Optical study of a 3-D Elliptical Hyperboloid Concentrator

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ABSTRACT

The optical performance of a solar concentrator is mostly depends on the geometry of the concentrator profile. In the present paper, work focuses on the optical efficiency of 3-D Elliptical Hyperboloid Concentrator (3-D EHC) using Optis ™ Ray-trace software. An extensive theoretical prediction, using a 3-D ray tracing technique has been adopted in the current investigation to calculate the optical efficiency of a novel 3-D EHC. The effect of source angle (from +90° to -90°) on the optical efficiency of a 3-D EHC is reported. Due to the wide acceptance angle of the Elliptical Hyperboloid solar Concentrator, the optical efficiency was found to be 87% for a concentration ratio of 18×. Due to the three-dimensional nature of the Elliptical hyperboloid solar concentrator, the optical efficiency and the concentration ratio are also a function geometric parameters such as the ratio of the concentrator height to each of the receiver's major and minor axes; a parametric study of these variables has also been conducted The aperture length was fixed for all simulations. Results presented also show the distribution of the concentrated radiant energy over the receiver/absorber. For the range of parameters investigated, an optimum design is presented.

1. Introduction

Solar concentration technology is crucial to the development of the solar energy industry. Concentrated solar energy has the potential to reduce the unit cost of electricity produced from photovoltaic sources. It is also necessary in solar thermal applications to increase the operating temperature for steam power cycle efficiency. The current research is concerned with the development of a novel 3-D Elliptical Hyperboloid Concentrator for a small scale solar powered water desalination system.

The development of solar concentration technology gained impetus after the discovery of the Compound parabolic concentrator (CPC). This led to the beginning of a relatively new branch in physics known as non imaging optics. Prior to the use of non-imaging concentrating collectors, no design had proven theoretically capable of achieving the sine-law limit to concentration. Furthermore, based on conventional concentrator imaging technology the optimum possible concentration ratio for solar collection without diurnal tracking, was shown to be three or at least needed a second concentrator stage to be employed. With these developments, much effort was put into the further development and application of non imaging optics techniques.

Since the invention of the compound parabolic concentrator (CPC) in 1974 (Hsieh, 1981) many papers have been published on literature that deal with a wide range of the design and analysis (El-Assay and Clark, 1987) (Hinrterberger and Winston, 1966) Chakraverty et al. (1987) Tchinda et al. (1998) Fraidenraich. et al. (1999) . However, a close examination of these papers reveals that the great majority of them are devoted to optical, thermal analysis and geometrical of the CPC with tubular absorber. Asymmetric compound parabolic concentrators Mallick et al. (2004) have also been proposed. Ideal concentrators such as the CC and the FLC were used to transmit new families of elliptic bundles Guti´errez et al. (1996). Based on the geometric vector flux field several researchers studied three dimensional (3-D) analysis of CPC The first three dimensional (3-D) compound parabolic concentrator (CPC) has been studied using the flow line method for solar application

(Winston and Welford,1979) as a component originating from the field of a Lambertian emitter in the form of a 2-D truncated wedge. Ray-tracing techniques are appropriate for line-axis system, which allow for evaluation of optical performance of complicated system geometries regarding diffuse and direct insolation. Analysis of optical efficiency by this technique has been used in many studies of solar devices and theoretical results have been published (Welford and Winston, 1980). A ray tracing procedure described (Spencer and Murty, 1968) for a set of conical surfaces with provisions for specifying their departures, orientation, positioning and separation. The optical analysis of a novel tubular solar thermal collector consisting of a combination of cusp mirror-cylindrical heat pipes with the use of ray trace technique was presented (Ortabasi and Buehl, 1980). The flux distributions showed that no burnout can be expected for the Cu/Cu/H2o heat pipes even at high concentrations of up to five suns

A 3-D Elliptical Hyperboloid Concentrator (EHC) is considered in this research which is a new type of concentrator with an elliptical cross section and a hyperboloid curvature. The main purpose of this study is to predict the optical performance of a using ray tracing technique. The optical efficiency refers to the fraction of light incident that reaches the absorber directly or through reflection from concentrator surfaces after entering the aperture. The optical performance of EHC has been evaluated for a range of geometric and operating parameters including angle of incidence, concentrator height and receiver diameter in terms of optical efficiency and energy flux distribution on the receiver. A high angular acceptance is usually desirable to avoid the necessity for tracking.

2. Ray tracing Diagram of Elliptical Hyperboloid Reflector surface

Ray-tracing, is the act of following the trajectory of ray's bundles through a system of reflecting is an important technique for characterising the performance of optical devices. Based on known physical laws and optical properties it is possible to determine the outcome of a given ray based on its point of origin and direction of movement. In present ray tracing analysis all incident rays are assumed to be parallel and carries equal amount of energy. The fig.1 described below how ray tracing reflection in two dimensional hyperboloid 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 some reflections within the 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 geometry of elliptical hyperboloid concentrator is presented in Fig. 2. Ali et al. (2010)

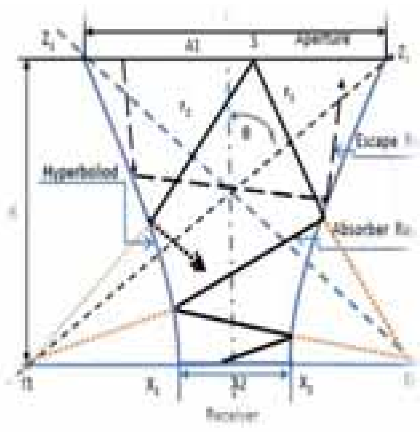


Fig.1. A 2-D Hyperboloid concentrator

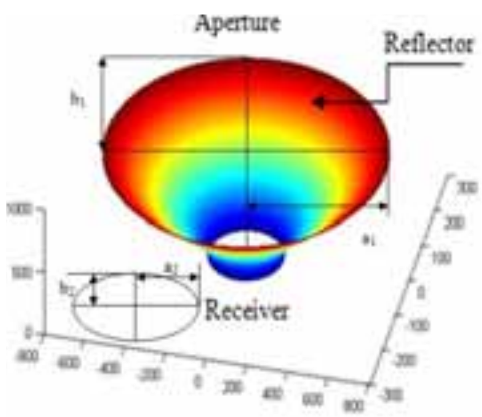
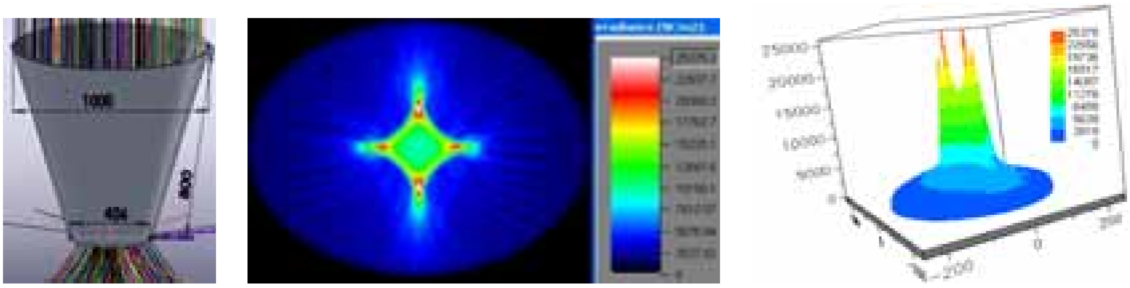


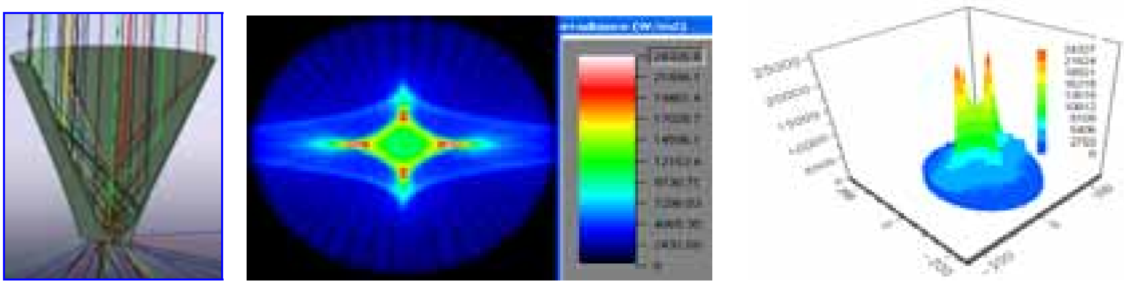
Fig.2. A 3-D Elliptical Hyperboloid Concentrator

3. Flux Density Distribution on the Receiver Area for Different Height of 3-D EHC

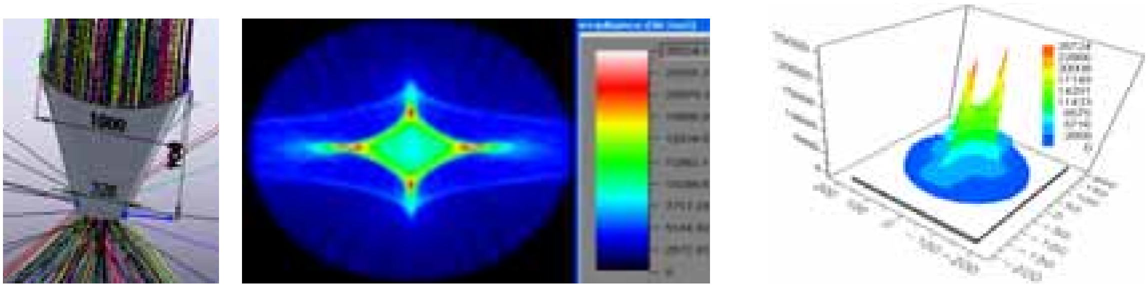
Using the ray tracing method described above the following results were obtained for the 3-D EHC. Fig. 3a shows the ray tracing diagram of the different shapes of the EHC geometry. The concentrated flux density at any point on a receiver surface is equal to an integral of an incoming radiation flux brightness that is a function of angular coordinates. The figure also shows the effect on the distribution of the incoming radiant energy varying with the values of the concentrator height and area of the receiver and the absorber. Fig. 3b and Fig. 3c shows the top view and the three dimensional view of the flux radiant distribution of the 3D EHC for various combination of the concentrator height and area of the receiver with a fixed aperture length of 1m respectively.



Concentrator height 800 (mm)



Concentrator height 850(mm)



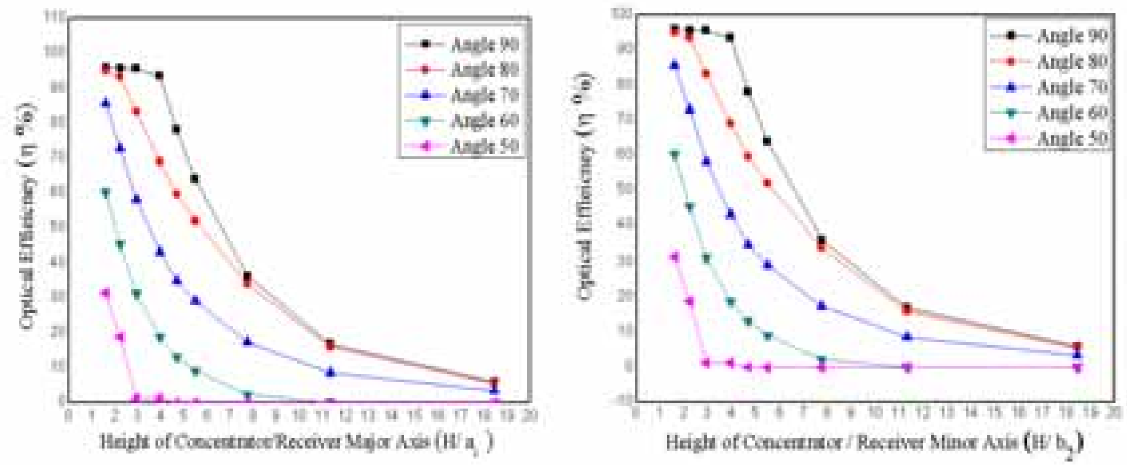
Concentrator height 900(mm)

3a **3b** **3c**

Fig.3. Flux distribution in the receiver area for different height of 3-D EHC

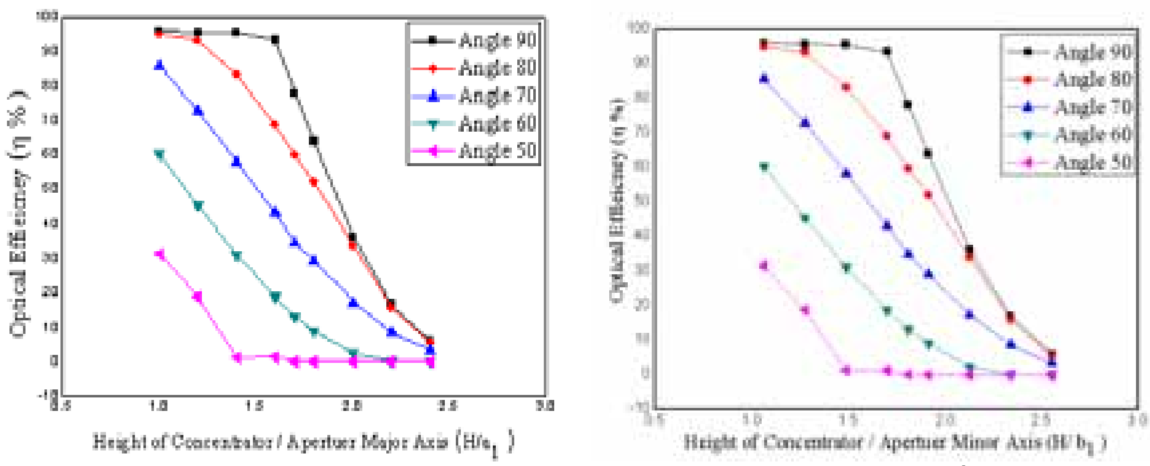
4. Optical Efficiency of a 3-D EHC for Non- Dimensional Concentrator

Fig. 4a and Fig. 4b show that the optical efficiency is maximum when position of the radiation source (i.e. sun) is directly above (that is 90º) the receiver and it decreases as the angle of the radiation decreases until all the radiation isn't absorbed by the receiver when the incident angle ±60º. Combined with the orientation of the source of radiations, the optical efficiency of the 3D EHC will be maximum when the height of the concentrator is twice the length of each of the receiver's major and minor axes. Similarly the optical efficiency is optimum when the concentrator height is approximately equal to the length of each of the aperture's major and minor axes respectively as can be seen in Fig. 5a and Fig. 5b. As the concentration increases in relation to each of the incidence angle of radiation and vice versa the optical efficiency decreases until all the radiation is totally absorbed by the receiver. When the length of the aperture major axis is half the length of the aperture minor axis the optical efficiency is maximum and the optical decreases as the ratio increases. Fig.6a , and 6b show that unlike the two cases explained above the optical efficiency of the 3D EHC is proportional to the ratio of the receiver's major axis and minor axis, the optical efficiency increases as this ratio increases from 0.5 and its maximum when the length of the aperture major is ninth that of the aperture minor axis. And also shows the concentration ratio is inversely proportional to the optical efficiency in relation to the variation of the ratio of the height of concentrator to each of the aperture's and receiver's major and minor axes.



a b

Fig.4. Optical efficiency and ratio of the height of the concentrator to receiver major and minor axis



a b

Fig.5. Variation of the optical efficiency with the ratio of "height of concentrator and aperture's major and minor axes" respectively for different incidence angle at the aperture.

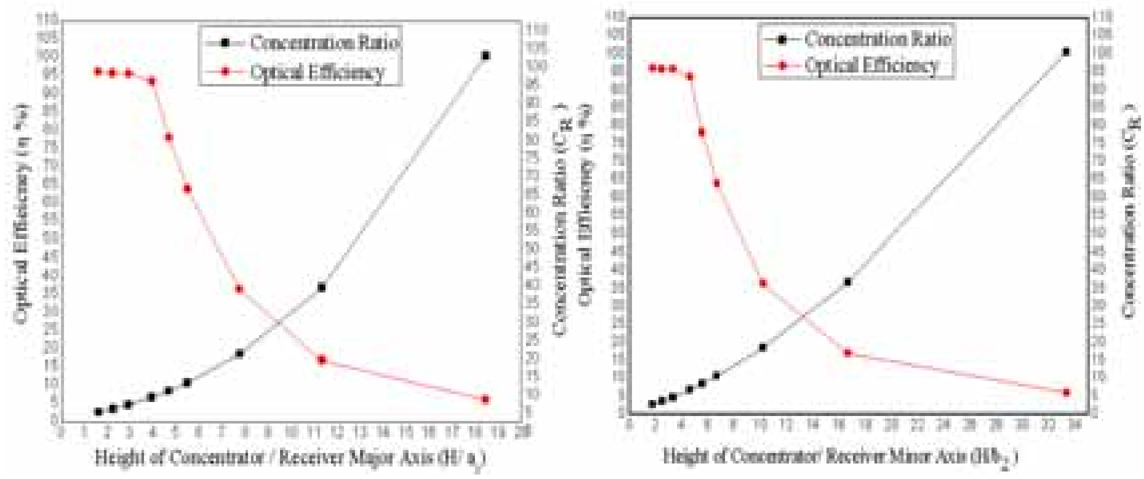
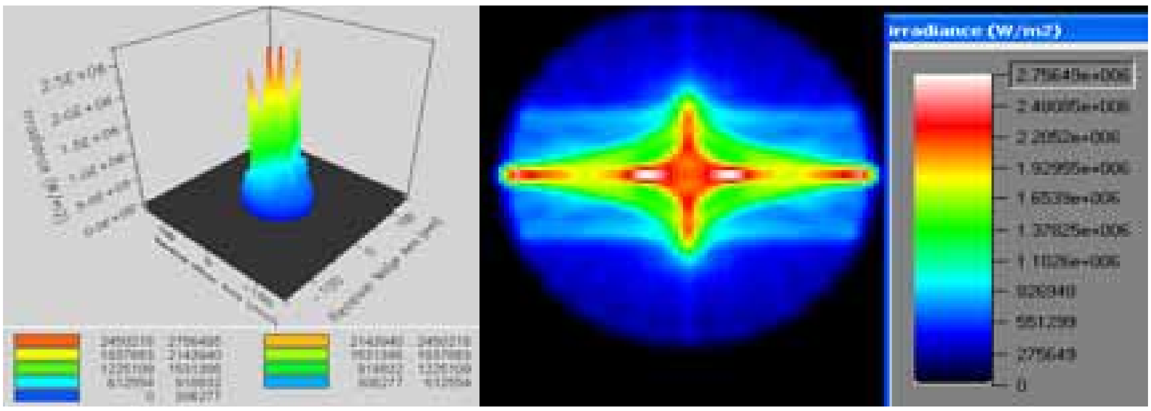


Fig. 6. Variation of concentration ratio and optical efficiency with the ratio of "height of concentrator and receiver's major and minor axes" respectively for perpendicular rays.

5. Optical Efficiency of a 3-D EHC for Specific Dimensions of Concentrator

Based on Optis^{TM}, an optical efficiency of a 3-D EHC was carried out. Fig. 7a shows the 3-D energy flow diagram. The distribution of the incoming radiant energy with variation of the different values of the receiver area can also been seen with the red region representing the region of maximum irradiance. These regions occur at different points as shown in Fig. 7a and correspond to the various combinations of the receiver major axis and minor axis. Fig.7b shows the top view of the energy distribution.

Fig. 8 demonstrates the effect of variation of the incident angle for different orientations of the source within the range ± 90o on the optical efficiency of 3-D EHC of CR18× and a concentration height of 0.86m. The maximum optical efficiency of 87% was observed for an incidence angle of ±20.



a b

Fig.7. (a, b) flux distribution in the receiver area for height of concentrator 0.860 m

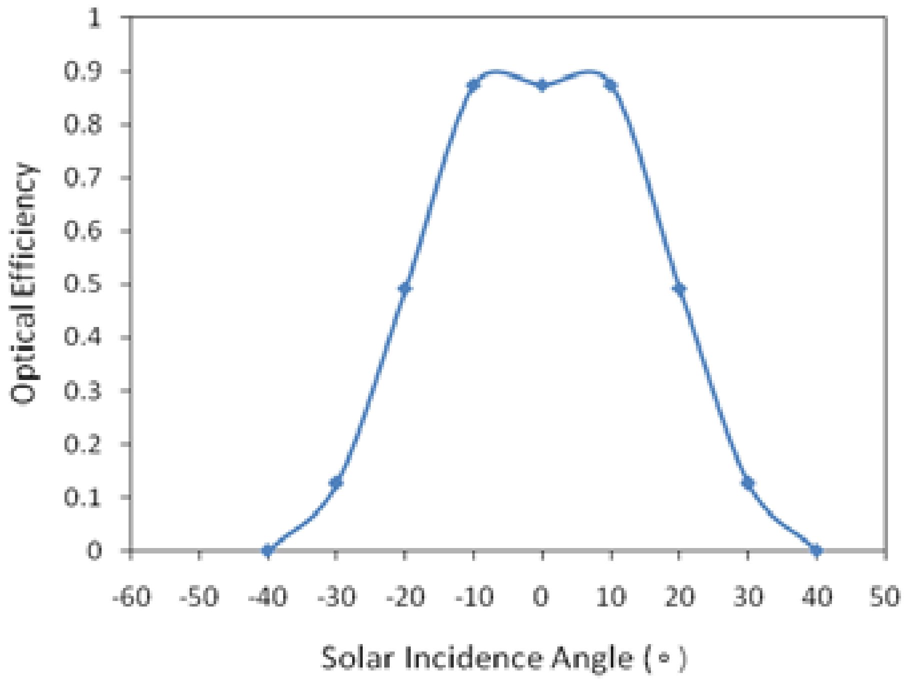


Fig. 8.Variation of optical efficiency with the solar incidences angle (º)

6. Conclusions

The 3-D EHC has been presented in this work. Using the ray tracing technique by Optis^{TM} to determine the optimal optical efficiency of the 3-D EHC design. Based on this study, the optimum optical efficiency was obtained when the orientation of the source of incoming radiation is perpendicular to the collector. The ratios of the height of concentrator to the receiver's and aperture's major and minor axes have the same effect on the optical efficiency. While the effect of the ratio of the receiver major axis to the receiver minor axis on the optical efficiency is inversely proportional to that of the ratio of the aperture major axis to the aperture minor axis. The optical of 87% and CR of 18× was obtained for a concentrator height 0.860 m, when the aperture major axis is 0.488m, minor axis is 0.472m, receiver major axis is 0.122m and minor axis is 0.106m. 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.

Acknowledgment

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7. References

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Nomenclature

Quantity	Symbol	Unit
Ellipsoidal Hyperboloid Concentrator	EHC	
Cone concentrator	CC	
Compound parabolic concentrator	CPC	
Flow line concentrator	FLC	
Concentration ratio	CR	
Optical efficiency	η	
Direction vector of the reflected ray	r_{reft}	
Incident direction of the incoming ray	r_{inc}	
Area of aperture	A_1	mm^2
Area of receiver	A_2	mm^2
Aare of flux distributor	A	mm^2
Height	H	mm
Aperture major axis	$2a_1$	mm
Aperture minor axis	$2b_1$	mm
Receiver major axis	$2a_2$	mm
Receiver minor axis	$2b_2$	mm
Radiant incidence	I_r	$W.m^2$
Radiant flux	Ø_r	W
Direction vector of the reflected ray	r_{reft}.	
Incident direction of the incoming ray	r_{inc}	