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Effects of Acceptance angle and Receiver radius on the Optical Performance of Compound Parabolic Collector

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Abstract *- The optical performance of a solar collector is highly influenced by its design. Among the key design parameters of compound parabolic collector (CPC) is the acceptance angle and the receiver radius which affect both its geometric and optical characteristics. This paper presents the effects of the acceptance angle and the receiver radius on the optical efficiency and concentration ratio of a heat pipe based compound parabolic collector (HPCPC) using a ray tracing technique. Nine different configurations of three acceptance angles (30^o, 40^o and 60^o) and receiver radii (12.5, 22.5 and 25mm) were simulated for eleven different hour angles. Results have showed that the wider the acceptance angle, the higher the efficiency but the lower the concentration ratio. The optical efficiencies of 60^o, 40^o and 30^o acceptance angles with receiver radius of 12.5mm were found respectively as 94, 87 and 81% at solar hour angle of 15^o. While their daily average optical efficiencies at static condition are 76.5%, 64% and 36% for 60^o, 40^o and 30^o acceptance angles respectively. Also the results have shown that the smaller the receiver radius, the higher the efficiency for a particular acceptance angle. Furthermore the irradiance distribution is greatly affected by the position of the sun (solar hour angle), as some areas on the receiver have high concentration of flux than others leading to the creation of hot spot.*

Keywords*: Acceptance angle, Concentration ratio, Optical ray tracing, Compound Parabolic Collector, Optical efficiency*

1.0 INTRODUCTION

Renewable energy must make significant contribution to the world energy requirements so as to reduce the greenhouse gas emission due to the excessive use of fossil fuel. Solar energy is the most promising renewable source due to its availability in some regions in the world especially those with high radiation like Nigeria. Solar energy has great potential in Kano, Nigeria, (12.05^{o}N, 8.52^{o}E) where the radiation available reaches 26.78 MJ/m^2.day (Nigerian Meteorological Agency, 2011). The available radiation can be harnessed by using solar photovoltaic or thermal solar collector which can be used for various applications such as lighting, drying, solar cooling, desalination, etc. The solar radiation falling in any location is received by a device called solar collector and then used for different applications. There are various types of solar collectors that are utilized in solar energy systems which can be either concentrating or non-concentrating. A non-concentrating collector has an equal area for capturing and absorption of solar energy while the concentrating counterpart consists of reflectors (concentrator) that focus incoming radiation onto the receiver. The non - concentrating collectors which includes flat plate and evacuated tube collectors are designed for applications requiring moderate temperature outputs up to 100^o C (Duffie, and Beckham, 2006).

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Concentrating collectors can be divided into imaging and non-imaging. When the sun's image is formed on the receiver it is called imaging collector which includes parabolic dish, parabolic trough, central receiver (or heliostat field collector) and linear Fresnel reflector (LFR) while the compound parabolic concentrator belongs to the non-imaging category. Non-imaging concentrators can meet low and medium concentration without tracking the sun and this makes them more affordable than imaging counterpart.

Compound parabolic concentrator (CPC) is a non-imaging concentrator that concentrates all solar radiations falling on it within a wide range of angle called "acceptance angle". Its first design was individually proposed in 1966 by Hinterberger and Winston in USA, Baranov and Melnikov in USSR and Ploke in Germany, but its potential was realized in 1974 (Duffie and Beckham, 2006). CPC has properties of both concentrating and flat plate collectors with low errors of alignment for reflective and receiving surfaces and high optical efficiency. Since when its potentials as concentrator for solar collectors was realised, several investigations were carried out by many researchers for wide range of applications (Manuel et al., 2009; Malato et al., 2004; Tamanot -Telto, 1999; Vilar et al., 2011).
Several studies were reported on the optical performance of CPC by means of simulations and experiments with the aim of either improving its performance or selection of best design among others. The geometric and optical properties of fully illuminated inverted V shape receiver

CPC with vertex angle greater or equal to the acceptance half angle, was analytically studied by Fraidenraich et al., (2008). Calculations of the energy obtained and cost benefit analysis were also carried out for different collector orientations and various vertex and acceptance angles. According to the authors, the results obtained has led to the best collector design for the Recife – PE city, Brazil with the concentration ratio between 1.0 and 1.2 for East – West orientation, acceptance and absorber vertex angles of 30^o and 65^o respectively. The performance of asymmetric and symmetric CPC with inverted and tubular receivers respectively was compared in terms of radiation conversion efficiency (Kothdiwala et al., 1999). The results showed that the asymmetric inverted absorber CPC (IACPC) outperformed the symmetric tubular CPC (TACPC) with 10 – 15% increase in the conversion efficiency. But the reason for the superior performance of the IACPC may be difficult to be attributed to the concentrators' shape; as they have different absorber shapes and also the TACPC has glass envelope around the receiver which will also affect its performance.

A yearly distribution insolation model for a 2D CPC was developed by Akio and Shigeo, (1995) to determine its optimum acceptance angle. The model considered the beam radiation distribution to be within $\pm23.5^o$ of declination and diffuse of having uniform irradiance. The authors considered acceptance angle of 26^o as optimum regardless of the diffuse radiation intensity. Although the authors concluded that their optimized CPC could be used in most locations in the world, it should be understood that their model considered only radiation on the receiver. Also the optimum acceptance angle may differ in places far away from the equator (which is the target in their model) due to some factors such as the variation of the daylight hours and the beam tilt factors. Also other studies proposed wider angles, such as 30^o (Carvalho et al., 1995), 45^o (Mills et al.,1986) and 56^o (Grimmer, 1979).

The optical and thermal performance of non-evacuated CPC solar collector with a cylindrical absorber with the heat loss coefficient expressed as function of temperature, was studied by Fraidenraich et al., (1999) using a mathematical model. Heat loss linear coefficient was shown to be dependent on the solar insolation while the second degree coefficient was independent of the insolation. A linear plot of efficiency against the ratio of the square of the difference between

The results obtained from the literature survey have showed that the acceptance angle of CPC plays a vital role in determining the solar radiation acceptance of the collector and hence it's optical performance. Hence this paper investigates the effects of the acceptance angle on the optical performance of the CPC using ray tracing technique. Optical performance investigation of different designs of CPC based on different acceptance angles and different receiver sizes were analyzed at different solar hour angles and solar times using global radiation of Kano, Nigeria.

2.0 GEOMETRY OF CPC

Compound Parabolic Concentrators (CPC) are non-imaging concentrators which processes properties of both concentrating and flat plate collectors with low errors of alignment for reflective and receiving surfaces and high optical efficiency. CPC consists mainly of two halves of parabolas and a receiver situated along their line of symmetry. It is characterized by the acceptance angle, collector height and aperture width as shown in Figure 1. There are several designs of CPC in terms of the concentrator shape, different acceptance angles and receiver types and sizes. This type of collector can be fitted with different types of absorbers which can be of fin type (like bifacial, wedge, flat, etc.) or tubular like heat pipe receivers as shown in Figure 1. Depending on the intended application, water storage tank, photo reactor and PV cell can also serve as receivers.

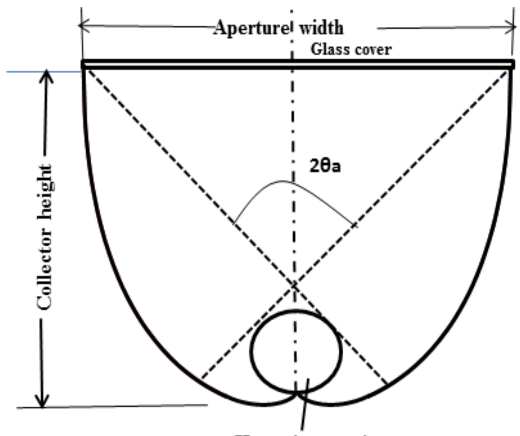


Figure 1: Compound Parabolic Collector

The effects of the acceptance angle and receiver radius on the CPC geometric parameters such as collector height, aperture width, concentration ratio, average number of reflection were fully investigated by Abdullahi et al., (2013). In such study, various charts relating these parameters with the acceptance angle of CPC and receiver radius were generated and analyzed using the model developed in excel spreadsheet. In such paper, details analysis of the effects of acceptance angle on the design and performance of CPC was carried which includes the solar radiation available, geometry of the collector and the thermal resistance of the heat pipe. The present work investigates the effects of CPC acceptance angle and the receiver radius on its optical performance at different solar hour angles.

3.0 MODEL FOR OPTICAL PERFORMANCE OF HPCPC

Ray tracing technique is employed in the analysis of concentrating collectors to determine the intensity and distribution of the rays on the receiver of the collector. The method is done with vectors by determining the direction and point of intersection of incident ray with the reflecting surface, and then the direction of the reflected rays which follow the law of reflection.
Similarly, Snell's law described the behavior of the refracting surfaces by defining the relationship between the angles of incidence and refraction for rays striking a surface between two media of different refractive indices. The technique is used to determine the optical performance of solar systems both thermal (Eames et al., 2011) and PV (Nazmi et al., 2012) systems.

3.1 Ray tracing model for prediction of the Optical performance of CPC

In this study, the effects of the acceptance angle of CPC and receiver radius on its optical efficiency was studied by advanced ray tracing technique using a software called Optisworks. Nine different geometries of CPC consisting of combinations of three different acceptance angles and three receiver radii were simulated. The use of Optisworks software for the ray tracing and simulation of the HPCPC involves many steps and definitions of various parameters as presented in Figure 2. The modelling process includes generating of the HPCPC profiles, modelling the source (sun), defining material properties, defining the incoming and receiver detectors and running the ray tracing and simulation. Due to the shape of the receiver of this work (cylindrical), eight detectors were used to identify the flux distribution on the top, bottom and two sides of the receiver.

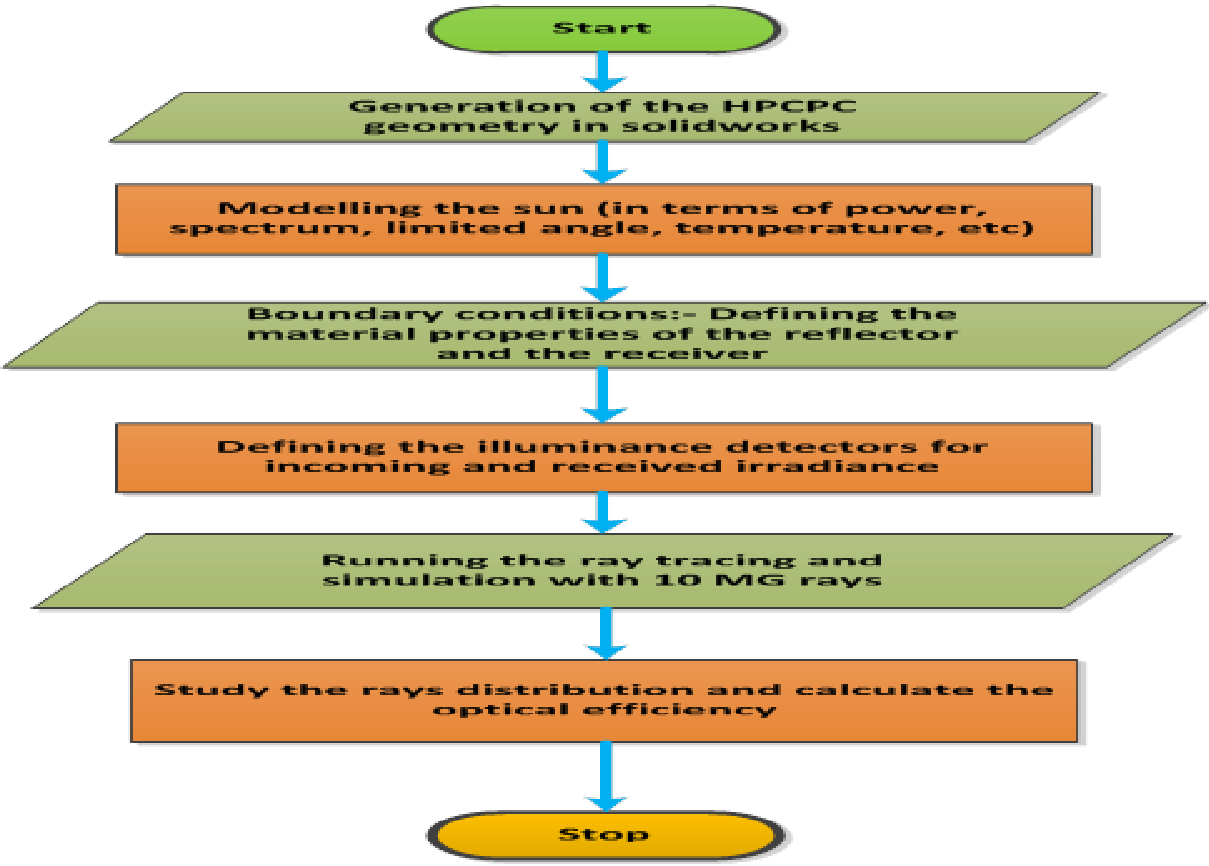


Figure 2: Flow chart of the modelling process of HPCPC using ray tracing technique

3.2 Effects of Acceptance angle and Receiver radius on the Optical Performance of CPC

Ray tracing technique is employed to study the effects of the acceptance angles and the receiver radii on the optical performance of the nine configurations of the CPCs. The simulation was carried out according to the process outlined in Figure 2 using the average global radiation. Irradiance of 1000 W/m^2 (Which is the standard usually used in solar simulation) as shown in Abdullah et al., 2015 and the geometries were simulated in static condition while their performances were evaluated at different solar hour angles. Table 3.1 gives the geometric and optical properties employed in this simulation.

The intensity type used was "Lambertian" and limited half angle of 0^o was set for the source. The lambertian reflectance is the property that defines ideal diffusely reflecting surface, as such the apparent brightness of the surface to an observer, is the same regardless of the observer's angle of view. The simulation was run at different solar hour angles with zero taken as the zenith position and the modelled sun moves in the E-W orientation along the length of the collector as shown in Figure 3.

The Optical simulation procedure employed in this work was validated with experimental data and presented in Abdullahi etal. (2015). In Abdullahi et al., (2015), the simulation procedure was used to study the optical performance of double receiver CPC while in the present study, the procedure was employed on simulating the effects of the acceptance angle and receiver radius on the optical performance of the CPC.

Table 3.1: Geometric and optical properties employed in ray tracing analysis of the various configurations simulated

Parameter	**HPCPC60**	**HPCPC40**	**HPCPC30**
Acceptance angle (^{o})	60	40	30
Receiver radius (mm)	12.5, 22.5 and 25	12.5, 22.5 and 25	12.5, 22.5 and 25
Reflectivity of the concentrator (%)	90	90	90
Receiver absorptivity (%)	100	100	100
Range of solar hour angle (^{o})	-75 to 75	-75 to 75	-75 to 75
Collector length (mm)	200	200	200

The performances of the nine geometries simulated were compared based on their optical efficiencies at different solar hour angles. When the simulation is run at a particular hour angle, the flux and the power (in Watts) on the collector aperture and on the receiver are determined. The power is determined by the detectors defined on the aperture and the receiver in the software (as shown in Figure 2). Such values of the power determined at different hour angles are used in calculating the optical efficiency.

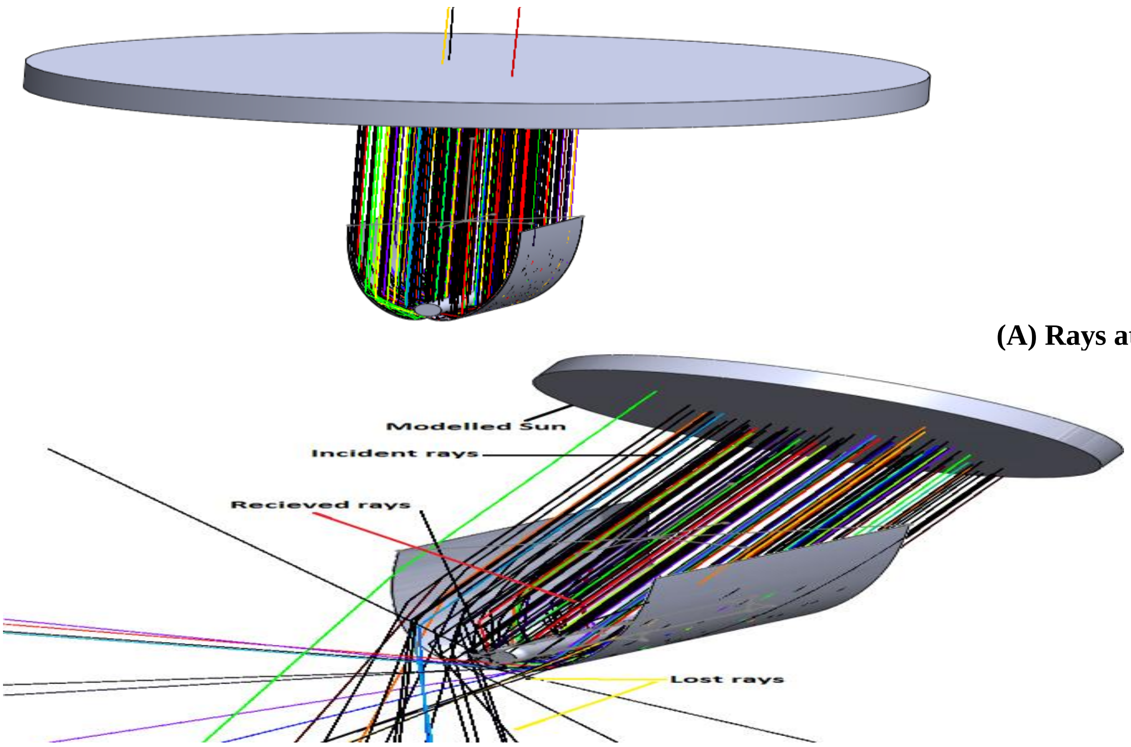
The optical efficiency was calculated as the ratio of the power received by the tube (P_{re}) to that received at the aperture (P_{ap}) of the collector as (Abdullahi et al., 2015):

$$\eta = P_{re} / P_{ap} \tag{1}$$

The half acceptance angle is related to the geometric concentration ratio, C as (Rabl, 1985):

$$C = \frac{A_{ap}}{A_{re}} = \frac{1}{Sin\theta_a} \tag{2}$$

Where A_{ap} and A_{re} are the aperture and the receiver areas respectively and $2\theta_a$ is the acceptance angle



(A) Rays at 0^o (zenith)

(B) Ray at 45^o

Figure 3: Trajectories of the rays incident on CPC at different solar hour angles

4.0 RESULTS AND DISCUSSION

Figures 4, 5 and 6 show the effects of the CPC receiver on the optical efficiency of the collector at constant acceptance angles of 30, 40 and 60° respectively. The optical efficiencies of the CPC with 30° acceptance and receiver radii of 12.5mm, 22.5mm and 25mm at different solar hour angles are presented in Figure 4. It can be seen from Figure that the optical efficiency decreases as the receiver radius increases. This is due to the increase in the reflector height with the receiver size and the upper part (which contributes less in focusing the radiation to the receiver) and may shade the rays from reaching the receiver. Also Figures 5 and 6 shows the optical efficiencies of the CPC with 40° and 60° acceptance angles respectively. These figure showed similar trends with Figure 4, which shows that for each acceptance angle, the optical efficiency decreases with increase in the receiver radius due to the reason stated.

It can also be seen from Figures 4 to 6 that the optical efficiency increases as the sun moves towards zenith (noon time). Example for HPCPC60R12.5, the optical efficiencies are 87.6%, 94% and 98% at solar hour angles of 30°, 15° and 0° (zenith) respectively (Figure 6). This is because as the sun moves toward the zenith, most of its incident rays will be within the acceptance angles of the CPC, hence they will be concentrated on the receiver, hence increasing the optical efficiency.

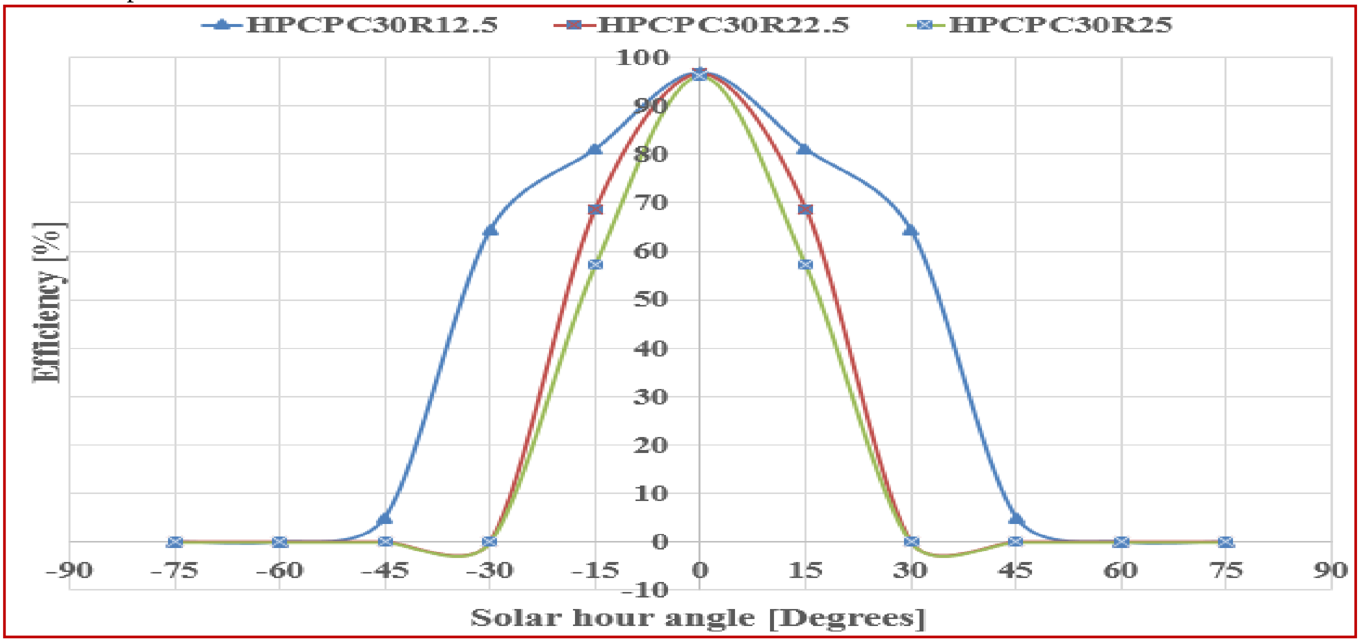


Figure 4: Optical efficiency of HPCPC30 at different solar hour angles

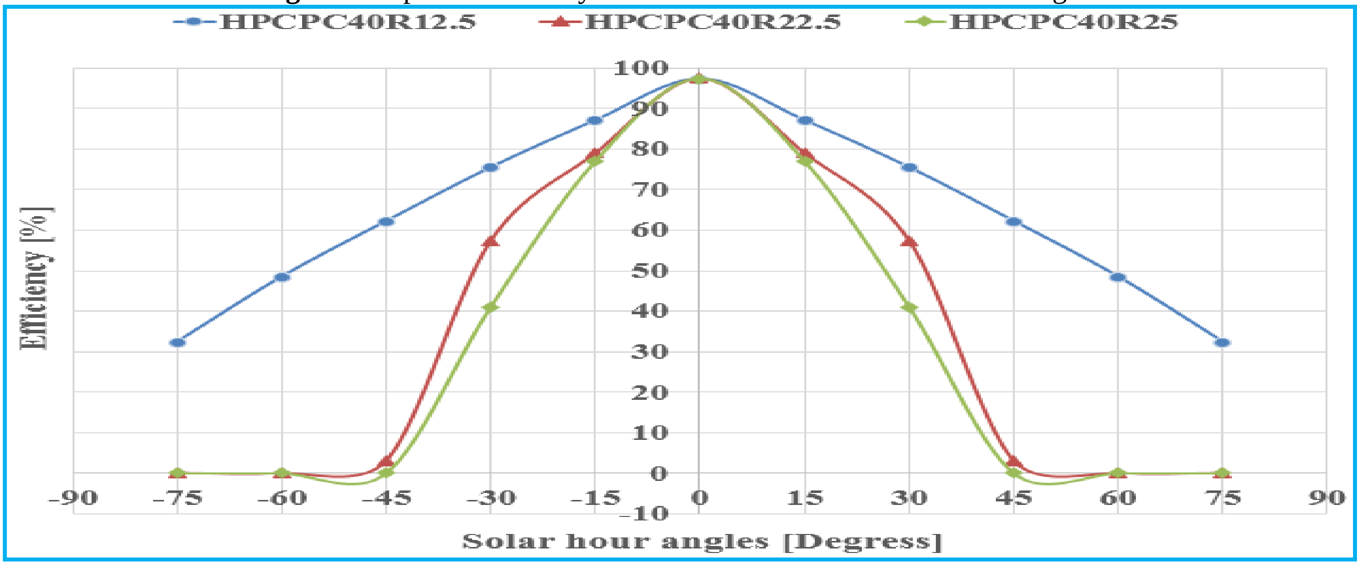


Figure 5: Optical efficiency of HPCPC40 at different solar hour angles

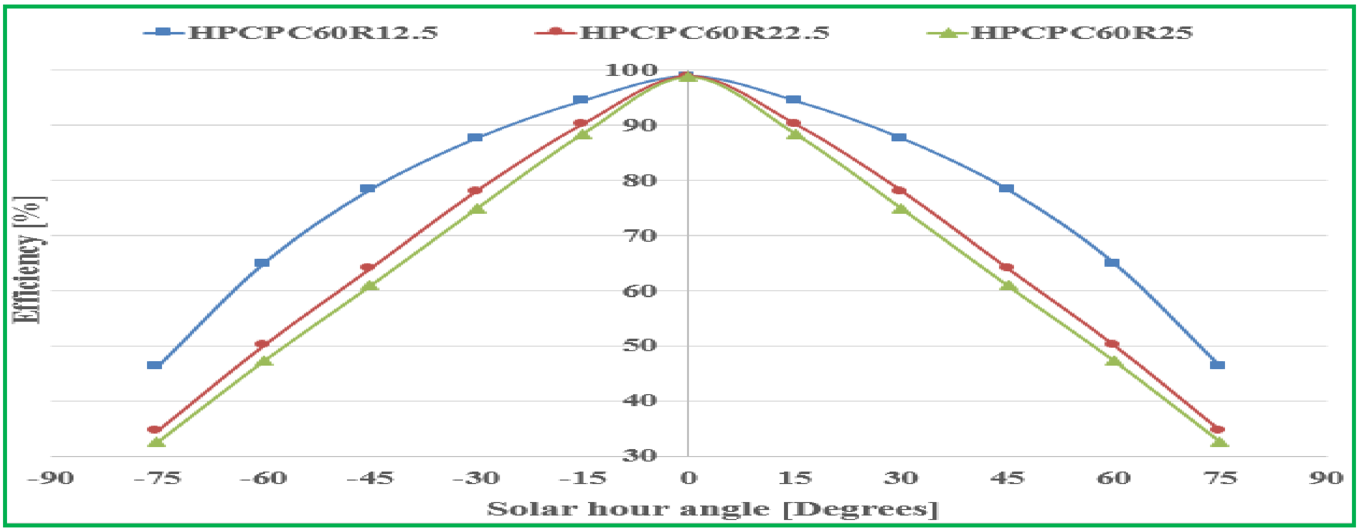


Figure 6: Optical efficiency of HPCPC60 at different solar hour angles

Figure 7 shows the variation of concentration ratio with the acceptance angle. The concentration ratios of the CPC is plotted against its acceptance angles as shown in Figure 7. It can be deduced from the figure that the optical efficiency of the HPCPC decreases with the increase in the concentration ratio. This is because the high the concentration ratio, the narrower the acceptance angle and hence the lower the rays acceptance of the collector. Hence, the configurations with narrow acceptance angle provide high concentration at the expense of the optical efficiency and operating hours.

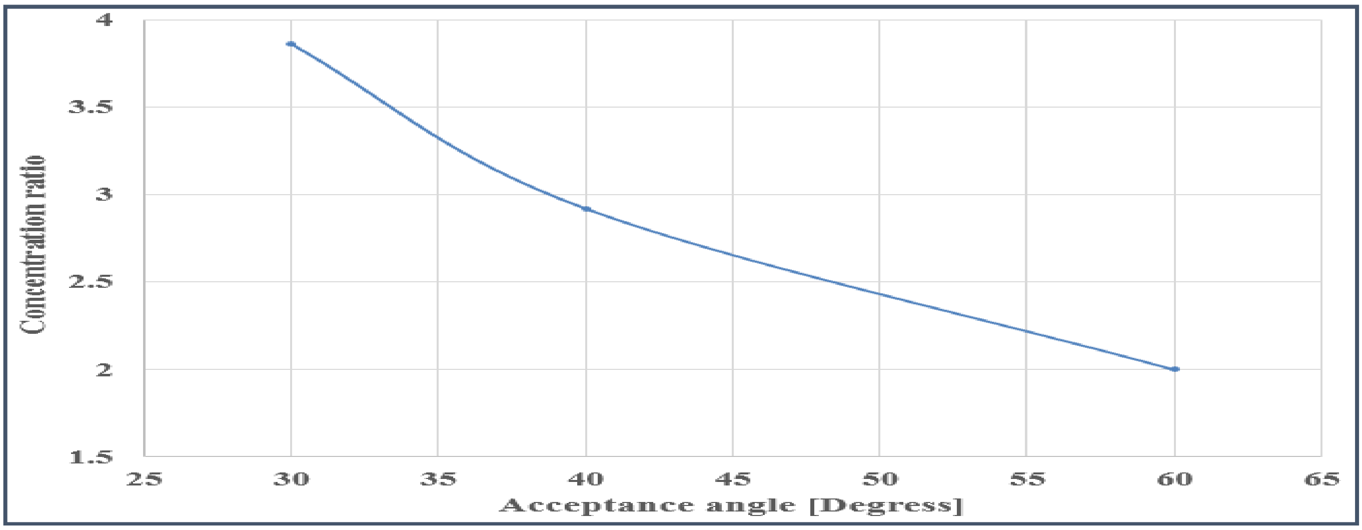


Figure 7: Variation of concentration ratio with the acceptance angle

The results obtained are in agreement with what was reported by Rabl, (1975) and Rabl, (1976); and Kalogirou, (2004), but analytical approach was used in their studies of the geometric and optical behavior of CPC.

The performance of the nine configurations (with acceptance angles of 30^o, 40^o and 60^o) and receiver radii (12.5mm, 22.5mm and 25mm) simulated were compared and the results are presented in Figure 8. It can be deduced from such figure that the optical efficiency increases with the increase in the acceptance angle due to the increase in the rays' acceptance. Example at solar hour angle of 15^o (i.e. at 11am or 1pm), the optical efficiencies of HPCPC60R12.5, HPCPC40R12.5 and HPCPC30R12.5 are 94%, 87% and 81% respectively. This shows that the HPCPC with wide acceptance angle operates with reasonable efficiencies for many hours in static position because all the rays within the half acceptance angle are concentrated on the receiver. Also the results shown that the HPCPC60R12.5 has the best performance in terms of optical efficiency and number of operating hours, but has the least geometric and flux concentration ratios.

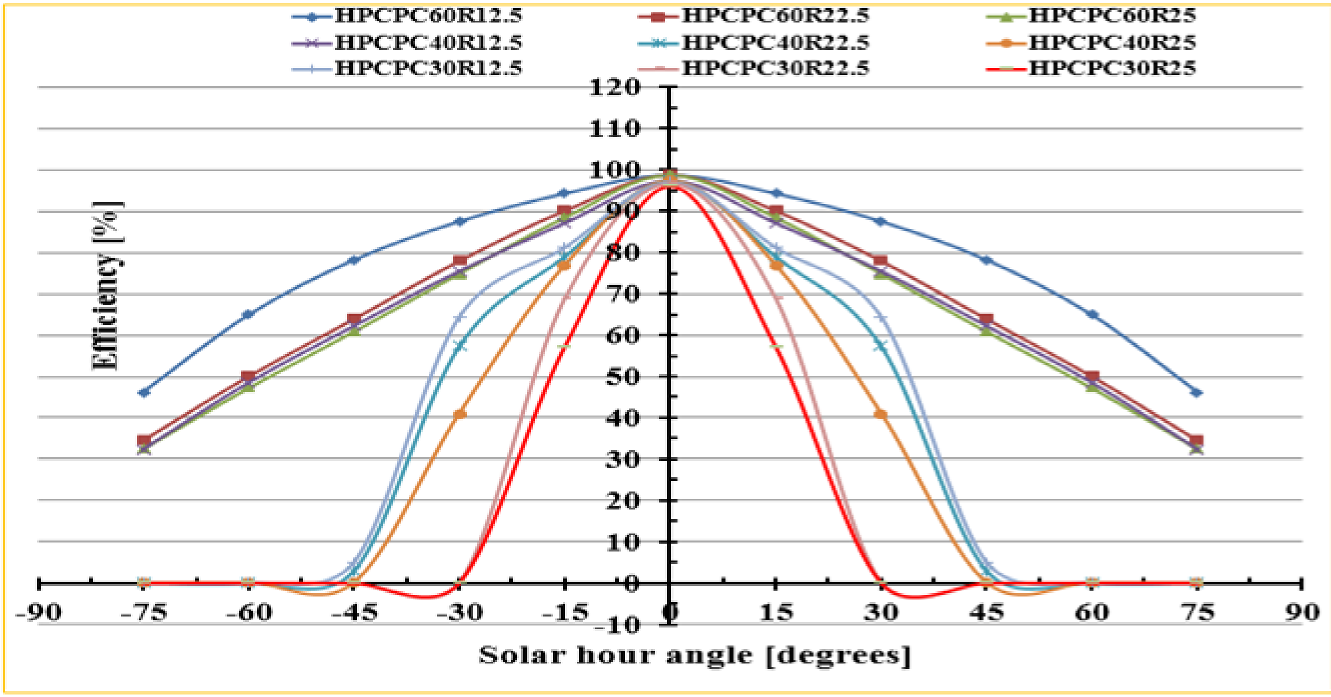
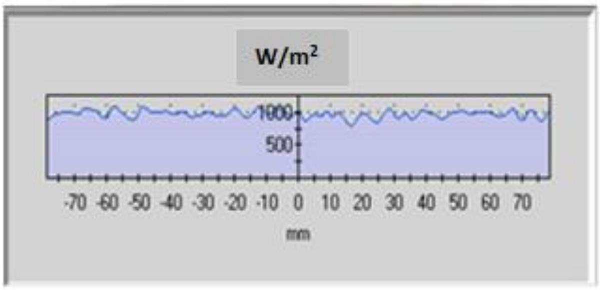


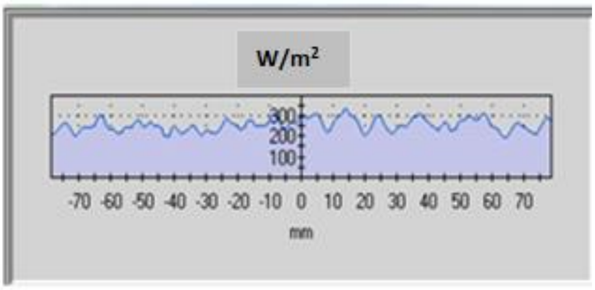
Figure 8: Optical performances of HPCPC configurations at different incident angles

Figure 9 shows the irradiance distributions on the collector aperture and the receiver. It can be seen that the incoming irradiance reduces as the source moves away from 0^{o} (zenith) and also the distributions of the flux on the receiver change. There is high concentration of flux at some areas on the receiver at lower incident angles which creates hot spots as shown in Figure 9 c and d. This shows that as the sun moves away from zenith, (apart from the reduction in the amount of the radiation falling on the collector aperture), the distribution of the flux is also becoming more non-uniform. The loss in the amount of the radiation is due to the angle at which the rays hit the collector since only those rays within the acceptance angle are concentrated on the receiver. Also the change in the incident angle as the sun moves to and away from the zenith is responsible for the high concentration of flux in some areas on the receiver.

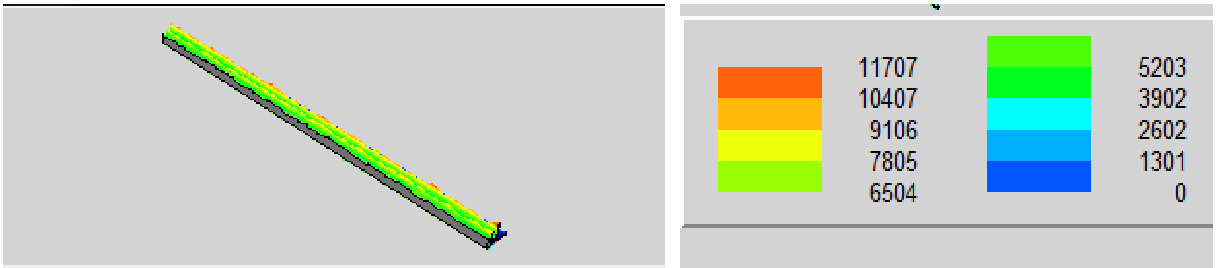
The optical performance of the CPC obtained in this work is in agreement with what was reported by Imhamed et al., (2013) and Nazmi et al., (2012), where ray tracing technique was employed in simulating the optical performance of static solar concentrators at different incident angles. The results of the present work are also found to be in agreement with that of Singh et al. 2016, in which investigations were carried out on the optical and energy conversion characteristics of two geometrically equivalent nonimaging concentrators; a compound parabolic concentrator and a V – trough reflector. Furthermore, Algareu et al., (2013) investigate the optical performance of four different small scale concentrators under the solar environment of Sabha city in Libya. They used an advanced ray tracing software (OPTISWORKS), to investigate the effect of geometry on the optical efficiency of small scale solar concentrators. Their results also shows similar trend with the present work.



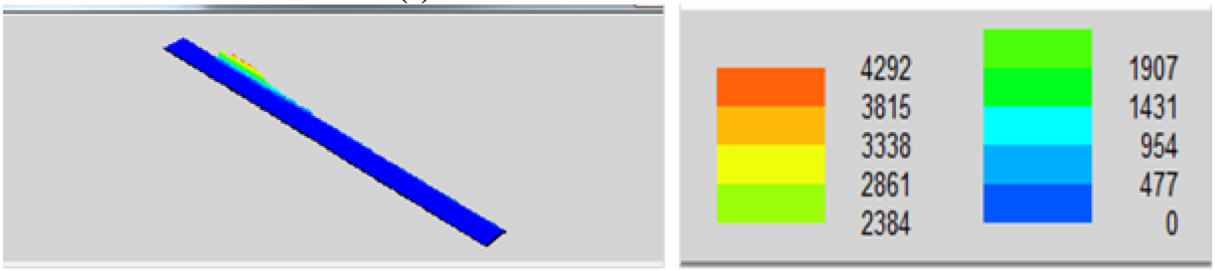
(a) Incoming irradiance at 0^{o}



(b) Incoming irradiance at 75^{o}



(c) Receiver bottom irradiance at 0°



(d) Receiver bottom irradiance at 75°

Figure 9: Irradiance distributions at different solar hour angles

5.0 CONCLUSION

The results obtained have shown that the acceptance angle and the receiver size of CPC influence its optical performance in terms of the optical efficiency as well as the flux and geometric concentration ratios. CPC with wider acceptance angle has higher optical efficiency but with the low concentration ratios. It can also be concluded that CPC can operate for reasonable hours at a static condition depending on its acceptance angle. Furthermore, the position of the sun relative to the collector aperture affects the distribution of the radiation on the receiver. This leads to the creation of hot spots on some parts of the receiver which can rise its temperature and leads to thermal losses.

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