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Performance of a building integrated photovoltaic/thermal concentrator for facade applications

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ABSTRACT

The use of building integrated photovoltaic/thermal (BIPVT) concentrators is an effective way to harness solar energy within the built environment, particularly for façade applications. However, in order to precisely predict the overall performance of building integrated façade collectors it is crucial to have a validated model that represents such systems.

In this study, a combined optical and thermal model was developed to describe the performance of a façade integrated BIPVT solar concentrator system and subsequently was validated with a physical prototype. Using the validated model, it was shown that key parameters such as tube spacing, and thermal conductivity between the solar cell and the absorber have a significant effect on the overall efficiency.

Finally, it is suggested that façade integrated BIPVT solar concentrator systems would serve as a complement to roof mounted photovoltaic systems, and that this may be a step towards net zero energy buildings.

1. Introduction

Energy consumption in the built environment accounts for nearly one third of global energy demand (IEA, 2011). A significant portion of this could be met through onsite energy generation utilising solar energy. However, traditional solar energy systems such as photovoltaic panels or solar thermal collectors retrofitted onto buildings after they have been built may result in poor aesthetics and sub-optimal energy outputs. Therefore, integration of combined photovoltaic/solar thermal collectors into a building's fabric could provide greater opportunity for the use of renewable energy technologies in buildings.

Generating thermal and electrical energy simultaneously from solar irradiation using photovoltaic/thermal (PVT) systems is an area of research that has received significant attention in recent years (Anderson et al., 2009; Ibrahim et al., 2014; Fudholi et al., 2014; Tripanagnostopoulos, 2012). However, there have been relatively few attempts to utilize such systems with low concentration ratio concentrating systems to increase the radiation incident on the PVT absorber, and even fewer that incorporate such systems into the fabric of a building.

A significant advantage of low concentration reflectors is that they do not need to track the sun, making them ideal for integration into a building's facade, though by doing this they will have a lower acceptance angle range than tracking collectors (Rabl, 1976). Despite this disadvantage, low concentration ratio collectors offer the advantage of collecting diffuse radiation as well as the beam component (Petter et al., 2012) and the possibility of using the traditional silicon solar cells less.

In their study, Tripanagnostopoulos et al. (2002), analysed PVT combined collectors incorporating low concentration ratio booster reflectors with a view to achieving high combined efficiency. In a parallel study, Tselepis and Tripanagnostopoulos (2002) performed a life cycle assessment of the combined collector and concluded that they were more cost competitive, had a shorter payback time and less environmental impact than that of standalone PV panels. As such, the combination of low concentration ratio reflective elements along with hybrid absorbers may further improve the cost competitiveness of the system by increasing the radiation on the absorber plate. Similarly, a study by Gajbert et al. (2007) found that low concentration ratio PVT modules have advantages over traditional modules and proposed a PVT collector with a parabolic reflector.

However, there appears to be few active attempts to utilise concentrating building integrated PVT systems, and a lack of detail in describing their combined thermal/electrical performances. Moreover, there are few studies that have investigated systems with a static reflector combined with a hybrid absorber for façade applications. In light of this, this work examines the design and

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performance of a PVT system that incorporates a reflective element with a view to increasing the radiation on a photovoltaic/thermal absorber plate, suitable for integration into a building façade.

2. Optical assessment of a BIPVT concentrator

Based on the literature, a complete design of BIPVT concentrating collector has several challenges at the design phase; in particular, a suitable optical arrangement needs to be found. 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 in order to improve the performance of the collector. However, for façade integrated collectors it is far more practical to use static solar concentrators with medium to low concentration ratios. With this configuration it is not necessary to track the sun thus making them ideal for use as building integrated solar collectors, where they are the part of the building and hardly movable.

One of the key benefits of low concentration ratio collectors is that they may work with an absorber equipped with conventional silicon solar cells to produce significant amounts of electrical energy. These absorbers are comparatively cheap, readily available in the market and do not need the precise optical design of high/medium concentrator devices. Research on low concentration reflectors conducted in the mid-70s (McDaniels et al., 1975; Rabl, 1976) was mainly around two distinctly different reflectors; one a modified compound parabolic reflector and the other based on a simple flat plate reflector, often referred to as a booster reflector.

Parabolic reflectors are one of the most widely used non-imaging concentrators; used in linear and trough collectors. By modifying the dimensions of the reflectors (either by truncating or extending) higher concentration ratios can be achieved. Similarly, changing the area of the reflector material allows variation of the acceptance angle without changing the concentration ratio for a particular range of angles. In this regard, systems using truncated semi parabolic concentrators have been proposed for building facade integrated collectors in the past (Gajbert et al., 2007; Brogren, 2004).

That said, flat reflectors are one of the simplest ways to increase the insolation incident on a solar collector. Fig. 1 shows a typical flat reflector collector design with an absorber inclination angle θ, where L_R and L_C are the lengths of the booster reflector and the collector respectively.

By changing the size of the reflector, the geometric concentration ratio (L_R/L_C) can be manipulated to achieve a higher level of solar radiation on the absorber. Unlike a flat plate collector, inclination angles of both the absorber and reflector can be manipulated to achieve an optimum output (Tanaka, 2011). Although concentrating systems with flat reflective elements have been used in different applications, the possibility of using them in façade applications appears to have been ignored.

Based on the suitability of CPC and flat reflectors for static concentrators, it was decided to examine the concentration ratio of these two possible configurations for a façade integrated concentrator. As such, a collector with a parabolic reflector incorporated similar to that described in Gajbert et al. (2007) and a second with a flat reflector, as shown in Fig. 2, were examined.

2.1. Comparison of possible geometries

To characterize the performance of the two systems it was decided to use the ray-tracing program FRED. FRED is an optical engineering software program that is capable of performing non-sequential ray tracing analysis of non-imaging optics, such as solar

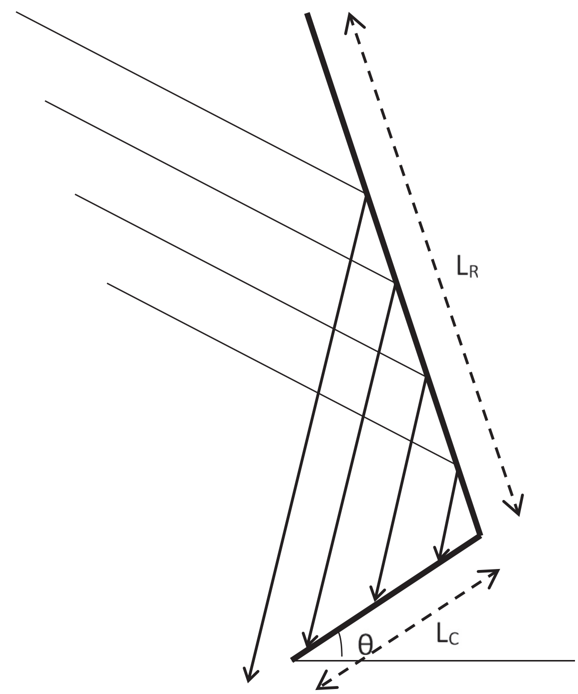

Fig. 1. Flat reflector collector.

concentrators (Photon Engineering, 2015). To simplify the ray tracing, it was decided to perform a one dimensional ray tracing study with a collimated optical source of rays, as an approximation of the beam component of solar radiation. It was assumed that the reflectors were perfect reflectors while the absorbers (the surface to be analysed) were perfect absorbers.

To make a fair comparison of the two concentrators the length of each reflector was approximately equal, as was the width of the absorber module, such that the geometric concentration ratio for both was approximately 3.6. In addition, a horizontal absorber of the same dimensions as that used with 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°. Fig. 3 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 ray's incident on the absorbers are then normalised against the number of ray's incident on the horizontal reference we can determine a relative concentration ratio, as shown in Fig. 3.

By considering both Figs. 3 and 4, the conclusion could be drawn that the parabolic reflectors give better performance at a range of elevation angles compared to the flat reflector, as Brogren and Karlsson (2002) suggested. However, in drawing this conclusion it is important to also consider the local concentration ratio (illumination pattern) on the absorber.

Fig. 5 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 non-uniformity in the intensity on the absorber. For example, at an elevation angle of 60° the illumination near the apex 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 them focusing the to a line.

Now if we consider the illumination profile from a flat plate reflector, as shown in Fig. 6, we can see that the magnitude of