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Prototype Design of a Low-Concentration Roof-Mounted Solar Thermal Collector for Industrial Heat Production

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Abstract

Low- and medium-temperature industrial process heat demand represents a significant proportion of the total energy consumed within Australia. Currently, the overwhelming majority of this heat is generated via the combustion of natural gas, with a smaller contribution by electric resistance heating and heat pumps. In order to reduce fossil fuel consumption a renewable alternative process heat supply is highly desirable.

Compound Parabolic Concentrators (CPCs) are low-optical-concentration non-imaging solar collectors which are capable of concentrating solar radiation over a broad range of acceptance angles. For this reason, CPCs lend themselves well to non-tracking, roof mounted applications for the generation of low- and medium-temperature thermal energy.

The authors have presented a second paper describing an *ab initio* CPC design, however this presents a number of manufacturing challenges: precise geometric tolerances must be met in order to ensure high optical efficiency; a reflector substrate was required to meet the geometric specification while achieving a high-quality surface finish to maximize mirror reflectance; and a new evacuated tube absorber was developed to address the specific geometric and hydraulic needs.

This paper presents the refinement of a CPC design for prototype manufacturability. Optical simulation is used to understand the sensitivity of the design to a range of manufacturing deviations, and this knowledge is applied to assess a number of candidate materials and manufacturing processes. Learnings from the prototype's development are considered in guiding the longer-term design for scale manufacturing.

A prototype collector is currently in production and will be tested in the latter months of 2016 at the RMIT University solar test laboratory in Melbourne.

1. Introduction

Industrial energy consumption consumes approximately 43% of Australia's total end use energy, and about 70% of this demand is gas. Of that, the majority is used for the production of heat low- and medium-grade heat (i.e. below 300°C) (IT Power 2015).

In the ongoing transition from conventional fuels to renewable sources throughout the economy, such temperatures are of interest as they are technically achievable using relatively simple solar thermal technologies.

Funded by the Australian Renewable Energy Agency (ARENA) and led by RMIT University, the Micro Urban Solar Integrated Concentrators (MUSIC) project aims develop a new class of rooftop solar thermal collectors supplying medium-grade heat for industrial processes.

The collector design builds on the Compound Parabolic Concentrator (CPC) design (Winston, 1974). The CPC is a non-imaging reflector which is able to achieve low-level concentration without tracking. The MUSIC collector will investigate the use of modern technologies, including novel manufacturing processes, highly reflective materials and efficient absorber materials, to achieve reasonable system efficiencies at temperatures that are difficult to reach using existing off-the-shelf products.

Previous research on CPCs has investigated a range of design considerations (Rabl, 1976), but limited work has been undertaken to understand the sensitivity of CPCs to manufacturing variations.

RMIT's work to date has focused on the theoretical optimisation of a design (Karwa, 2015), producing an *ab initio* specification which is the subject of a separate paper (Stanley, 2016). The specification calls for a series of parallel CPC channels (each approximately 113mm wide at the aperture, and a total height of 90mm), with a 16mm diameter absorber encapsulated in an evacuated glass tube.

The primary prototype manufacturing challenge is to produce a precise surface geometry for the mirror which adheres closely to the design specification, at reasonable cost for a small production run.

A promising candidate manufacturing method for producing the reflective finish was identified early in the process: drawing from automotive industry experience in manufacturing headlight reflectors, the approach directly metalises a highly polished polymer substrate using a vapour deposition process. Alternatively, the surface may be formed from one of a number of commercially available highly reflective aluminium sheet materials, or by adhering a metalised polymeric reflector film to a substrate.

The remaining challenge – to refine the specification to produce a manufacturable design – requires an understanding of the impact of the range of potential geometric deviations on the optical performance of the collector system, combined with an understanding of a range of viable manufacturing processes. This paper presents the process of selecting a suitable manufacturing method, refining the design, and the production of the first MUSIC prototype.

2. Optical characterisation and theoretical modeling

A CPC has a compound parabolic shape formed by the combination of two parabolas placed at a non-zero angle from each other (Winston, 1974). The geometry of CPC is as summarized in Figure 1. The angle between the axes of the two parabolas is known as the *acceptance* angle θ_A. Light entering the CPC from within the acceptance angle is reflected and focused on the region between the focal points (FA and FB) of the two parabolas. An absorber placed in this region will effectively capture the concentrated solar energy. The regions of the two parabolas that are indicated by dotted lines are generally truncated, as these regions do not contribute significantly towards solar concentration and truncation leads to material, size, weight and cost reduction (Rabl, 1979 and Carvalho, 1985).

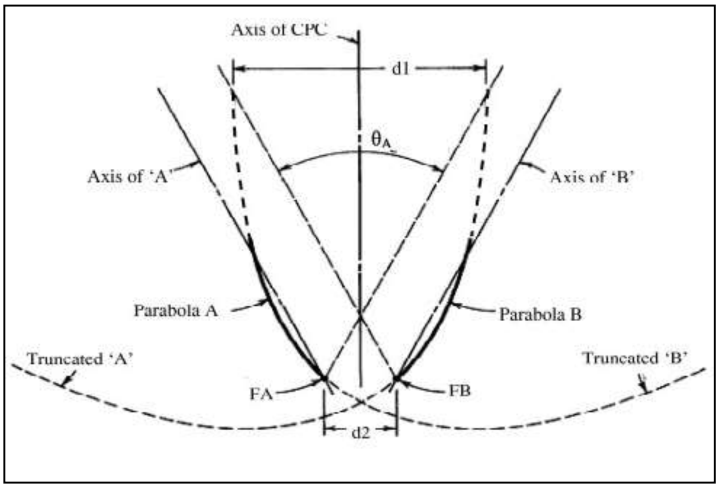

Figure 1: Basic Geometry of CPC (Gudekar, 2013)

The relationship between the concentration ratio (CR) and acceptance angle θ_A of a CPC is given by Equation 1

$$\mathrm{CR} = \frac{1}{sin\left({}^{\theta_A}/_{2}\right)}$$

Equation 1

For a truly ideal CPC, the CPC reflector must touch the receiver. In practice, the presence of the glass enclosure around the receiver results in a narrow gap between the receiver and the CPC. Additionally, the receiver must not touch the enclosure, which further adds to the receiver reflector gap. This results in a part of the reflected solar radiation passing through the gap and missing the receiver (see Figure 2c). This loss, called the gap loss, depends on the receiver shape (O'Gallagher, 2008).

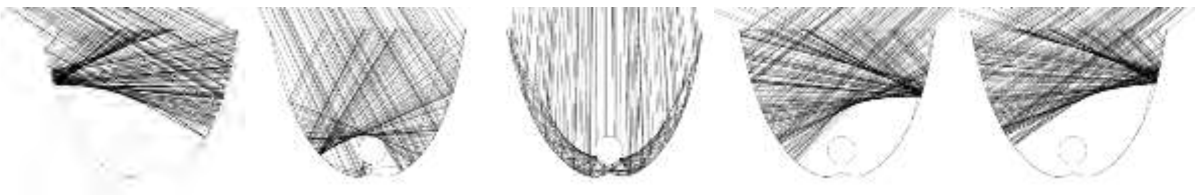

Figure 2 (a-e): Optical response of a CPC to varying source directions

To allow for assembly of an absorber and glass tube from components that are not perfectly straight, as well as to provide for manufacturing needs such as including space for a port through which a vacuum is pulled, the receiver was specified with a 4.5mm gap between the absorber surface and the cusp of the CPC reflector.

Equation 2 relates the irradiance, working fluid and ambient air temperatures to the overall collector efficiency. The efficiency at ambient operating temperature η_0 is often described as the *optical efficiency*, as it describes the peak efficiency of the collector at normal irradiance, while the optical response of the collector is characterised using an *incidence angle modifier* (IAM), which corresponds to the decrease in irradiance absorbed under non-normal incidence.

$$\eta = \eta_0 - a_1 \frac{t_m - t_a}{G} - a_2 \frac{(t_m - t_a)^2}{G}$$

Equation 2

In practice, the IAM is derived from physical measurements of efficiency of a production sample collector at varying incidence angles. Indicative IAM curves for different technologies are presented in Figure 3. The IAM is unity at normal irradiance; for flat plate collectors this is the peak efficiency as the performance reduces with incidence angle (roughly following a cosine curve) due to the optical effects of the glazing, while evacuated tube collectors may in fact *increase* efficiency at small incidence angles (while the irradiated absorber area is constant for small incidence angles, the incident light on the aperture plane reduces – with efficiency taken as a measure of heat output to light on the aperture, collector performance appears to increase). The CPC IAM is more complex as the light pathway varies greatly for small changes of incidence angle. Efficiency appears highest at the edge of the acceptance window as reflected light rays at this point tend to concentrate towards the top of the absorber region and thus minimise the gap loss (see Figure 2 (b) and (d)).

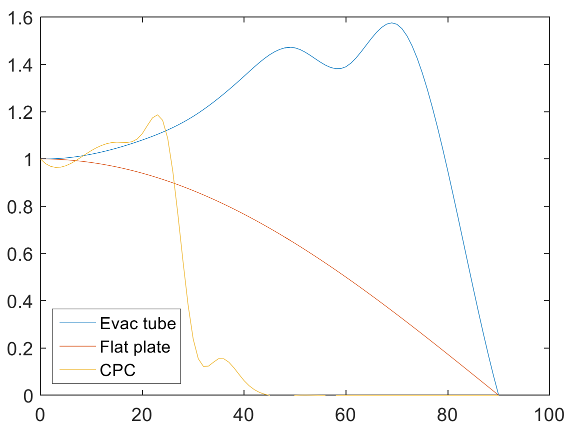

Figure 3: Indicative IAMs for different collector technologies

In this work, we will assess the impact of geometric deviations from ideal by deriving an estimate of the IAM for each deviation. The estimate is calculated from a series of optical models by varying the relative position of a simulated solar cone light source over a range from 0° to 180° and measuring the irradiance incident on the aperture plane and at the absorber. A number of deviation parameters were considered as outlined in Section 3.1, and these were varied over a range from minimal to extreme.

To compare the performance difference between individual curves, a scalar value η_{aw} (Equation 3), representing the average efficiency over the acceptance window, was defined:

$$\eta_{aw} = \frac{\int_{-\theta_A}^{\theta_A} \eta(\theta) d\theta}{2\theta_A}$$

Equation 3

2.1. Deviations considered

The analysis was undertaken for the following range of deviation parameters:

1. Absorber position (horizontal)
2. Absorber position (vertical)
3. Reflector deviation from straightness (vertical curvature)
4. Reflector deviation from straightness (horizontal curvature)
5. Mirror reflectance
6. Mirror cusp radius
7. Surface offset
8. Mirror specularity

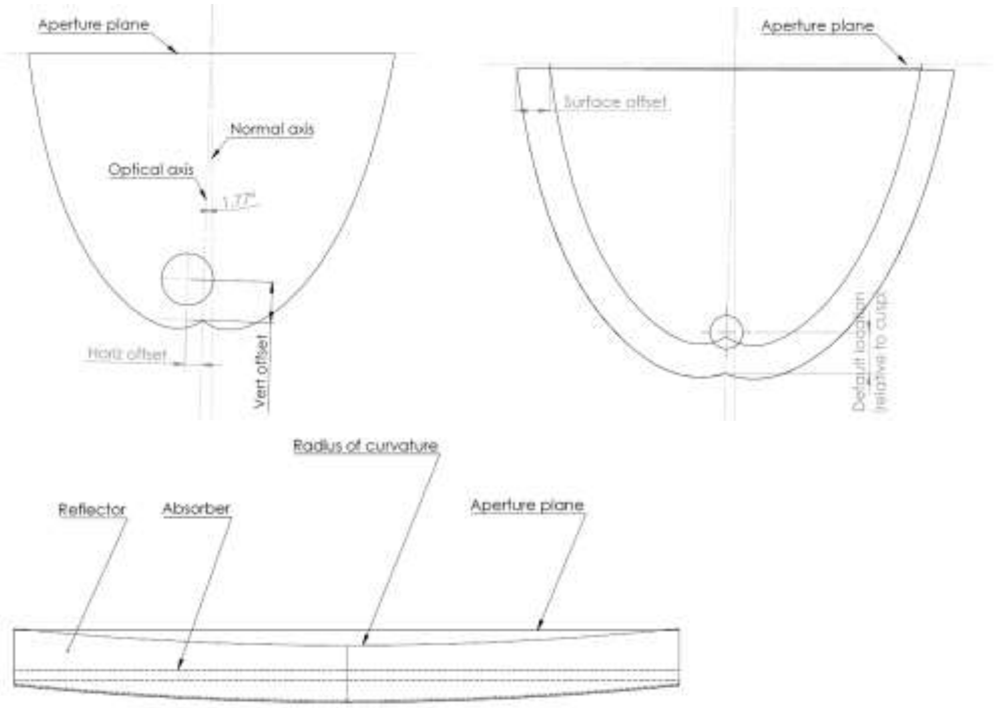

Figure 4 a-c: Manufacturing deviations as modelled – (a) vertical and horizontal offset of the absorber; (b) offset from the absorber surface; and (c) vertical curvature of the reflector

2.2. Modelling procedure

The geometry was modelled using the Solidworks CAD package. Optical analyses were performed as Monte Carlo ray-tracing simulations, with 1M rays, in the LightTools V8.0.0 optical engineering design tool. For simplicity, the mirror and receiver were modelled as having properties of 100% reflectance and absorbtance (respectively), and the optical impact of the encapsulating glass tube around the absorber was ignored. Investigation into the impact of these parameters is highlighted as an important point for future work.

3. Results and discussion

3.1. Simulation results

The impact of a deviation of absorber position from ideal on the optical efficiency is presented in Figure 5(a) where it is apparent that a larger deviation reduces efficiency for most elevation angles within the acceptance window. It is interesting to note that there is some increase in efficiency for values just outside the acceptance window, but the overall performance is clearly reduced.

The impact of horizontal misplacement of the absorber on the average efficiency within the acceptance window is presented in Figure 5(b). Results appear to indicate that the impact is fairly linear, with a performance drop of ~2.75% per mm of horizontal misalignment.

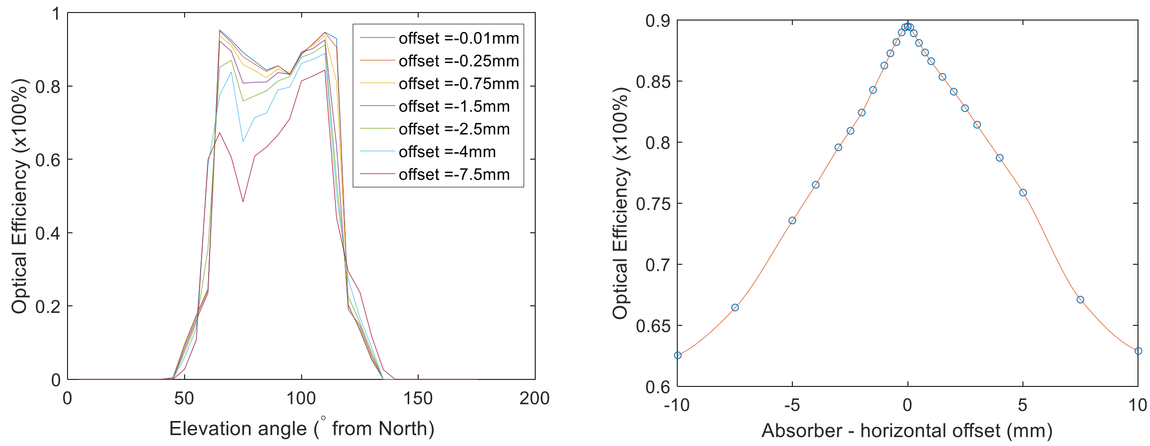

Figure 5 (a-b): Performance impact of offsetting the absorber horizontally

The effect of a deviation of absorber position in the vertical direction is presented in Figure 6Figure 6 (a-b): Performance impact of offsetting the absorber vertically; (c) detail of the impact of small movement *downwards*; and (d) Performance impact of offsetting the reflector surface

. For negative deviations (moving the absorber up), we see that the effective acceptance window *widens* – light rays entering the aperture at high incidence angles, which in the specified design would have been reflected through the region above the absorber (for example see Figure 2(a) and (e)), are now absorbed.

For positive deviations (absorber moving down), we see the impact of the reduced gap – rays now from sources closer to normal incidence, which previously passed through the gap below the absorber, are now collected and performance is increased. For small deviations of less than 2mm, when integrating across the entire acceptance window, the impact appears quite non-linear (see Figure 6(b) and (c)).

Note that in practice the glass evacuated tube prevents the absorber from being positioned closer to the reflector cusp than is specified in the design. The *vertical offset* as defined here will always be less than 0.

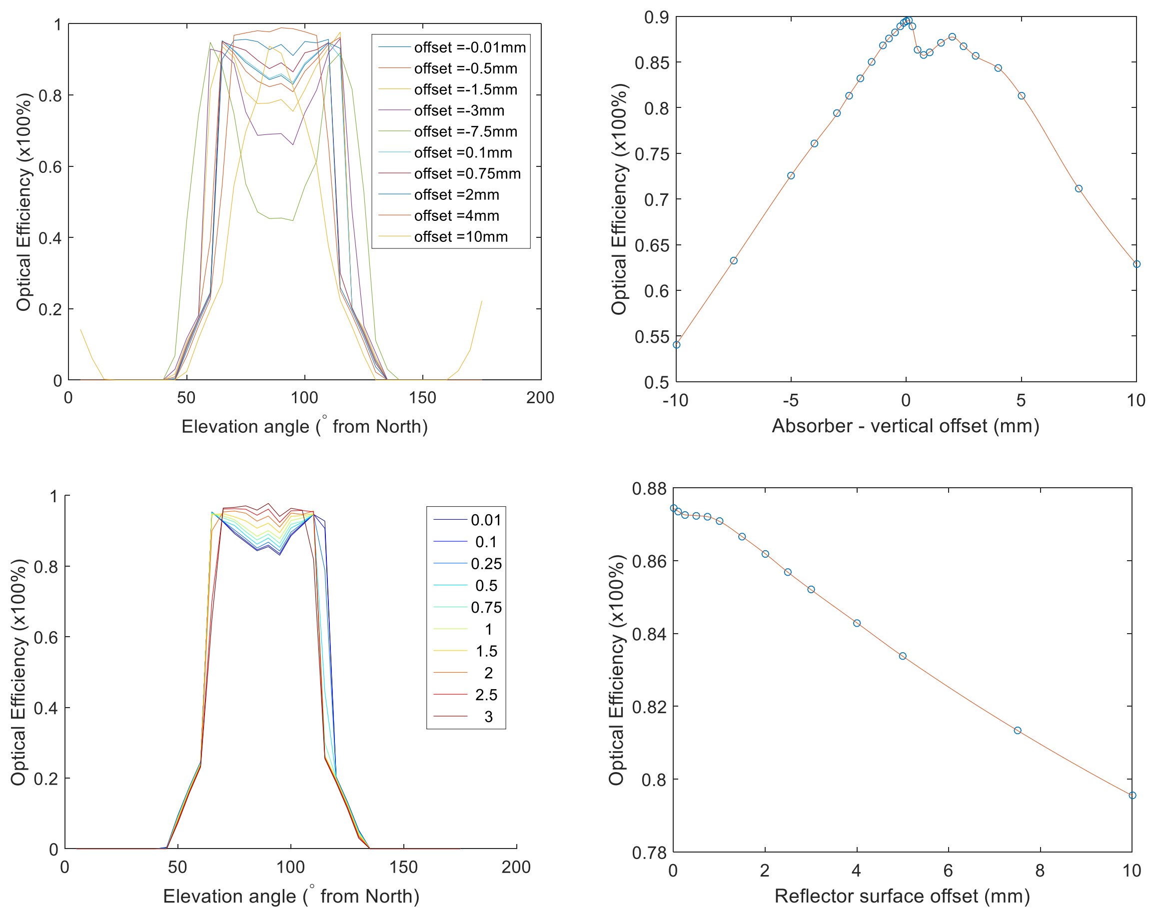

Figure 6 (a-b): Performance impact of offsetting the absorber vertically; (c) detail of the impact of small movement *downwards*; and (d) Performance impact of offsetting the reflector surface

An offset of the reflector from ideal (by widening the geometry, with each point on the surface moving in its normal direction away from the optical axis) has the impact presented in Figure 6(d). Here, we see the robustness of the CPC design, which appears to be quite insensitive to such perturbations: a performance reduction of less than 0.5% is produced by a surface offset deviation of 1mm. The effect is slightly non-linear, with an increased impact being felt for deviations of more than ~1mm (i.e. higher sensitivity of ~1% per mm).

3.2. Prototype manufacturing considerations

A number of candidate manufacturing options were considered for producing the reflector. These were assessed using a weighted criteria approach in Table 1. Four of the methods were selected for further investigation.

3.3. Prototyping attempts

3.3.1. 3D printing

The advantages of hard polymers are numerous and include low material costs, light weight and durability. Mirroring of a plastic surface can be achieved either by adhering metalised films, or direct metalising of the part. The disadvantage is the high tooling costs associated with mould fabrication for processes such as injection moulding (IM). This means that IM is only viable for very high production volumes, where the unitised cost associated with the tooling becomes economical. However, a model produced using advanced 3D printing techniques will provide an indication of the potential of a polymer design.

Table 1: Summary of assessment criteria for alternative reflector manufacturing processes

Option	Comments: pros/cons	Cost score	Quality Score	Overall Score	Recommendation
1. Machining	**Cons:** relatively high unit cost	6	6.5	**39**	Consider for prototype
2. Hot wire cutting	**Cons:** relatively high unit cost	6	6.5	**39**	Consider for prototype
3. 3D printing	**Pros:** Representative of an injection-moulded part **Cons:** high unit cost	4	5	**20**	Consider for prototype
4. Hand lay-up	**Pros:** relatively low cost mould **Cons:** labour intensive	5	6	**30**	Consider for prototype
5. Vacuum forming	**Cons:** Q: large minimum radius, low surface precision	5	4	**20**	Rejected
6. Spray lay-up	**Pros:** low cost **Cons:** low precision	5	3	**15**	Rejected
7. Extrusion	**Cons:** High tooling cost	2	9	**18**	Consider for scale manufacturing process
8. Injection moulding	**Cons:** very high tooling cost	1	8	**8**	Consider for scale manufacturing process
9. Sheet metal forming	**Pros:** very high reflectivity	1	6	**6**	Rejected
10. Rolled Al	**Cons:** very high tooling cost	1	9	**9**	Consider for scale manufacturing process

Testing of six different metalised plastic samples conducted at the ANU demonstrated reflectances from 85-92% depending on surface preparation and post-metalising surface coating. It is also possible to deposit silver, with AM1.5 integrated reflectance of approx. 95%, however this is considerably more expensive and so was not considered at this stage.

To test the efficacy of a direct metalised plastic CPC a small 100mm long prototype was 3D printed from ABS plastic, as seen in Figure 8. Manual treatment was required to remove the incremental print lines which are left over from the 3D printing process in order to achieve a surface finish representative of the smooth surface possible from an injection moulded part. This consisted of hand sanding and applying a two-pack acrylic enamel paint to eliminate surface scratching and result in a smooth glossy surface ready for metalising. `

Figure 7: 3D printed plastic CPC (a) showing the print lines resulting from the printing process; and (b) painted with 2-pack polyurethane (high gloss black) in preparation for vapour deposition of the aluminium reflective surface

Figure 8: Aluminium metalised plastic CPC

The resulting surface was of very high quality, but the cost of production, even at low manufacturing volumes, eliminated this as a viable option for full-sized prototyping.

3.3.2. Hand lay-up

A glass fiber composite prototype was manufactured first by machining a pattern from jelutong, a timber commonly used by patternmakers for its fine texture and ease of workability. After sanding and undercoating to fill the grain, the pattern was painted using high-gloss 2-pack polyurethane (see Figure 9). A male fibreglass mould was made from the pattern, and fibreglass parts laid-up by hand over the mould.

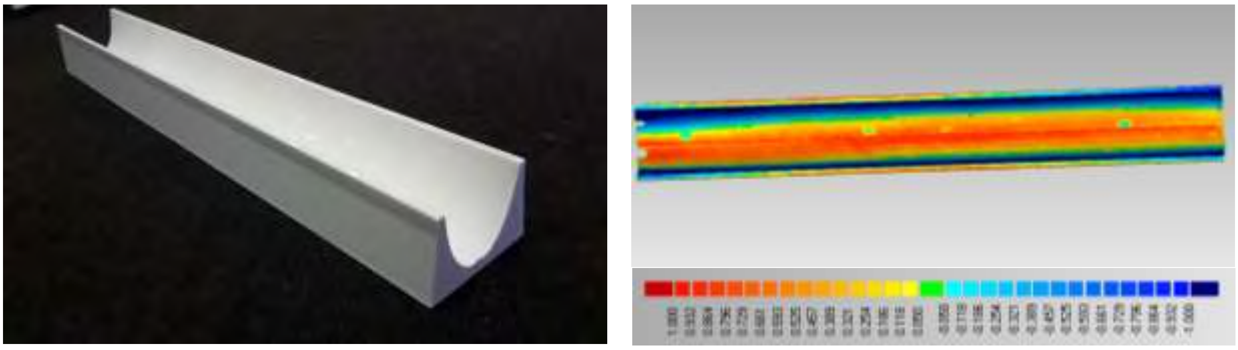

Figure 9 (a) The mould pattern; and (b) scan results of the fibreglass part

The final parts were assessed using a 3D laser scanner. Unfortunately, it appears that there were residual stresses in the composite matrix which caused some movement of the geometry when removing parts from the mould as shown in Figure 9(b). The surface deviates by over 1mm at the bottom of the channel and by more than -1mm at the top. Returning to the 'surface offset' deviation model (Figure 6(d)), we estimate the impact of an overall deviation of up to ~2mm as being in the order of 1.5 to 2%, which was deemed as unacceptable.

However, scans indicated that the machined and painted pattern adhered closely to the design, lending some hope to the proposed final alternative.

3.3.3. Machining and hot wire cutting

For machining and hot wire cutting, polystyrene foam was identified as a possible material for use as a substrate. This material is exceptionally light weight (20-70 kg/m^3), and is very cheap and widely accessible. The material would be CNC machined or hot wire cut to provide the desired profile, and if successful the mirror surface applied using an adhesive film.

Several polystyrene CPCs were fabricated from both extruded polystyrene (XPS) and expanded polystyrene (EPS) using hot-wire cutting and CNC machining and the accuracy of the resulting surface was measured using a 3D laser scanner. Unfortunately, the flexibility of the material made it unsuitable for producing a precise surface using a machining process, and the length of the hot wire required to achieve to (1m) length of the prototype design allowed vibrations which resulted is the surface gouging shown in Figure 10. As a result it was deemed that process variability in the polystyrene cutting/shaping process would require considerable improvement before this method could be used to produce cheap and reliable CPC substrates from foams.

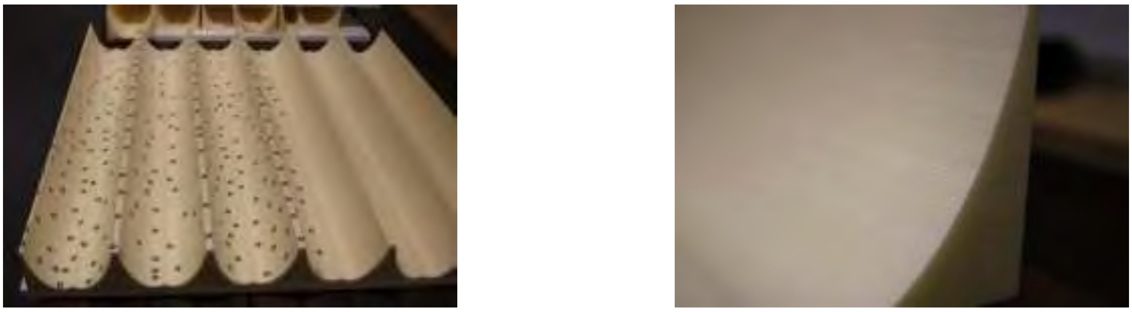

Figure 10: (a) Extruded polystyrene foam (XPS) six channel CPC module. The spots on the CPC surface are used here for 3D laser scanning of the manufactured surface; and (b) detail of surface gouging caused by vibrations of the hot-wire during the cutting process

As discovered when producing the timber pattern for the fibreglass lay-up (Section 3.3.2), a machining and painting process can produce a highly smooth surface to a tight geometric tolerance. Two materials were trialled in attempts to manufacture a CPC substrate: medium-density fibreboard (MDF), and a polyurethane-based material known as Renshape® which was explicitly developed for machinability.

Scan results (Figure 11(a)) indicate acceptable geometric quality, with most of the surface within ±0.2mm of the design ideal, although some tool path lines are apparent and produce small regions with deviations out towards 0.5mm.

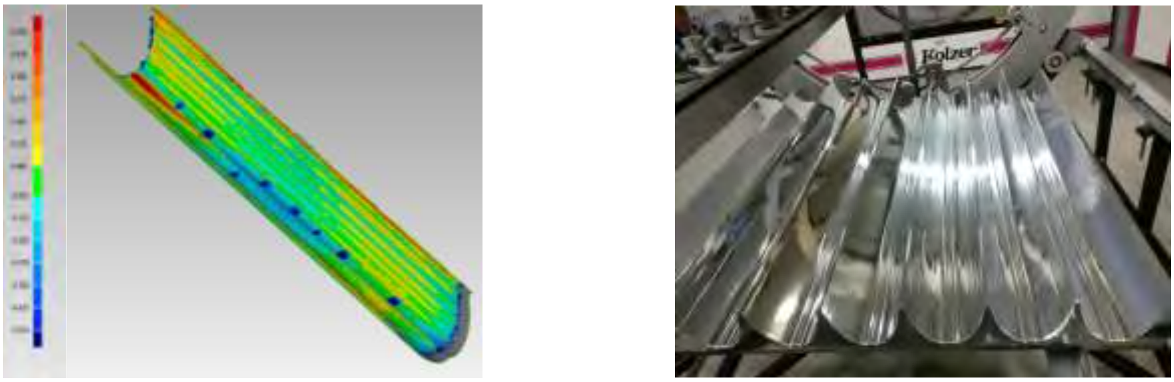

Figure 11: (a) Scan results of the MDF part; and (b) the final mirrored reflector

Some difficulty was encountered during the deposition process, as the MDF off-gassed and contaminated the vacuum, but the mirror appears to be of reasonably high quality. Further testing will ascertain the true quality of the mirror by measuring the reflectance.

4. Conclusions

This paper summarises a number of investigations undertaken in adapting a theoretical CPC design for prototype manufacturability, with an emphasis towards understanding the impact of geometric deviations from the design specification on the optical efficiency of the collector system.

A range of deviations were considered, and their effect simulated by modeling the resulting optics.

Several prototype manufacturing processes were considered, with a weighted criteria method being used to create a shortlist of four viable candidate processes. Attempts were made to produce components using these processes, and an assessment of the results used to gauge the performance impact of the observed deviations.

The final process selected was to machine the reflector geometry from two alternative materials: MDF and Renshape® tooling board. After machining, the surfaces were coated in a high-gloss 2-pack polyurethane paint to provide a substrate for the vacuum deposition of an aluminium reflector.

The remainder of the collector system is currently being assembled and will be tested in the coming months at the RMIT University solar test laboratory in Melbourne.

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