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Prototype fabrication and experimental investigation of a conjugate refractive reflective homogeniser in a cassegrain concentrator

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ABSTRACT

The conjugate refractive reflective homogeniser (CRRH) is experimentally tested within a cassegrain concentrator of geometrical concentration ratio 500× and its power output compared to the theoretical predictions of a 7.76% increase. I–V traces are taken at various angles of incidence and experimental results showed a maximum of 4.5% increase in power output using the CRRH instead of its purely refractive counterpart. The CRRH utilises both total internal reflection (TIR) within its core refractive medium (sylguard) and an outer reflective film (with an air gap between) to direct more rays towards the receiver. The reflective film captures scattered refracted light which is caused by non-ideal surface finishes of the refractive medium. The CRRH prototype utilises a 3D printed support which is thermally tested, withstanding temperatures of up to 60 °C but deforming at >100 °C. A maximum temperature of 226.3 °C was reached within the closed system at the focal spot of the concentrated light. The material properties are presented, in particular the transmittance of sylguard 184 is shown to be dependent on thickness but not significantly on temperature.

Utilising both TIR and standard reflection can be applied to other geometries other than the homogeniser presented here. This could be a simple but effective method to increase the power of many concentrator photovoltaics.

1. Introduction

Concentrator photovoltaic (CPV) designs have been pushing higher concentration ratios to achieve higher conversion efficiencies and cost effectiveness. As the concentration ratio of an optic is increased, the acceptance-angle decreases, making it more difficult to manage the design deviations and uncertainties (optical tolerances) (Baig et al., 2012; Canavarro et al., 2013). A homogeniser optic is typically needed to match beam shape and size to the receiver and improve the optical tolerance of the overall optical system (Baig et al., 2012; Canavarro et al., 2013). Final stage optics within a CPV commonly take the form of a compound Parabolic Concentrator or V-trough but other shapes are being investigated such as the dome lens (Hatwaambo et al., 2008; Shanks et al., 2016c, 2015; Victoria et al., 2009; Winston, 1970). There are homogenising optical designs with varying advantages already available but as designs progress and perhaps become more complex the material, surface quality and solar cell coupling method needs to be further investigated.

One key consideration in all of the above named designs is the material to be used and the resulting surface quality (Fend et al., 2003; Yin and Huang, 2008). Previous simulation work has been carried out to show the importance of considering the surfaced roughness and subsequent light scattering during the design and simulation stages of development (Shanks et al., 2016a). This previous study investigated a cassegrain concentrator design similar to that of SolFocus (Gordon et al., 2008) but focused on the surface quality of the refractive homogenising optic. The system presented here and in the previous work was optimised for acceptance angle (Shanks et al., 2016b). There are many cassegrain concentrators which have been investigated in the past (Chen and Ho, 2013; Chong et al., 2013; Dreger et al., 2014; McDonald et al., 2007; Roman et al., 1995; Terry et al., 2012, 1996; Victoria et al., 2013; Yehezkel et al., 1993) but further insight into the material and manufacturing choices is needed. Cassegrain set ups are known for having slightly lower acceptance angles than their Fresnel lens counterparts but can reach higher concentration ratios and hence why this type of system was chosen to not only understand the

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design constraints but see if a new homogeniser would improve the performance, especially for future designs of higher solar concentration levels. The surface roughness of refractive optics which utilise total internal reflection (most homogenisers) causes scattering of incoming light and incomplete TIR despite incident light fulfilling the acceptance angle criteria of the optic. Surface imperfections will also increase the reflection upon entering the refractive optic. The degree of this surface inhomogeneity depends on the manufacturing process and material used with higher quality optical finishes and coatings costing more (Yin and Huang, 2008).

As indicated in the previous theoretical study (Shanks et al., 2016a), high quality glass homogenisers and similar refractive optics which utilise TIR will not suffer much optical loss due to poor surface quality. Glass is the preferred choice of material to achieve very smooth and accurate optical finishes and the inverted pyramid glass homogeniser and CPC optics can be bought off the shelf at reasonable costs. However, more complex prototypes are costly to fabricate using glass and even if glass is used these optics then need to be attached optically to the solar cells using an encapsulate. When coupling a homogeniser to a solar cell as a secondary step, the lateral spillage of the silicone causes significant optical losses from leakage through it. If to avoid spillage the joint is under-filled, the joint could be weaker and possibly result in an air gap also producing optical losses (Benítez et al., 2010). These losses cannot be quantified until full production is achieved. In the present study we have eliminated the step of the optical coupling the solar cell separately with the solar cell by preparing a mould, which allows this.

In this way we can manufacture the V-trough homogeniser, simultaneously join it to the solar cell and reduce alignment errors by using this mould. To do this we use the refractive material Sylguard 184 which is predominantly used as an encapsulate and has the advantage of setting at room temperature. This is important as we should not subject the cell to any unnecessary heating before use and because typical high temperature mould setting can involve expansion and contraction of the material which could damage the solar cell when part of a closed mould such as this.

As already discussed, using an alternative material to glass will most likely result in more surface scattering. To compensate for this we add an outer reflective casing with an air gap to ensure both TIR and standard reflection can occur, trapping scattered rays. This hence becomes the Conjugate Refractive Reflective Homogeniser (CRRH).

Identifying the losses within a homogenizer of a high concentrating photovoltaic system, quantifying them and applying simple solutions towards improving them will improve the performance of the full system. Within the growing area of solar concentrator research there needs to be a clearer understanding of how theoretical designs will perform in real conditions with real optics. For this reason this paper is the experimental counterpart to a previous theoretical study on the CRRH within a cassegrain concentrator (Shanks et al., 2016a). Hence, one of the focuses of this study is to confirm how much of the theoretical predictions could be realised (7.76% theoretical power increase), what materials and manufacturing methods are feasible and their performance in a high temperature environment.

At present, manufacturing processes for optics include precise grinding, milling, polishing, and a variety of coating methods for a smooth finish (Xu et al., 2013). Most current manufacturing processes struggle to produce acceptable priced prototype optics of new specific shapes and reliable accuracy (Kaushika and Reddy, 2000; Tsai, 2013). Here, we have tested plastic mirrors for their advantages in cost, weight and smooth surface quality. One of the challenges of CPV technology is its increased initial investment in comparison to flat plate PV due to the added optics and tracking required (Fraas, 2014). Computer-controlled diamond turning machines, as well as other modern materials and moulding techniques, have significantly improved the design and accuracy of refractive optics such as Fresnel lenses (Leutz and Suzuki, 2001). In this study we have utilised 3D printing and tested a structure for its heat tolerance within a CPV system. 3D printing is a very powerful prototyping tool which needs further testing for use within CPV research. The 3D printed support structure also compensates for the possibly weaker coupling joint of the 1 step moulding. This study, though specific in design and material, highlights a general issue in optics and prototyping and suggests simple but effective methods of compensating for losses due to surface roughness.

2. Theoretical work

A previous study has been undertaken which optimised a cassegrain concentrator design of 500× geometrical concentration (Shanks et al., 2016b). This design was optimised for acceptance angle by investigating the ray displacement at 1° incidence angle for a range of focal length and separation distance parameter of the two reflector dishes in the system. Use of a homogeniser was required to improve the acceptance angle of the cassegrain set up and a refractive homogeniser was chosen instead of a reflective one to take advantage of total internal reflection (TIR). As already discussed this TIR is however only fully effective if the homogeniser surface quality is very smooth. In the previous study, this tall homogeniser optic was found to lean when the system was tilted to track the sun (Shanks et al., 2016b). For all these reasons a new homogeniser optic utilising an outer reflective casing was proposed and investigated also (Shanks et al., 2016a). This previous study focused on the theoretical concept of compensating for surface roughness in the homogeniser by catching refracted rays with a reflective film. Various materials and surface structures were investigated (Shanks et al., 2016a). Manufacturing the optic however needed to be done in a reliable and effective manner. Hence, the reports here utilising 3D printing.

The cassegrain concentrator and its final dimensions can be seen in Fig. 1 (Shanks et al., 2016b). The design aimed to simultaneously obtain a high optical efficiency and a good acceptance angle. The concentrator consisted of a parabolic primary reflector, inverse parabolic secondary reflector and a refractive crossed V-trough homogenising tertiary as shown in Fig. 1. In comparison to the SolFocus design (Gordon et al., 2008), the primary parabolic dish has a higher focal length (270 mm) and a taller homogeniser (75 mm). Everything has also been cut to a square shape to allow compact arrays. Manufacturing uncertainties were considered and various material surface scattering profiles of the optics in the system were simulated (Shanks et al., 2016a). A 3–42% drop in optical efficiency was shown to occur (Fig. 2) depending on the material and scattering profile of the homogeniser.

Hence, the new conjugate refractive-reflective homogeniser (CRRH) was proposed as a solution to improve the homogeniser optical losses. The CRRH utilises the addition of a straight reflective film to the dielectric homogeniser with a 1 mm air gap kept between the dielectric medium and reflective film. The reflective sleeve ensures total internal reflection is maintained for the majority of light rays and the previously lost scattered light is also caught. This simple but effective method to recover rays which fail TIR has been used elsewhere (Baig, 2015). Baig et al. (2015, 2014) discuss the optical losses caused by the encapsulation medium used in connecting low concentration optics to solar cells. Light rays incident in this overlap region do not reflect towards the solar cell but continue through the encapsulation medium until lost.