Optical Properties of Low Concentration Ratio Façade Integrated Solar Collectors

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Abstract

The optical properties of façade integrated solar collectors are largely dependent on the location and the direction that they are deployed at. The amount of radiation on the absorber plate will change with the time of the day and the season. As such the optical performance of the collector is a strong function of sun elevation and azimuth angle. In this regard a geometrical model that is a function of the elevation angle of the sun may provide a good approximation of optical performance of the proposed flat reflector façade solar collector.

Therefore this paper develops and presents an experimentally validated geometrical relationship incorporated with the sun-earth geometric relationships to predict the optical characteristics of a façade integrated solar concentrator with flat reflectors.

1. Introduction

In an urban environment, with limited supply of roof space, low concentrating façade integration opens an innovative way of designing façade integrated collector solar collectors. Most of the existing facade integrated concentrating collector designs have used a truncated parabola as a reflector featured with photovoltaic absorbers (Brogren and Karlsson 2002). However, the uneven illumination profiles on the absorber due to parabolic reflectors means less sensitive CIGS modules have to be used (Gajbert, et al. 2008) instead of commercial silicon modules.

A comparative analysis performed by Piratheepan and Anderson (2014) illustrated that using a flat plate reflector concentrator may be a viable alternative to parabolic reflectors. Furthermore in their study they showed that the application of a parabolic reflector is perhaps better suited to thermal applications, where non-uniform illumination of an absorber surface is less problematic. They showed that a flat reflector offers similar variation in concentration ratio to that observed with a parabolic reflector but provides a more uniform illumination profile on the absorber surface. Because of the non-uniform nature of illumination provided by a parabolic reflector, the problems associated with cross currents, it would appear that a flat reflector provides an ideal compromise for such building integrated solar systems.

The optical performance of flat reflector collectors were analysed as early as 1975 by Seitel. In work by (Ronnelid and Karlsson 1999) it was reported that up to a 25% increase in annual output was achieved when fixed planer external reflectors were used in conjunction with an absorber. In another study Brogren (2004) noted that flat plate over edge reflectors are often used to increase the radiation on the absorber plate of solar devices at lower elevation angles.

However, the use of a flat plate over edge reflector in a façade integrated module appears to be limited due to its low concentration ratio. That said, because of the fairly uniform illumination on the absorber provided by a flat reflector, commercially available Si modules could be used instead of expensive CIGS modules. In light of this, this study describes and analyses the optical characteristics of a façade integrated solar collector incorporating a flat plate reflector as shown in Figure 1.

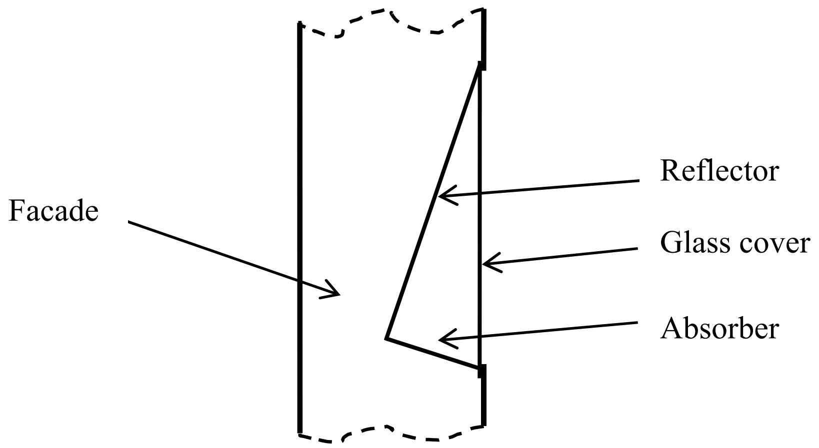


Figure 1 façade integrated concentrator

2. Methodology

2.1 Ray tracing

In order to verify a suitable geometry for a building integrated concentrator it is important to understand the effect of the absorber tilt and the reflector tilt on the optical performance of the collector. Now, because the façade length is relatively long compared to the cross sectional dimensions of the collector, the end losses are negligible. Similarly, the variation in solar azimuth angle variation is linked to the variation of elevation angle of the sun across a day, hence the concentrator can be treated as a 2-dimensional geometry. As such the FRED ray tracing software package was used to analyse the effect of parameters such as reflector tilt (θ_r), absorber tilt (θ_a) and solar elevation angle (α) on the optical performance of a collector, as shown in Figure 2. FRED is a surface-based optical engineering software program capable of performing non-sequential ray tracing analysis of non-imaging optics (Photon Engineering 2014). In order to trace the beam radiation it was decided to use the collimated source as an approximation of the beam component of the solar radiation.

To explore the angular relationship between the absorber and the reflector, it was decided to vary the tilt angle of the absorber and the reflector over a range of conditions and combinations. Subsequently, the relative number of rays received by the absorber was determined against the elevation angle of the source.

As shown in Figure 2, increasing the inclination angle of the reflector decreases the ability of the absorber to receive more radiation at higher solar elevation angles. Furthermore, in Figure 3, at an absorber angle of 20°, the total number of rays received by the absorber over the range of elevation angles is high without becoming shaded by the reflector at higher elevation angles. The reason for this being that if the reflector tilt (θ_r) is increased, the reflector starts to shade the absorber at higher solar elevation angles, while when the absorber angle is increased the proportion of the rays missing the absorber increases at lower elevation angles. To keep the aperture of the collector significantly high and gather a significant portion of the radiation at moderate elevation angles without losing much radiation at possible high and lower elevation angles, a reflector-absorber combination with a 20° absorber tilt angle would seem appropriate. This would also eliminate the shading effect of the reflector on the absorber plate at high solar elevation angles during the summer.

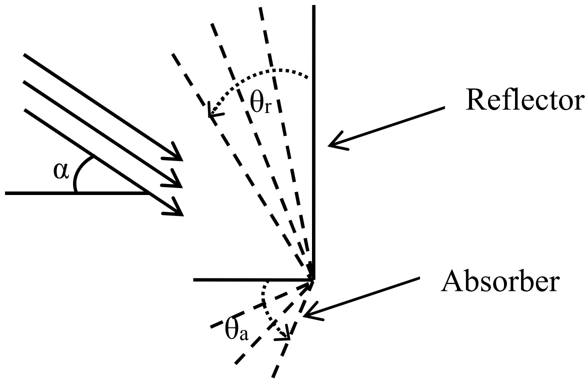


Figure 2 Angle of rotation of reflector and the absorber combination

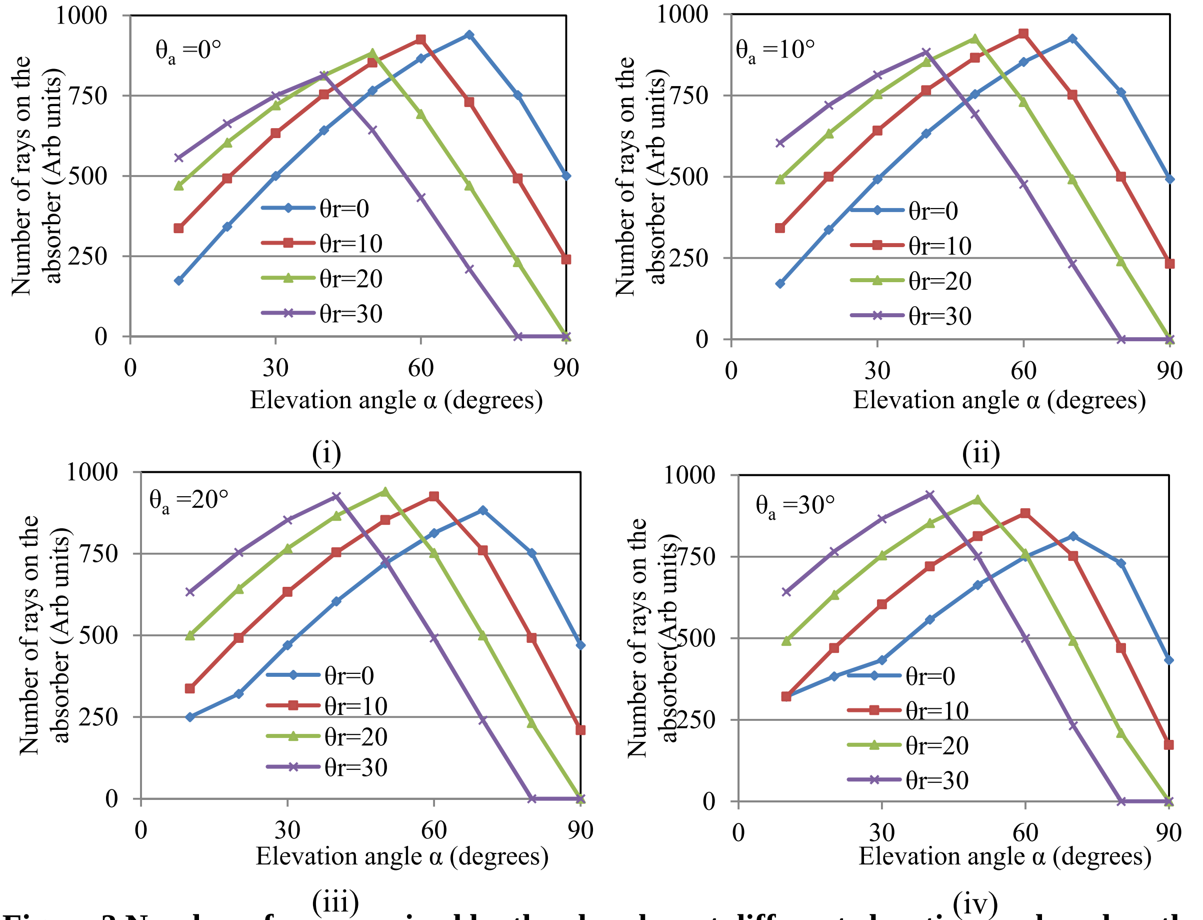


Figure 3 Number of rays received by the absorber at different elevation angles when the absorber is fixed

2.2 Geometric relationship

Now, although ray tracing was able to provide insights into the potential geometric configurations of the concentrator, these results were not particularly generalizable. Hence, to investigate the concentration ratio of the particular combination, it was decided to develop a geometric relationship in terms of the principle angles.

Although the geometrical concentration ratio is defined by the ratio of the area of the aperture to that of the absorber, the concentration ratio defined by Kostic, et al. (2010) is a more practical expression of mean flux concentration ratio C and is given by Equation 1.

$$C = \frac{G_{tot}}{G_{net}} \qquad (1)$$

Here the G_{tot} is the total radiation received by the absorber plate under a reflector while the G_{net} is the net radiation received by a horizontal absorber plate without any reflector. By measuring the beam radiation on a horizontal plane, the total radiation on to the absorber plate can be estimated if the appropriate geometrical relationship is established in terms of direct (G_{dir}) and reflected (G_{ref}) radiation.

As a significant portion of the radiation falling on the absorber comes from the reflector, it is essential to include the reflectance of the reflector to precisely calculate the radiation on the absorber. By incorporating the reflectance ρ_{Al} of the reflector, mean flux concentration ratio C can be expressed by Equation 2.

$$C = \frac{G_{dir} + \rho_{Al} G_{ref}}{G_{net}} \qquad (2)$$

As shown in Figure 4, if α is an incident angle from the Sun and β is the inclination angle of the absorber plate from the horizontal axis, using the dimensions of the reflector height L_R and the absorber width L_A, the inclination angle β can be determined.

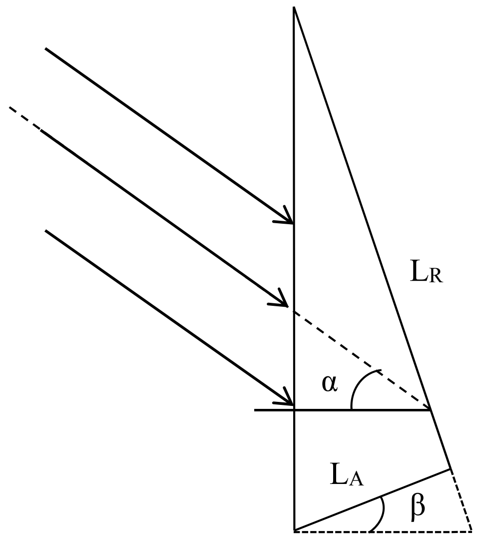
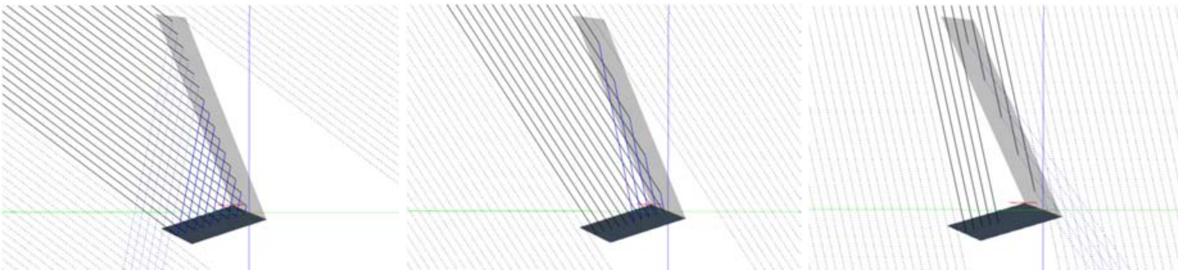


Figure 4 Geometric representation of the collector

As shown in Figure 5 (i), when the elevation angle *α<(90°-2β)*, some of the rays hitting the reflector will not be incident on the absorber surface. Furthermore, when the elevation angle α is between *(90°-2β)<α<(90°-β)*, the reflector will receive the sum of all the rays coming from the reflector and rays directly falling on the absorber as shown in Figure 5 (ii). However, when the elevation angle is above *90°-β*, the reflector will shade the absorber therefore the absorber will not receive reflected rays from the reflector while the amount of direct rays falling on the absorber will reduce as shown in Figure 5 (iii).



(i) (ii) (iii)

Figure 5 Optical ray tracing at different elevation angles

Based on this, an expression for the concentration ratio *C* can be given by Equation 3:

$$C = \begin{cases} \left[\frac{\cos(\alpha+\beta)(\tan(\alpha+\beta)+\tan\beta)}{Sin\ \alpha}\right]\rho_{Al} + \frac{1}{\cos\beta} & \alpha < (90° - 2\beta) \\ \left[\frac{\cos(\alpha+\beta)(3+\tan\beta)}{Sin\ \alpha}\right]\rho_{Al} + \frac{1}{\cos\beta} & (90° - 2\beta) < \alpha < (90° - \beta) \\ \frac{\sin\alpha\,(1-\tan(90-\beta))(\tan(\alpha-(90-\beta)))}{\sin(\beta+\alpha)} & (90° - \beta) < \alpha < 90° \end{cases} \quad (3)$$

However, to examine the influence of these optical characteristics across a year, there is a need to understand the variation in the variation in the sun's position across the year. Hence, to combine the concentration ratio with the solar elevation angle α, the Sun Earth geometric relationship is used. The elevation angle α can be expressed in terms of (fundamental angles) latitude *(L)*, declination (δ_s) and the hour angle (h_s) as given by Equation 4 (Goswami 2000).

$$\alpha = sin^{-1}(\sin L \sin \delta_s + \cos L\ cos\ \delta_s cosh_s) \quad (4)$$

Here, declination angle δ_s can be estimated using existing relationships on the literature and the hour angle h_s can be expressed in terms of the local solar time.

Finally, by combining the Equations 3 and 4 the concentration ratio of the collector at a particular time on a particular day can be calculated.

2.3 Experimental testing

In order to validate the mathematical model and its findings it is necessary to compare the outcome with an experiment. For the experiment, an absorber plate was assembled by placing standard silicon solar cells under a static reflector made from aluminium sheet covered in a silver metalized film with 94% reflectance (3M Solar mirror film 1100). The reflector was affixed to a supporting frame with an inclination of approximately 20° to the vertical while the photovoltaic cells were placed at an angle of 20° to the horizontal. Subsequently, a Delta-T SPN1 Sunshine pyranometer was mounted adjacent to the concentrator to measure the beam and diffuse radiation. The voltage generated by the photovoltaic absorber was measured simultaneously with the current, measured across the 1mΩ shunt resistor, in order to determine the power produced by the concentrator. A schematic representation of the experiment that was developed is shown in Figure 6.

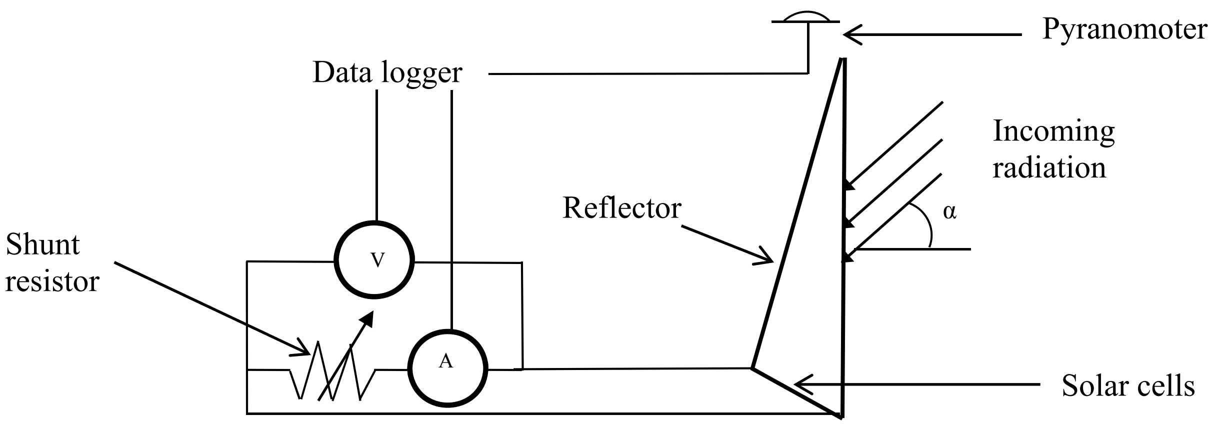


Figure 6 Schematic diagram of the test rig

Now, when radiation falls on a solar cell, it produces a current proportional to the radiation falling on it, so to determine the concentration ratio, the current produced by the concentrator was compared with the current produced by a reference cell mounted adjacent to the concentrator. By finding the ratio between the short circuit currents measured across the absorber and across the reference cell, the relative concentration ratio *C* could be estimated.

3. Results

3.1 Experimental results

To validate the optical model several sets of readings were taken from the test rig at various solar elevation angles. In order to do so, the readings were taken on different days over the year when the sun was near solar noon to reduce the effect of shading due to the design of mounting enclosure. As shown in Figure 7 the geometrical model of the optical concentration ratio including the solar elevation angle is capable of predicting the concentration ratio with good accuracy.

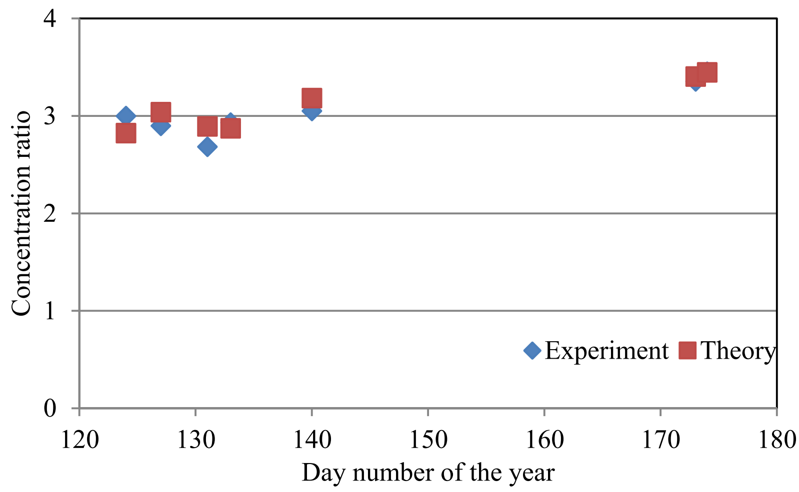


Figure 7 Experimental concentration ratio and calculated concentration ratio

3.2 Modelling results

Having shown experimentally that the geometric model could be used to evaluate the performance of the collector, it was decided to examine its capabilities on any given day and time of the year. When the annual concentration ratio variation is plotted, as shown in Figure 8, the optical concentration ratio is higher during winter days with low solar elevation angles (for example day number 120-210) than during the summer period (for example day number 330-60) with a higher solar elevation angle. Similarly, for a given day, the concentration ratios in the morning and evening are again high due to low elevation angle of the sun while as noon approaches the concentration ratio decreases.

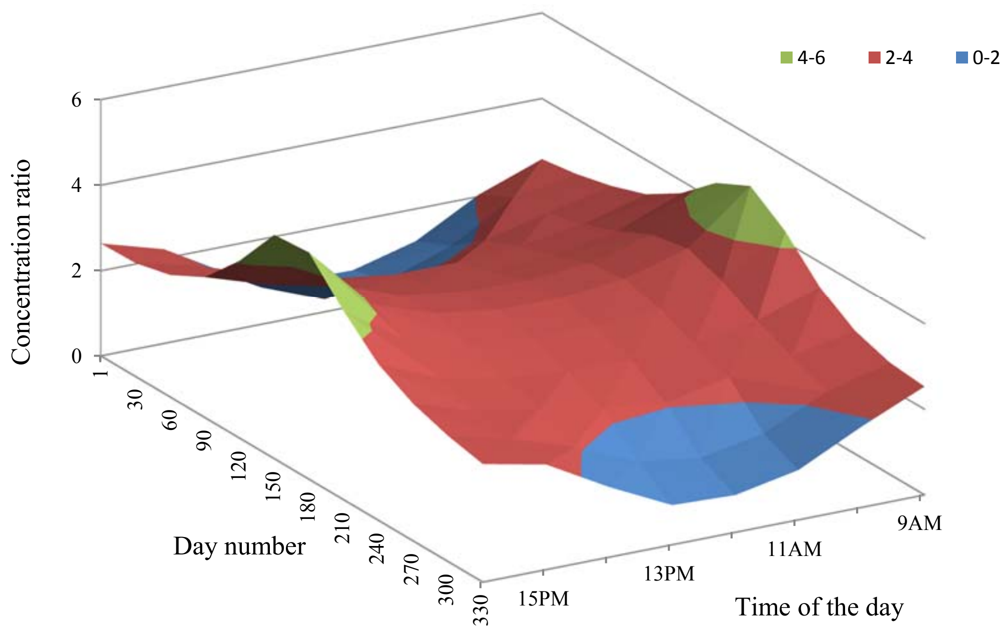


Figure 8 Concentration ratios over the year

To illustrate this point, the total radiation reaching the absorber on a typical clear summer day (January 9 in Kaitaia, NZ) is shown in Figure 9. Here the total radiation falling on the absorber is high in the morning and the afternoon as the sun elevation angle is significantly lower than that of during the midday. However as the elevation angle of the sun approaches 75° during the middle of the day, the absence of reflected radiation on the absorber reduces the total radiation falling on the absorber.

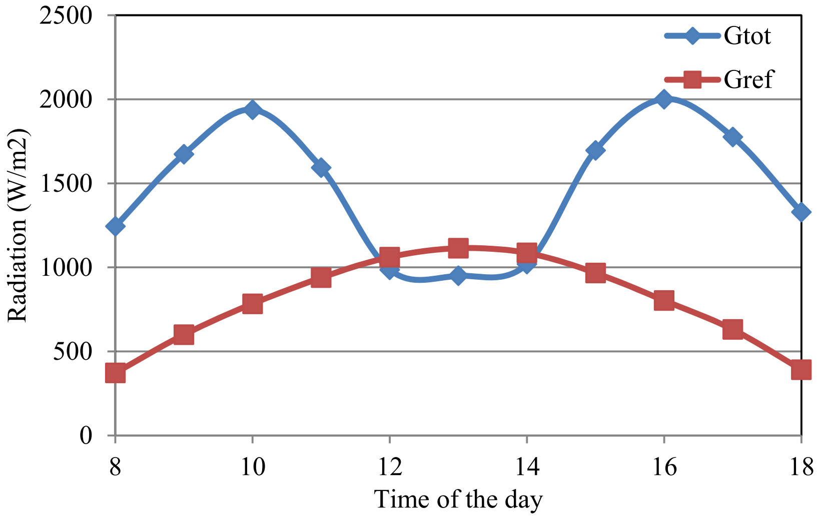


Figure 9 Change in concentration ratio on 9th of January

Notably though, as shown in Figure 10, the radiation falling on the absorber on a typical clear winter day (June 30 in Kaitaia NZ) is always enhanced by the reflected radiation from the reflector, as the maximum sun elevation angle at solar noon is only 37°. Furthermore, it is important to note that the reflector has increased the radiation falling on the absorber by at least 3 times throughout this winter day. This highlights one of the major benefits of the static reflector.

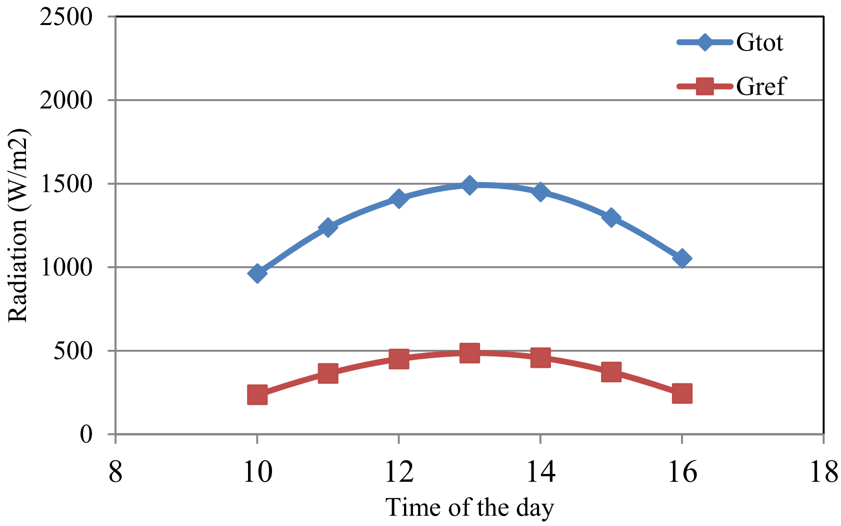


Figure 10 Change in concentration ratio on 30th of June

5 Conclusion

From the results, it was shown that the optical model incorporating the Sun-Earth geometrical relationship presented in this paper was able to calculate the total radiation falling on the absorber plate of a façade integrated solar concentrator. Further, it was found that the collector performance was significantly improved during winter days with lower elevation angles than the summer days. This can potentially increase the performance of the collector significantly especially during the winter, spring and autumn seasons, possibly the period when energy is needed the most.

Furthermore, the possibility of combining roof top collectors, which perform well under high solar elevation angles, with low concentration ratio façade integrated solar collectors would allow these systems to complement each other throughout the year, and may well be the next step towards zero energy buildings.

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