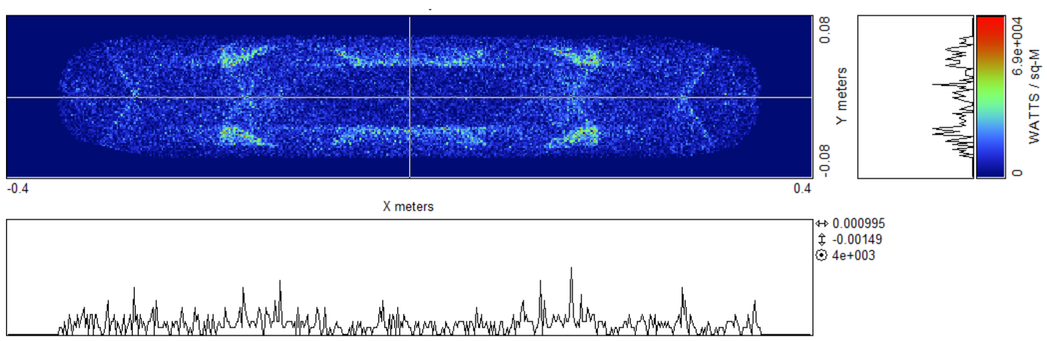


Fig. 6 Variation of optical efficiency for different concentrator heights



(a)



(b)

Fig. 7 Flux (2D) on receiver for two different heights of the concentrator (a) H_c = 0.4 m (b) H_c = 2 m

6.2 Effect of concentration ratio

The effect of concentration ratio (CR) of the EHC system is studied by varying from 5 to 30 in the steps of 5 by keeping H_c = 1.6 m. The aperture area at the bottom (receiver side) is kept constant and the aperture area at the top (entry of the concentrator) is varied to get different concentration ratio. The concentration ratio is defined as the ratio of aperture area of concentrator (A_{ap}) to that of aperture area of receiver (A_r). It is given by:

$$CR = \frac{A_{ap}}{A_r} \qquad \text{(eq. 7)}$$

The effect of concentration ratio on optical efficiency is shown in Fig. 8. Lower the concentration ratio, higher the optical efficiency and it is peaked at normal incidence and drops drastically for other incidence angles. It can be seen that for CR of 5, the optical efficiency is 80% at normal incidence, however, at incidence angle of 15°, it reduces to 60%. Similarly for incidence angle of at 30° and 45° incidence angle, optical efficiency further reduces to 33% and 10% respectively. As the CR increases, optical efficiency reduces. It can be seen that for higher concentration ratios (CR = 20, 25 and 30), the variation of optical efficiency for incidence angles ranging between ± 45º do not vary much. This is due to fact that aperture area at top is wider and hence it accepts more amount of solar radiation for wide range of incidence angles. Variation in CR is the variation of the aperture area of the concentrator with respect to the aperture area at the bottom (receiver), which is kept constant. Higher concentration ratio ensures higher concentration of the solar radiation on the receiver but, the optical efficiency of the system decreases to very low say, about 10%, which is not a desirable factor for the design of the concentrator.

The variation of flux on the receiver for CR 5 and CR 30 is shown in Fig. 9. The maximum flux on the receiver for CR 5 is about 4.8×10^4 W/m^2, whereas, for CR 30, it is about 3.6×10^4 W/m^2. The maximum flux of CR 5 is higher than that of CR 30, because more number of rays are reflected towards the same location of the receiver from small surface area of concentrator in case of CR 5. But, in case of CR 30, the rays are reflected from wider surface area of concentrator. It can be seen that for CR of 5, more rays are incident on the left and right side surface of the receiver than on the top on the receiver.

But for CR 30, the flux is seen distributed over the entire surface of the receiver. Figure 10 shows the flux distribution over the concentrator surface for two different concentration ratios 5 and 30. The distribution of flux on the concentrator is more uniform for lower concentration ratio system than the higher concentration ratio system. It can be seen that the flux distribution over the concentrator for CR 30 is uneven and non-uniform showing peak flux at certain points on the concentrator. Hence, the aperture area of the concentrator plays a major role in deciding the flux incident on the receiver. The effect of the geometry of the concentrator on the optical performance of EHC have been discussed. It can be seen that the height of the concentrator plays a major role on the flux incident on the receiver and the acceptance angle of the solar rays. The aperture area of the concentrator (other words concentration ratio) is also important to which level the concentration of the solar rays on the receiver are desired.

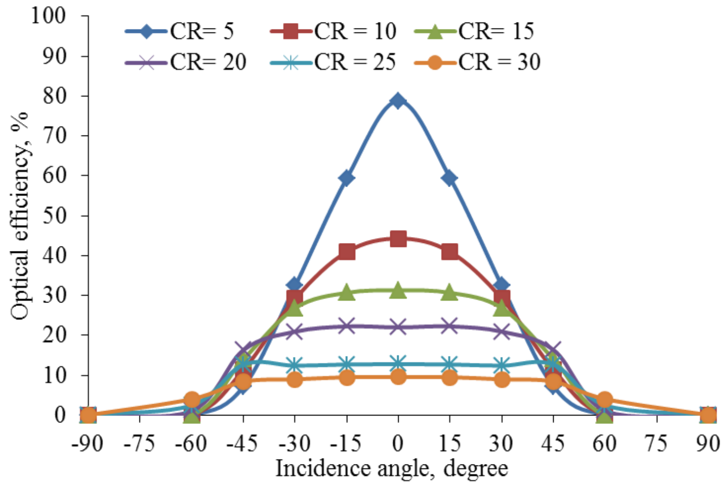


Fig. 8 Variation of optical efficiency with concentration ratio for different incidence angles

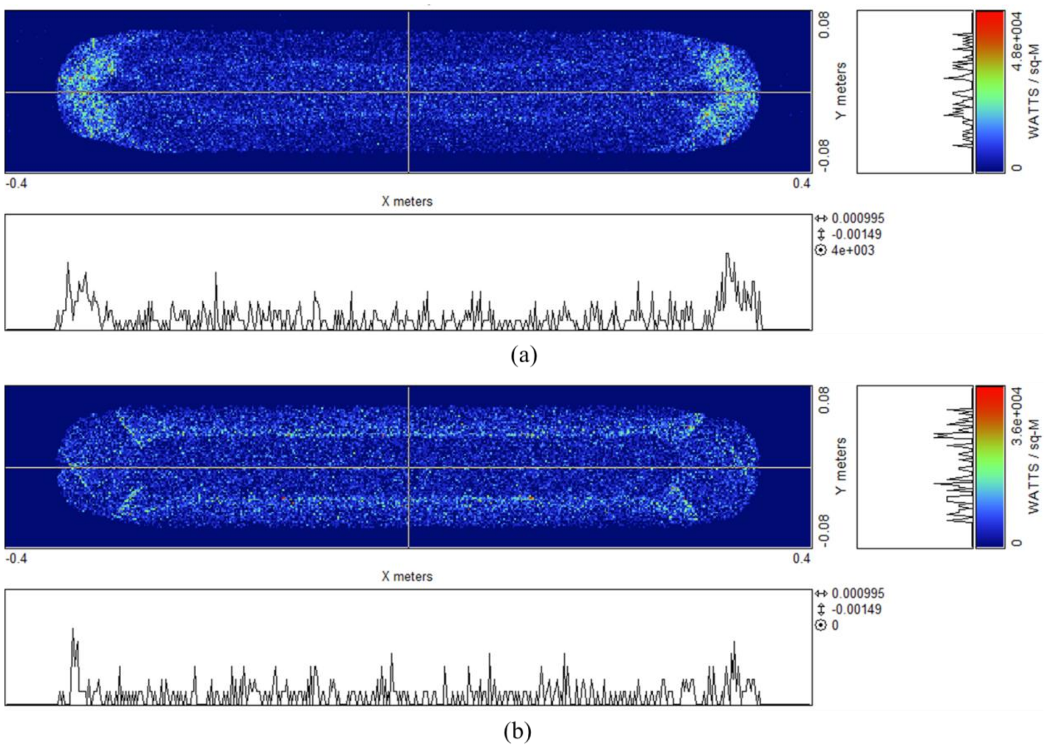


Fig. 9 Flux distribution (2-D) on the receiver for different concentration ratios (a) CR = 5 and (b) CR = 30

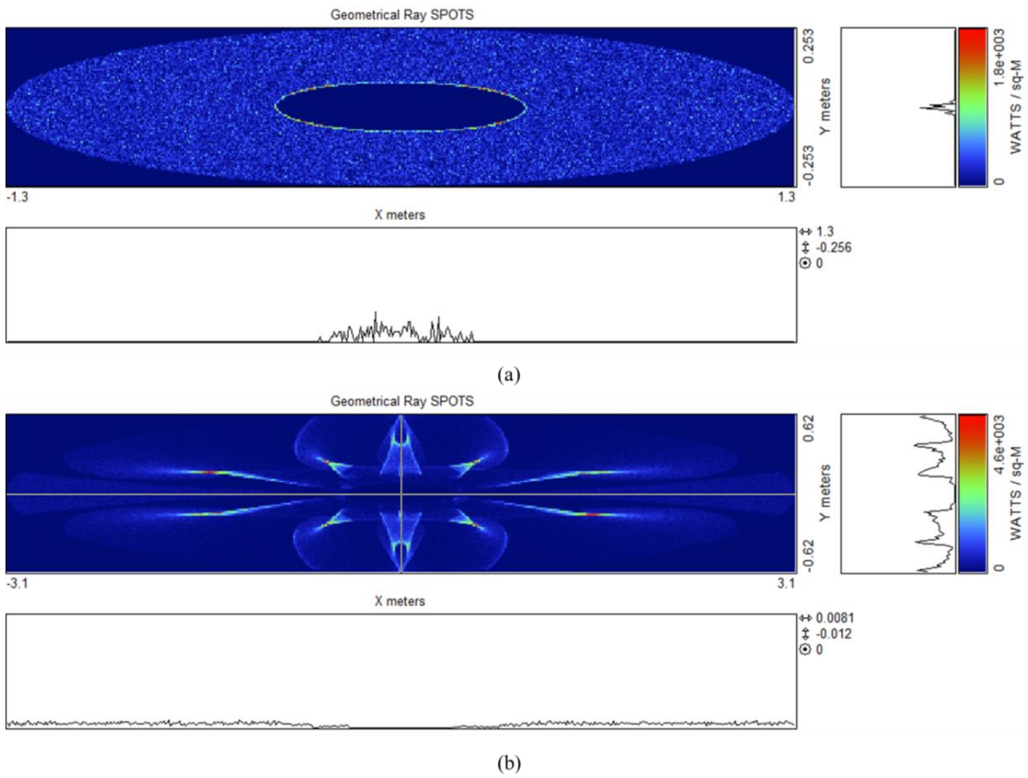


Fig. 10 Flux distribution (2-D) on the concentrator at different concentration ratios (a) CR = 5 and (b) CR = 30

6.3 Effect of receiver aperture

The effect of aperture width (W_r) of the top surface of the trapezoidal surface receiver of EHC on the optical performance is studied by keeping CR = 20 and H_r = 1.6 m. The different aperture width say, 30 mm, 45mm, 60mm, 90mm and 120 mm are studied. The variation of the optical efficiency of EHC for different aperture width is shown in Fig. 11. It can be seen that the variation of the optical efficiency for different aperture width is negligible and it is found to vary around 22% for all aperture width considered. The flux distribution (2-D) on the receiver for different aperture width of 30 mm and 120 mm is shown in Fig. 12. When the receiver aperture width increases, the flux that is intercepted on the inclined surface is reduced, hence reducing the flux on the side surfaces of the receiver. Hence, it can be concluded that the effect of aperture width on the optical performance is negligible.

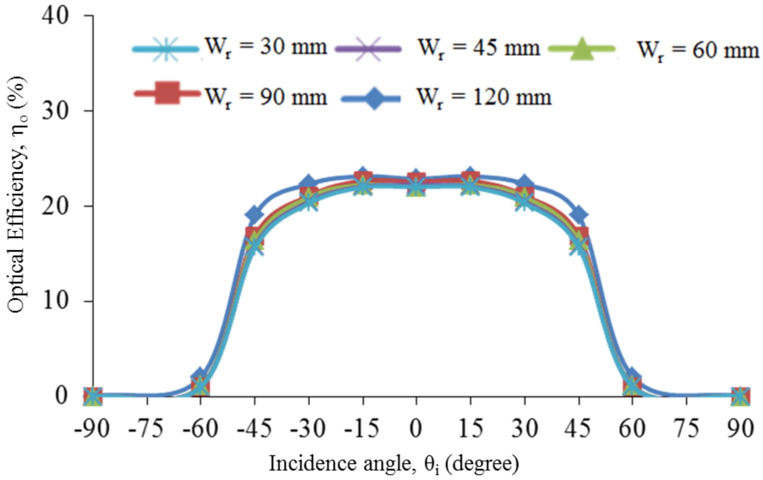
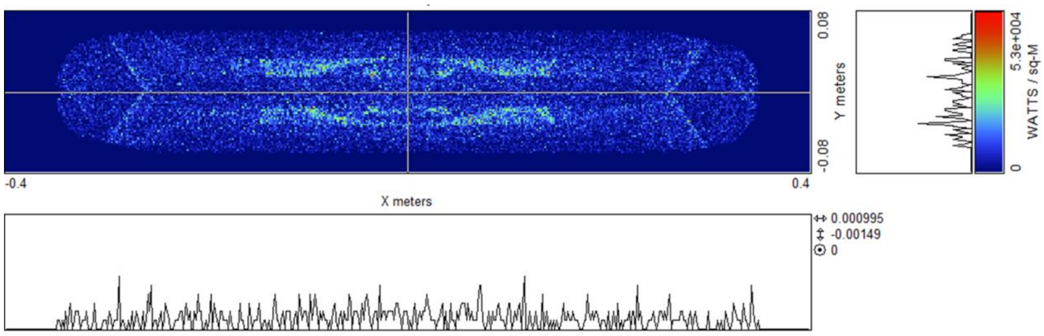
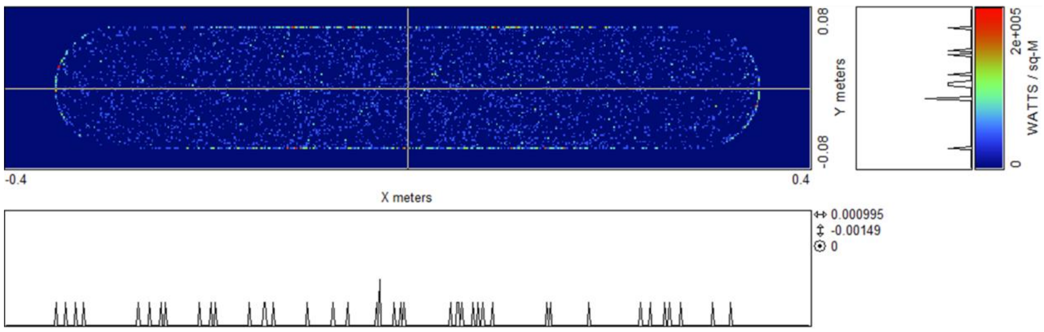


Fig. 11 Variation of optical efficiency for different aperture width



(a)



(b)

Fig. 12 Flux distribution on the receiver for different aperture width (a) 30 mm (b) 120 mm

6.4 Effect of receiver height

The effect of receiver height on the optical performance of EHC has been studied by varying the receiver height in four different values say 60, 90, 120 and 150 mm. Fig. 13 shows the variation of optical efficiency for different receiver height and it can be observed that the optical efficiency increases with receiver height. The flux variation on the receiver for different receiver height is shown in Fig. 14. It can be seen that, when the receiver height is varied, the amount of flux intercepted by the receiver is affected, consequently the optical efficiency of the system. It can be seen that the location of peak flux shifts from centre and moves outward when the height is increased. The variation of maximum flux on the receiver for different receiver height is found to be varying between 12kW/m^2 to 13 kW/m^2.

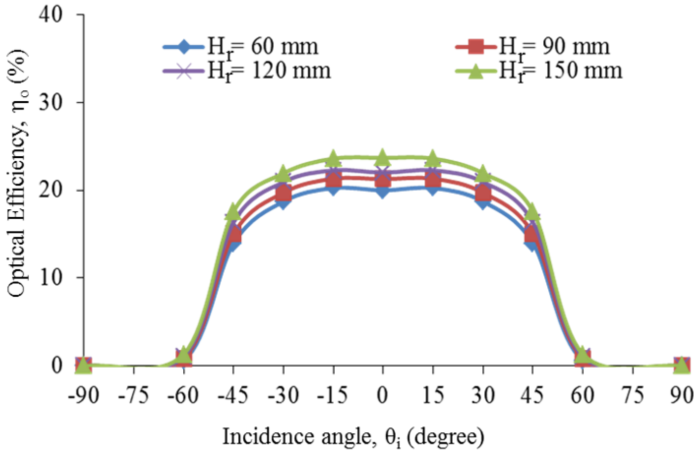


Fig. 13 Variation of optical efficiency for different receiver height

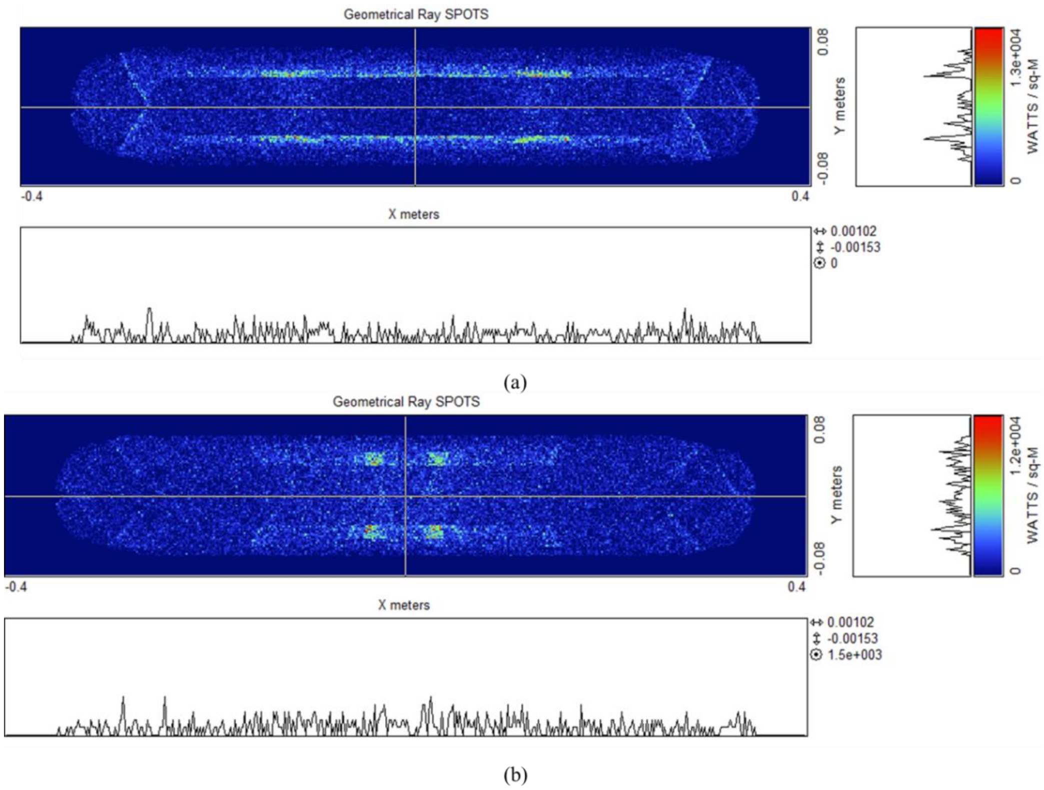


Fig. 14 Flux distribution on the receiver for different aperture width (a) 150 mm (b) 60 mm

7. Conclusion

The optical ray tracing analysis of a non-imaging concentrating collector with two types of receiver is studied. The effect of various parameters such as concentrator height, concentration ratio, receiver width and receiver height on optical performance of the system is studied. The flux distribution and optical performance of two types of receiver say flat receiver and trapezoidal surface receiver are compared and further based on the performance, trapezoidal receiver is considered for further analysis. The optical efficiency of the EHC system was found to be maximum at normal incidence and varies for different incidence angles. The optical efficiency varies between 5 – 15 % for the concentrators with height less than 1m whose acceptance angle is about ± 60º, whereas for concentrator height greater than 1m, acceptance angle is ± 45º and optical efficiency varies between 20 – 30 %. It can be observed that, for concentrator height of 0.4 m, peak flux intensity is 2.5×10^4 W/m^2 whereas for concentrator height of 2 m, it is 6.9×10^4 W/m^2. The effect of variation of CR is also studied. The effect of receiver aperture and height also play role in deciding the flux incident on the receiver. The effect of variation of receiver aperture width is negligible and it is found to vary around 22%. Similarly or variation of receiver height, flux incident varies between 12 –

$13kW/m^2$. This system can be effectively used for low and medium temperature applications based on the location with less/no tracking.

Nomenclature

a	Semi-major axis of concentrator at bottom aperture (m)
A	Semi-major axis of concentrator at top aperture (m)
A_{ap}	Aperture area (m^2)
A_r	Area of receiver (m^2)
b	Semi-minor axis of concentrator at bottom aperture (m)
B	Semi-minor axis of concentrator at top aperture (m)
c	Distance between focal point and centre of ellipse (m)
H_c	Height of concentrator (m)
H_r	Height of EHC receiver (m)
I	Flux (W/m^2)
m	Number of reflections
N	Number of rays
Wr	Aperture width of EHC receiver (m)
X,Y,Z	Cartesian coordinates (m)
Greek symbols	
θ_a	Half acceptance angle (degrees)
θ_i	Solar incidence angle (degrees)
η_o	Optical efficiency (%)
Abbreviations	
ASAP	Advanced Systems Analysis Program
CR	Concentration Ratio
EHC	Elliptical Hyperbolic Concentrator

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