Experimental evaluation of low concentration collectors for façade applications

Piratheepan Mahendran[1], Timothy Anderson[1]

[1] Department of Mechanical Engineering, Auckland University of Technology, Auckland, New Zealand

pmahendr@aut.ac.nz

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Abstract:

In this study two possible configurations for a static low concentration ratio façade integrated concentrator were examined using optical ray tracing; the first incorporating a parabolic reflector and the second using a flat reflector element.

Subsequently an experimental apparatus was developed and testing conducted to validate the findings of the ray tracing. It was shown that the illumination provided by a parabolic reflector was non-uniform and that this could result in premature failure of the absorber. Further, it was found that a flat booster reflector offered similar variation in concentration ratio to that observed with a parabolic reflector, but provided more uniform illumination. As such, it would appear that a flat reflector provides an ideal compromise for such building integrated solar systems.

1. Introduction

Energy use in buildings accounts for nearly one third of the world's energy demand and rising with the population and technological growth [1]. A significant portion of this demand could be reduced through on-site energy cogeneration utilizing solar energy. Intelligent building design and incorporating photovoltaic systems within the building envelope are two solutions that could reduce the long term energy cost while reducing the environmental impacts [2].

One of the principle shortcomings of photovoltaic systems is the cost of the photovoltaic module which is relatively high compared to the other components associated with the system. Reducing the cost of the photovoltaic module or value addition would make these systems significantly cheaper. One such way is using low concentration reflectors to increase the solar insolation on the surface of the module [3].

In considering a solar concentrator the most common defining characteristic is the concentration ratio, defined by the ratio of the aperture area to the receiver area. Obviously it is desirable to maximize this parameter, however to achieve optimal performance from systems with high concentration ratios it is necessary to track the sun. With a building integrated façade system this is possible but generally impractical; a more practical solution is to use static solar concentrators with medium to low concentration ratios.

Unlike tracking collectors, low concentration ratio collectors have the advantage of collecting both beam and diffuse radiation [4]. This allows the possibility of using standard silicon PV absorbers with less need for precise optics during the installation phase. In addition, concentrating the solar radiation on the module could deliver moderate temperature outputs that could be captured by a cooling system, thus forming a cogeneration unit or Building Integrated Photovoltaic/Thermal Concentrator (BIPVTC).

The use of BIPVTC in an urban environment, with limited supply of roof space, opens an innovative way of designing building energy systems. Systems of a similar premise to this, but only generating electrical output, have been discussed by researchers in the UK and Ireland [5], [6], Sweden [3], [7], [8] and Brazil [9]. However, the idea of building integrated PVT concentrator technology is still to be fully examined.

One of the key challenges of developing a BIPVTC system, using standard silicon cells, is in understanding the nature of the illumination distribution on them. This needs to be understood as it affects the electrical output from the cells and also the capture of the thermal energy. Therefore this study aims to improve the understanding of this illumination profile and how it may affect the performance of building integrated concentrators.

2. Simulation Method

In this study, it was decided to examine concentration ratios of two possible configurations for a façade integrated concentrator. The first was a collector with a parabolic reflector incorporated similar to that described in [8] and the second with a flat reflector, as shown in Figure 1.

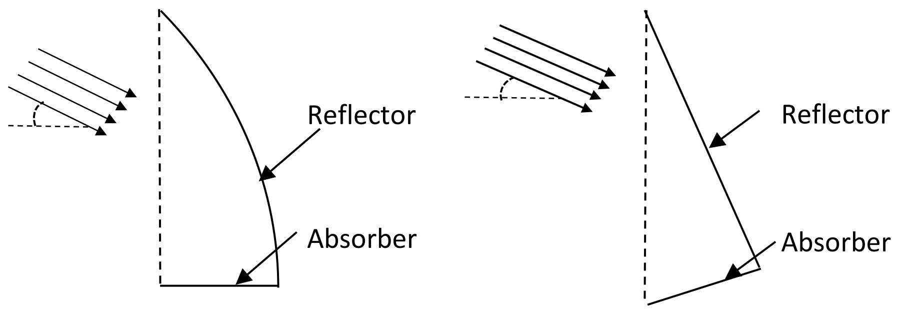

Figure 1 Façade integrated concentrator profiles

The reason for these two designs was to allow a comparative analysis of the illumination profile on the absorber surface. If a series of solar cells on the absorber modules are illuminated differently, the electric current produced by the highly illuminated cells reaches the less illuminated cells and dissipates thermal energy at that point thus creating a hotspot [10]. Hotspots are undesirable as they may permanently damage or reduce the performance of the cells.

To characterize the performance of the two systems it was decided to use the ray-tracing program FRED followed by an experimental comparison. FRED is an optical engineering software program that is capable of performing non-sequential ray tracing analysis of non-imaging optics, such as solar concentrators [11]. To simplify the ray tracing, it was decided to do a one dimensional ray tracing study with a large optical source that can produce collimated rays, as an approximation of the beam component of solar radiation. It was assumed that the reflectors were perfect reflectors (without any optical defects) while the absorbers (analysing surface) were perfect absorbers.

To make a fair comparison of the two concentrators, the height of each reflector was kept constant as was the length of the absorber module. The geometrical concentration ratio (length of aperture/length of absorber) for both was approximately 3.6, similar to that reported by Gajbert, et al [8]. In addition, a horizontal absorber of the same dimensions as that in the concentrators was modelled to serve as a benchmark. With each system the illumination pattern on the absorber plate was observed while varying the solar elevation angle (α – measured up from horizon) of the rays between 0 and 90°.

3. Simulation Results

Figure 2 shows the total number of rays received by the absorbers from both modules compared to the reference module for different elevation angles of the source. If the number of rays incident on the absorbers are then normalised against the number of rays incident on the horizontal reference we can determine the relative concentration ratio, as shown in Figure 3

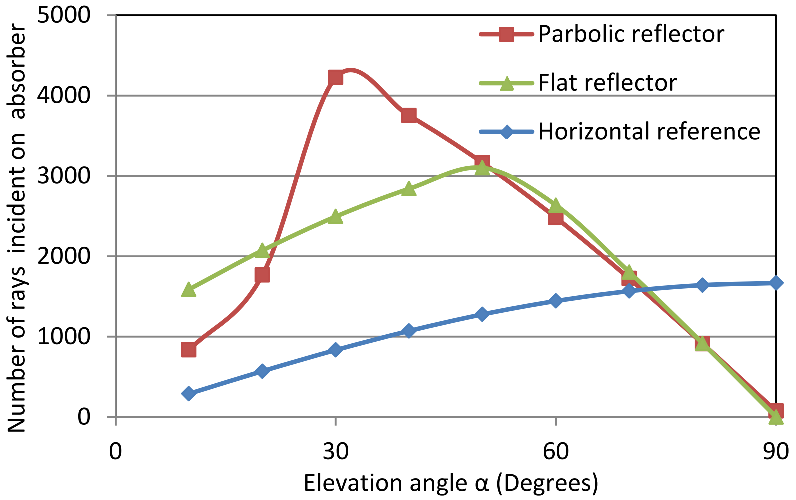

Figure 2 Number of rays hitting the absorber v elevation angle (α) of the source

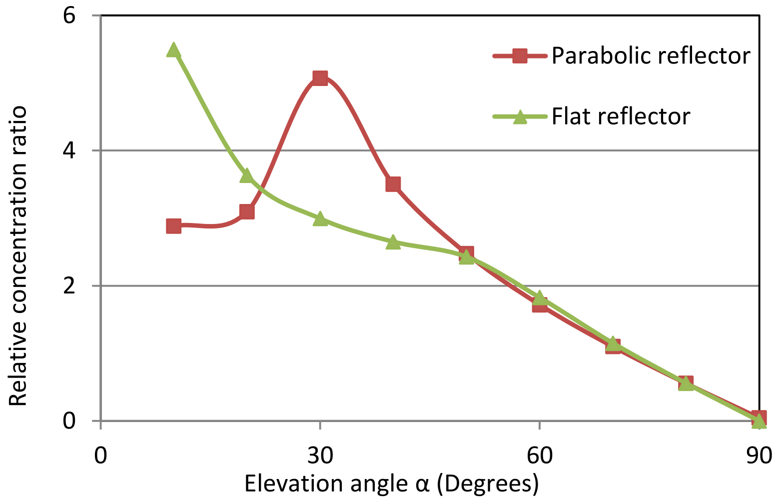

Figure 3 Elevation angle v relative concentration ratio

By considering both Figures 2 and 3, the conclusion could be drawn that the parabolic reflectors may give better performance at range of elevation angle compared to the flat plate reflector as [12] suggested. However, in drawing this conclusion it is important to also consider the illumination pattern on the absorber.

Figure 4, shows the variation in illumination across the width of the absorber with the parabolic reflector (taking the junction of absorber and reflector as the origin). From this, for the mid-range elevation angles, there is a significant nonuniformity in the intensity on the absorber. For example, at an azimuth angle of 60° the illumination near the origin is over seven times that at the edge of the absorber. This shows that the illumination profile of parabolic reflectors tends to be non-uniform and the patterns are discrete and discontinuous in nature due to their focusing to a line.

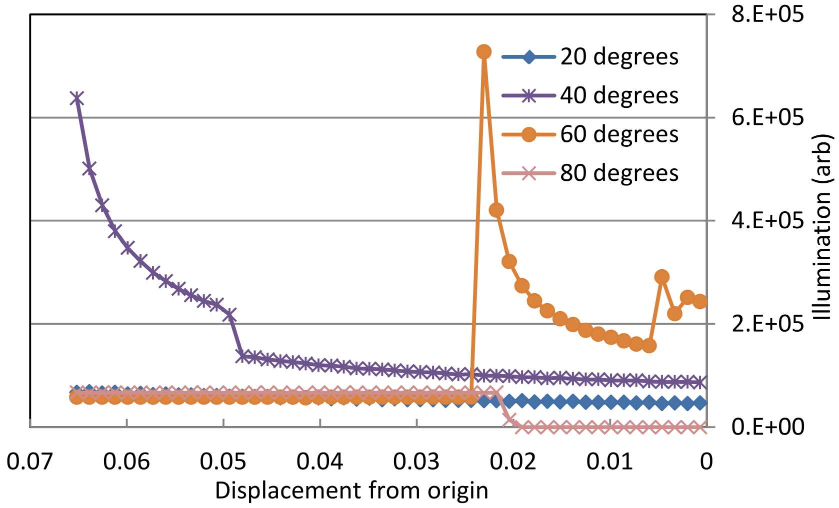

Figure 4 Illumination on the absorber module at various elevation angles under parabolic reflector

Now if we consider the illumination profile from a flat plate reflector, as shown in Figure 5, we can see that the magnitude of the average illumination is significantly lower than that of a parabolic reflector. This is interesting because they have the same dimensions but the illumination is more uniform in its distribution. That is, local concentration ratio across the absorber is far more consistent at a particular elevation angle across the absorber surface. Hence each part of the module will produce similar electric current output, so that undesirable effect of hotspots and thermal energy dissipation otherwise caused under the parabolic reflectors can be avoided.

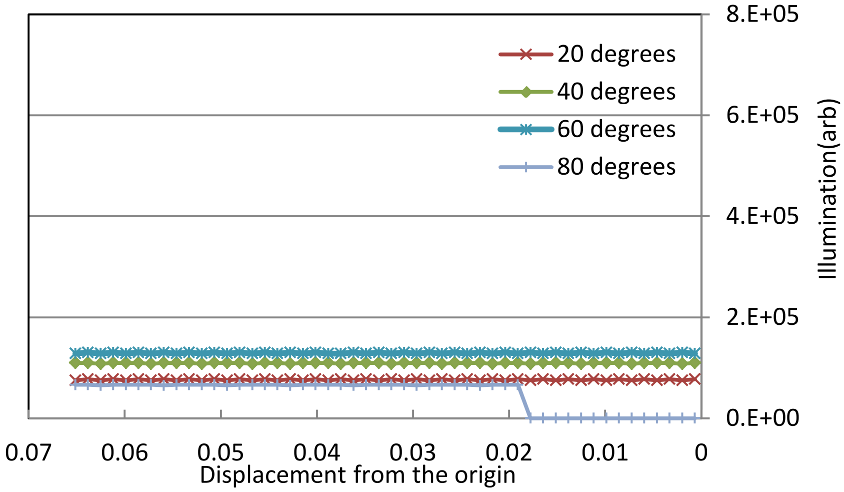

Figure 5 Illumination on the absorber module at various elevation angles under flat reflector

4. Experimental method

In order to validate the results obtained from the ray tracing it was decided to build two test rigs corresponding to those modelled in the ray tracing analysis. One featured a truncated parabola and the other a flat reflector. Both reflectors were made with silver metallized (3M Solar Mirror Film 1100) films with 94% reflectance affixed to a supporting frame to form the respective shapes. The parabola was made with a focal length of 600mm while the flat reflector was built with the dimensions shown in Figure 6.

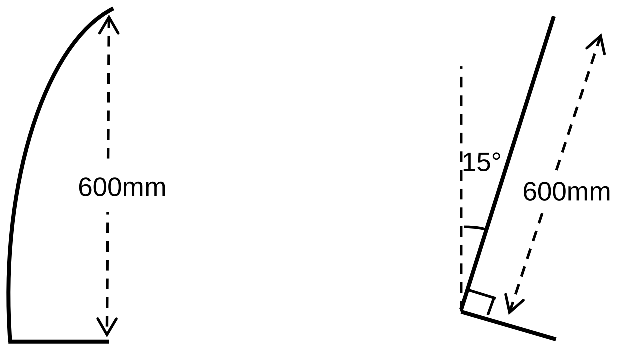

Figure 6.Schematic diagrams of the reflectors

To determine the illumination profile the absorber plates were fabricated with a series of small solar cells on them, as shown in Figure 7. Seven thin single-sun mono-crystalline solar cells with a width of 20mm were affixed uniformly across the absorber next to a larger (156mmX156mm) mono-crystalline solar cell. In addition, two reference cells were placed adjacent to the concentrators to measure the non-concentrated radiation output.

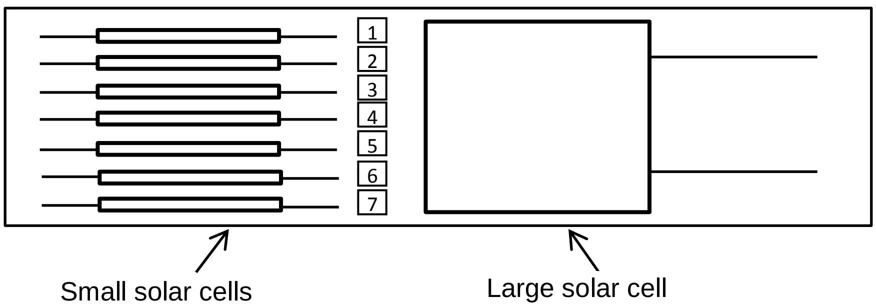

Figure 7 Schematic diagram of the absorber

When radiation falls on the absorber, each solar cell produces a short-circuit current proportional to the radiation falling on them [13] that can be compared to that of the reference cell. By dividing the short circuit current of each small concentrated cell by that of the reference cell, the local relative concentration ratio across the absorber can be determined. Similarly, the short circuit current from the larger cells should correspond to the average flux falling over the width of the absorber, allowing determination of the overall relative concentration ratio. For the experiments the short circuit current from the solar cells was recorded at elevation angles of 30, 45 and 60 degrees.

5. Experimental results

From the experiments the relative concentration ratio obtained from the larger cells under the parabolic reflector at 45 degrees was 2.90 while the relative concentration ratio under the flat plate reflector was 2.54. This value corresponds to the value obtained from the ray tracing, as shown in Figure 3. This implies that the usage of parabolic reflectors will deliver higher concentration ratios without considering the local concentration distribution and its consequences along the absorber.

In order to analyse the local concentration ratio across the absorber we compare the relative concentration ratios at a sun elevation angle of 30°, 45°, and 60°. Under these conditions the local concentration ratio changes across the absorber as shown in Figures 8, 9 and 10.

From the ray tracing, at 30° elevation angle, the peak of the local concentration ratio was achieved at the edge of the absorber. The experimental value follows the trend of the ray tracing output as shown in Figure 8. Furthermore, at an elevation angle of 45°, it can again be observed that both ray tracing and the experimental values follow the same pattern. There is a slight difference in concentration values between the experiment and the ray tracing that is attributable to some limitations in the experiment. In particular, ray tracing allows a finer resolution of data to be achieved, whereas in experiments we are only able to get discrete measurements. Furthermore, the lower local concentration value from the experimental results could be due to the silicon cell reaching its saturation current [14]. Hence it might not have responded to the light intensity beyond that particular limit.

On the whole though, it can be seen that the flat plate reflector provides a relatively uniform local concentration ratio across the absorber for all conditions. Hence the electric current produced by each cell across the module under the flat plate reflector will be similar. This reduces the cross currents that cause the hotspot across the cell and so would appear to be an appropriate compromise for the system.

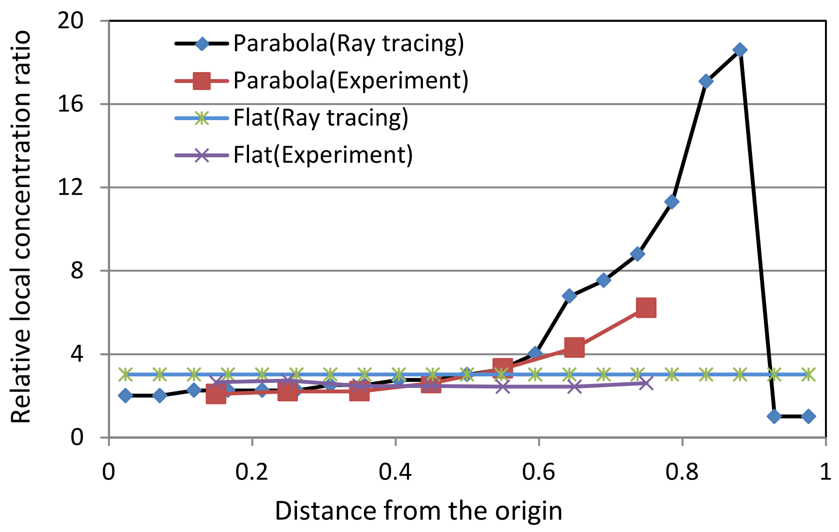

Figure 8 Relative local concentration ratios across the absorber at 30 degree elevation angle

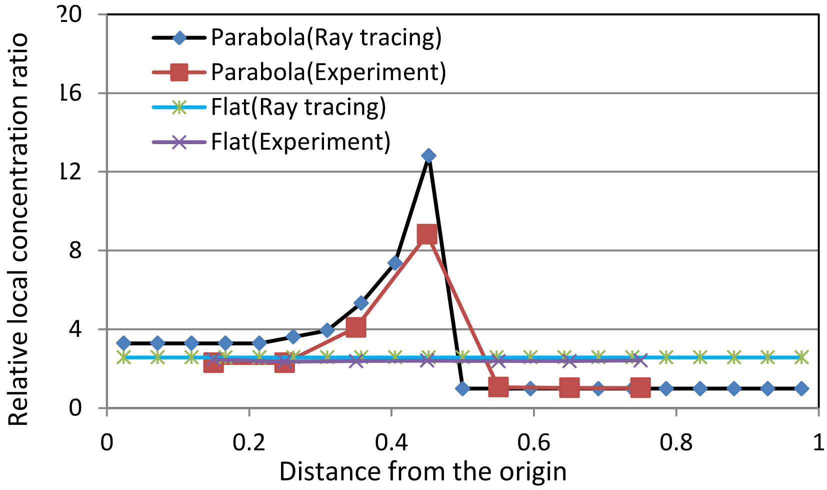

Figure 9 Relative local concentration ratios across the absorber at 45 degree elevation angle

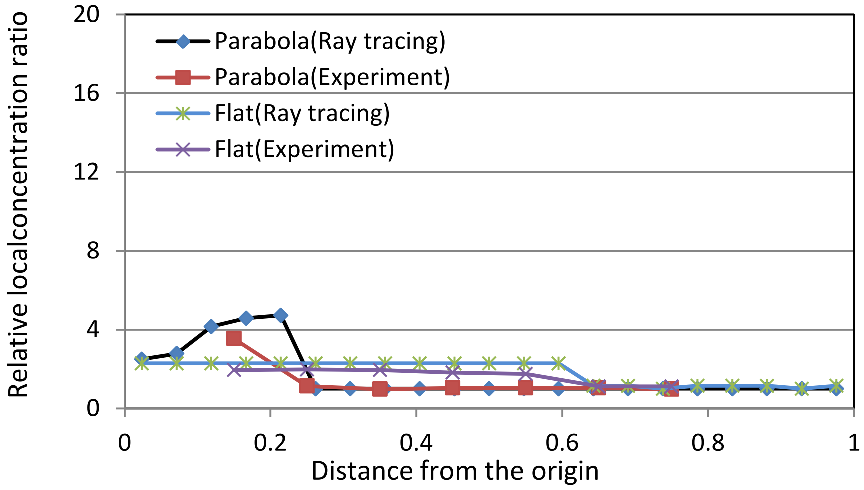

Figure 10 Relative local concentration ratios across the absorber at 60 degree elevation angle

6. Discussion and conclusion

From these results, it is possible to draw the conclusion that parabolic reflectors are well suited for applications in mid-latitude locations. However, their application is perhaps better suited to thermal applications where non-uniform illumination of an absorber surface is less problematic.

If one were to utilize a parabolic reflector for a BIPVTC application, the non-uniform illumination could cause high ohmic losses and could also produce internal current flow even when it is open circuited. Hence, if the parabolic reflector is used as a concentrating device for photovoltaic concentration it may not improve the performance of the module due to the cross currents forming hotspots in lower irradiated cells. In turn this may lead to permanent defects or premature failure of cells [14].

Furthermore, this work has shown 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. In the case of a BIPVTC module, this could eliminate the problems associated with cross currents. Because of the non-uniform nature of illumination provided by a parabolic reflector, it would appear that a flat reflector provides a compromise for such building integrated solar systems.

That said; the cooling effect in a BIPVTC may negate this effect, however this would require further work..

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