Optical characteristics of low concentration ratio solar collectors for façade applications

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***Abstract*— This work shows that there is significant scope for the development of static solar concentrators to be integrated into the façade of buildings. It has shown that solar concentrators using parabolic reflectors may be well suited to applications in mid-latitude locations, however, the non-uniform illumination they provide means they are perhaps better suited to thermal applications. Due to the non-uniform nature of illumination provided by a parabolic reflector, flat reflectors provide an ideal compromise for building integrated photovoltaic (BIPV) and photovoltaic/thermal (BIPVT) concentrators.**

Keywords- solar energy; photovoltaics; concentrator; building integrated

I. INTRODUCTION

The International Energy Agency (IEA) has found that buildings are responsible for approximately 1/3 of global primary energy consumption [1]. Furthermore, the amount of energy consumed by buildings is rising due to increasing global population and technology development. This raises concern over the use and availability of existing energy resources. In the long term, a substantial percentage of the energy use can be reduced by intelligent building designs [2]. Incorporating energy production within the building envelope through sustainable energy generation on site could reduce the long term cost of building while minimizing the environmental impacts.

Building integrated photovoltaic (BIPV) modules are one such technology that could be utilized to generate energy from the building envelope. Unlike standalone solar power systems there is no additional requirement of land, the cost of the PV façade or roof can offset the cost of the building structure it replaces, and power generated on site replaces the electricity otherwise purchased at the commercial rates. In addition, connecting such system with the grid will avoid the storage cost and ensure the secure supply of energy to the building [3].

Such systems bring challenges to the architecture and aesthetic design of the building as factors such as geographic location, limited roof space, and shading in highly dense city buildings force the designer to think beyond the roof and onto the façade [4]. However, the form of these systems may limit their desirability to architects and end users. This is a significant consideration in developing new solar products that are to be used in the built environment (as opposed to stand-alone large scale systems). A study by Probst and Roecker [5] found that integrating solar collectors presented a number of challenges to developing a system that was considered to be not only “acceptable” to architects but was in fact desirable. They also note that in the future, building integrated solar collectors “should be conceived as part of a construction system”.

The shortcoming of building integrated photovoltaic modules though is their relatively low efficiency, as they covert only 10-20% of the solar irradiance to useful electricity, this problem is exacerbated when modules are integrated into vertical facades. In response to this Karlson and Wilson [6] proposed the Maximum Reflector Collector (MaReCo) design in 2000, followed by Brogren and Karlson [7] who utilized a parabolic over edge reflector to increase the radiation falling on façade integrated PV modules. Systems of a similar nature have also been discussed by [8-15].

While increasing the radiation onto BIPV modules will lead to increased output it is important to also note that the remainder of the energy not converted to electricity is either lost by heat or reflected off. In addition a small proportion of the heat is sunk into the cells, resulting in reductions in their efficiency [16]. In general the increase in cell temperatures lowers the power output of typical crystalline silicon by 0.3 to 0.5% /K [17-20].

To overcome the issue associated of decreased electrical output with increasing temperature from BIPV systems it is possible to incorporate cooling into them thus forming a Building Integrated Photovoltaic Thermal system (BIPVT). Such systems are designed to keep the temperature at a desirable level while they co-generate thermal energy as well. Such systems offer combined energy efficiencies of up to 30-45% while the amount of space and the material needed to build two separate collectors is minimized due to the hybridization [21, 22].

This suggests there is an opportunity for cost effective, visually appealing BIPVT systems designed for use as walls. Moreover, by incorporating reflective concentrators into these collectors it may be possible to increase the electrical output and reach higher temperatures than would be possible with a “flat plate” configuration.

II. METHOD

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.

In this study it was decided to examine two possible configurations for a façade integrated concentrator; the first incorporating a parabolic reflector similar to that described by [9] and the second using a flat reflective element as shown in Figure 1.

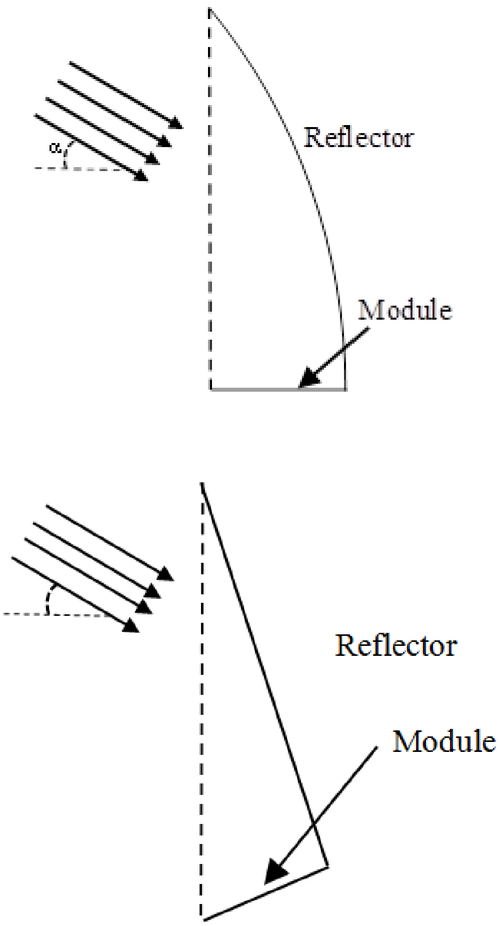

Figure 1. Façade integrated concentrator profiles

The reason for choosing the two designs was to allow a comparative analysis on the illumination profile on the absorber surface. In particular, the illumination profiles of parabolic reflectors tend to be non-uniform and the patterns are discrete and discontinuous in nature. In the case where a series of photovoltaic cells are connected together as the absorber module some of them may be highly illuminated and others not. As such the current from highly irradiated cells will move along the series of cells until it reaches the non-illuminated cell and dissipate as thermal energy on that cell thus creating a hotspot [23].

As pointed out by Coventry [20], in the case of partially and completely illuminated cells, the region which is illuminated extensively will generate a higher current compared to the lower illuminated part of the module. This effect will lead to the generation of cross currents that lead to the dissipation of thermal energy.

Alternatively to a parabolic reflector which will focus to a line or point, flat mirror type reflectors could be considered as circular mirrors with an infinite radius; as such they will tend to focus on a plane [24]. This may resolve the problem of uneven irradiance of the reflectors so that the existing commercially available silicon photovoltaic modules can be used instead of an expensive alternative module.

Now to characterize the performance of the two systems it was decided to use the ray-tracing program FRED [25]. FRED is a surface-based optical engineering software program capable of performing non-sequential ray tracing analysis of non-imaging optics, such as solar concentrators.

To simplify the ray tracing, it was assumed that radiation entering through the aperture of the concentrator was coming from a collimated source, an approximation of the beam component of solar radiation. It was assumed that the reflectors were perfect reflectors of any specular rays while the absorbers (analyzing surface) were assumed to perfectly absorb any beams incident on them directly, as well as reflected rays from the reflector.

For the two concentrators, the height of each reflector was kept constant as was the length of the absorber module. For this work the concentration ratio was approximately 4, similar to that reported by [9]. In addition a vertical absorber of the same dimensions as that in the concentrators was also modeled to serve as a benchmark.

With each system the illumination pattern on the absorber plate was observed while varying the azimuth angle (α - angle from the horizontal) of the rays between 0 and 90°. To ensure an illumination pattern representative of reality, the source was designed to deliver approximately 100,000 rays through the concentrator aperture.

III. RESULTS

Having undertaken the ray tracing analysis it was decided to examine an analysis of the effective radiation captured by the absorber surfaces. Figure 2 shows the ray counts falling on both concentrators' absorbers and also on a plane vertical absorber for varying azimuth angles. From this it can be seen that both concentrators lead to an increased number of rays being intercepted, obviously because the reflectors are directing more beams to the absorber. It should also be noted that there is a difference between the low angle performance of the flat and parabolic reflector, this is due to the absorber of the flat reflector being inclined below the horizontal thus allowing it to capture radiation at these azimuth angles. Similarly, for a vertical surface, the majority of the radiation is captured when the beams are normal, but this decreases as the azimuth angle increases because the effective area decreases.

Also, by virtue of the geometry of both absorbers, at high azimuth angles the number of captured beams decrease as the reflector begins to shade the absorber. This closely follows the observations that [9] made in their study. In their work they showed that the current response from a PV cell illuminated by a parabolic reflector exhibited an almost identical profile response to that of the parabolic reflector shown in Figure 2.

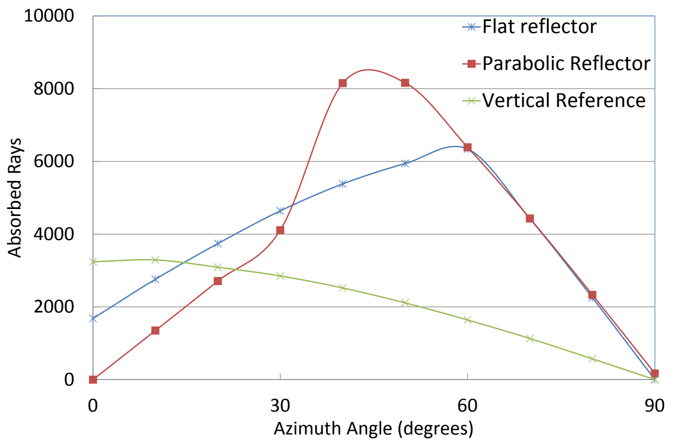

Figure 2. Illumination v azimuth angle

Considering the incident beams more generally, we can normalize against the vertical absorber to ascertain the effective concentration ratio, as illustrated by Figure 3. As in Figure 2 it can be seen that at azimuth angles below approximately 30°, that the flat reflector is delivering better performance than the parabolic reflector. However, again beyond 60° the response is identical.

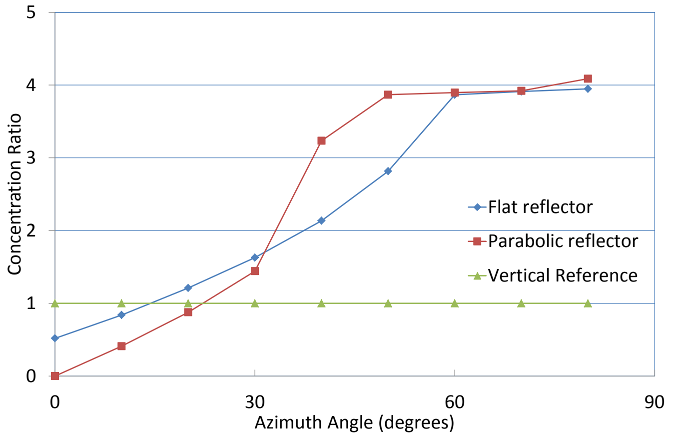

Figure 3. Effective concentration ratio v azimuth angle

Now in considering both Figure 2 and 3 the conclusion could be drawn that, at mid-latitudes, the parabolic reflector will give superior performance. However, in drawing this conclusion it is important to also consider the illumination pattern on the absorber.

From examination of Figure 4, we can see that when we plot the variation in illumination along the length of the absorber (taking the junction of aborber and reflector as the origin), that for mid-range azimuth angles, there is a significant non-uniformity in the intensity. For example, at an azimuth angle of 60° the illumination near the origin is over seven times that at the end of the absorber. This illustrates the point that the illumination profiles of parabolic reflectors tend to be non-uniform and the patterns are discrete and discontinuous in nature due to their focusing to a line.

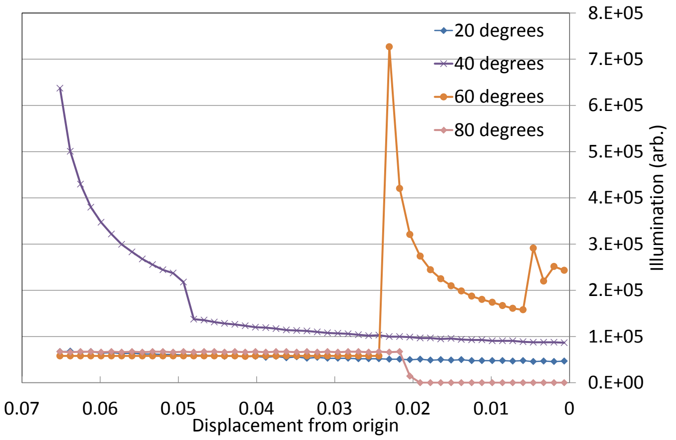

Figure 4. Illumination of absorber module at varying azimuth angles with parabolic reflector

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 illumination is significantly lower than for a parabolic reflector but is far more uniform in its distribution. In essence this supports the hypothesis that flat mirror type reflectors could be considered as circular mirrors with an infinite radius that will focus on a plane.

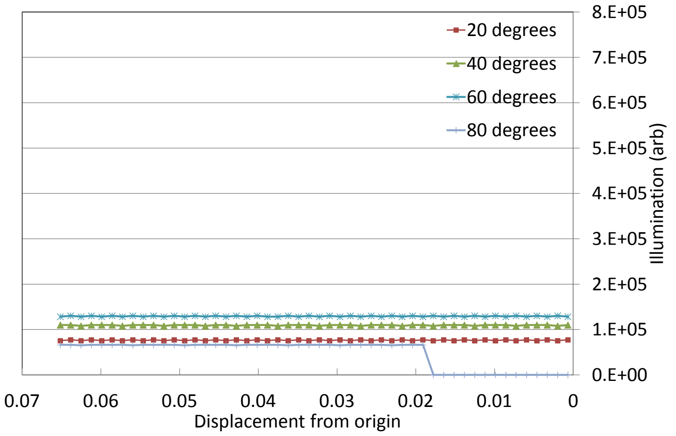

Figure 5. Illumination of absorber module at varying azimuth angles with flat reflector

IV. DISCUSSION AND CONCLUSION

From the ray tracing modeling that was performed it is possible to draw a number of conclusions. Firstly, there appears to be significant scope for the development of solar concentrators to be integrated into the façade of buildings and such systems may be able to make an improvement to energy use in buildings.

More specifically however, it would appear that parabolic reflectors may be well suited to 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 BIPV or BIPVT applications, the non-uniform illumination would cause high ohmic losses and would also produce internal current flow even when it is open circuited. This would affect the total current output, short circuit current and open circuit voltage [26] and as noted by [20] the highly illuminated region will generate a higher current compared to the less illuminated part of the module. This effect will lead to the generation of cross currents that can eventually lead to premature failure.

Finally, 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 to the absorber surface. In the case of a BIPV or BIPVT module, this would 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 an ideal compromise for such building integrated solar systems.

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