THE DESIGN PHILOSOPHY AND CONSTRUCTION OF A HIGH CONCENTRATION COMPOUND PARABOLIC CONCENTRATOR

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Abstract

A compound parabolic concentrator (CPC) with a concentration ratio of 16:1 is under development at CSIR for volumetric receiver and solar fuels development. The ideal shape has been approximated by 6 and 12 facets in the longitudinal and circumferential directions respectively. A sandwich construction method has been pursued to achieve the cooling channels: the 2mm mirror panels are bonded to a laser-cut 2mm aluminium heat conduction plate, itself bonded to a 4.5mm aluminium plate into which a serpentine cooling channel has cut by waterjet. A 1mm stainless steel backing plate on the rear surface (itself welded to laser-cut stainless steel longitudinal ribs) provides the necessary shape and structural rigidity. The spectral transmission of the 2mm soda lime mirror glass used for the concentrator facets was measured using a uniform light source and an ASD FieldSpec(TM) spectroradiometer. This, together with the SMARTS solar spectrum model, was used in a ray tracing analysis which determined the overall efficiency of the concentrator to be 68.7%. Construction is nearly complete and actual efficiency will be determined using a hemispherical cavity calorimeter.

Keywords: CPC, compound parabolic concentrator, sandwich

1. Introduction

A 25m^2 target-aligned research heliostat has been developed at CSIR [1] to provide the concentrated solar flux required to enable research in the following areas: 1) volumetric receiver development for solar-driven Brayton cycle power production and 2) solar fuels. The focal length of the heliostat is 66m (resulting in a theoretical minimum focal spot diameter of 615mm), implying a maximum possible solar concentration of 80 suns. Either volumetric receiver development or solar fuel research requires a solar flux level at least an order of magnitude higher, so further concentration of the focal spot is required. This paper describes the development of a suitable compound parabolic concentrator (CPC).

2. CPC design process

2.1. Reflective geometry

Prior CPC developments considered were those of Weizmann Institute of Science (WIS) [2,3] and of DLR [4,5]. These truncated CPC's both have an acceptance half-angle of 20˚, as the solar flux is supplied by a field of heliostats, and concentration ratios of the order of 4. In the present case the flux is supplied by a single current 25m^2 (actually 23.75m^2) heliostat, to be joined in the future by an adjacent 13.4m^2 heliostat. The diagonals of the two square heliostats and a suitable clearance gap then gave rise to the chosen acceptance half-angle of 9˚. Choosing a future maximum outlet theoretical solar flux of 2000 suns (considered an upper limit for achieving temperatures above 900˚C for Brayton cycle operation as well as the solar gasification of coal) when illuminated by the two heliostats, this led to a concentration ratio of 16:1.

The design procedure followed was similar to that described by [3]. The exit aperture diameter (153mm) was fixed by the desired concentration of 16:1. The untruncated concentration ratio determined by

$$C_{\max} = \frac{1}{\left(\sin\left(\theta_{acceptance}\right)\right)^2} = \frac{1}{\left(\sin 9^{\circ}\right)^2} = 40.8$$

The exit aperture and concentration ratio allowed the parabolic curves to be defined. The CPC was then truncated to an entrance aperture of 650mm (oversized relative to 614mm to account for focal spot non-uniformity), giving a CPC height of 717mm. Due to the difficulty in obtaining or manufacturing a glass mirror with the desired parabolic lengthwise curvature and circular tangential curvature, planar facets were used to approximate the shape. The 5-facet approximation of the parabola used in the WIS CPC [3] was compared with the parabolic curve passing through edges of the five facets. The difference in angle between the tangent to the parabola at the inlet and outlet of each facet edge for the 5 facets were (from inlet to exit apertures) 3.95˚, 4.87˚, 5.90˚, 6.74˚ and 5.50˚, giving an average of 5.4˚. This was used as a guideline for the 16:1 CPC: the parabolic shape was approximated by 6 facets, giving a difference in tangent angle at each facet edge of 5.049˚. The resultant shape is shown in figure 1.

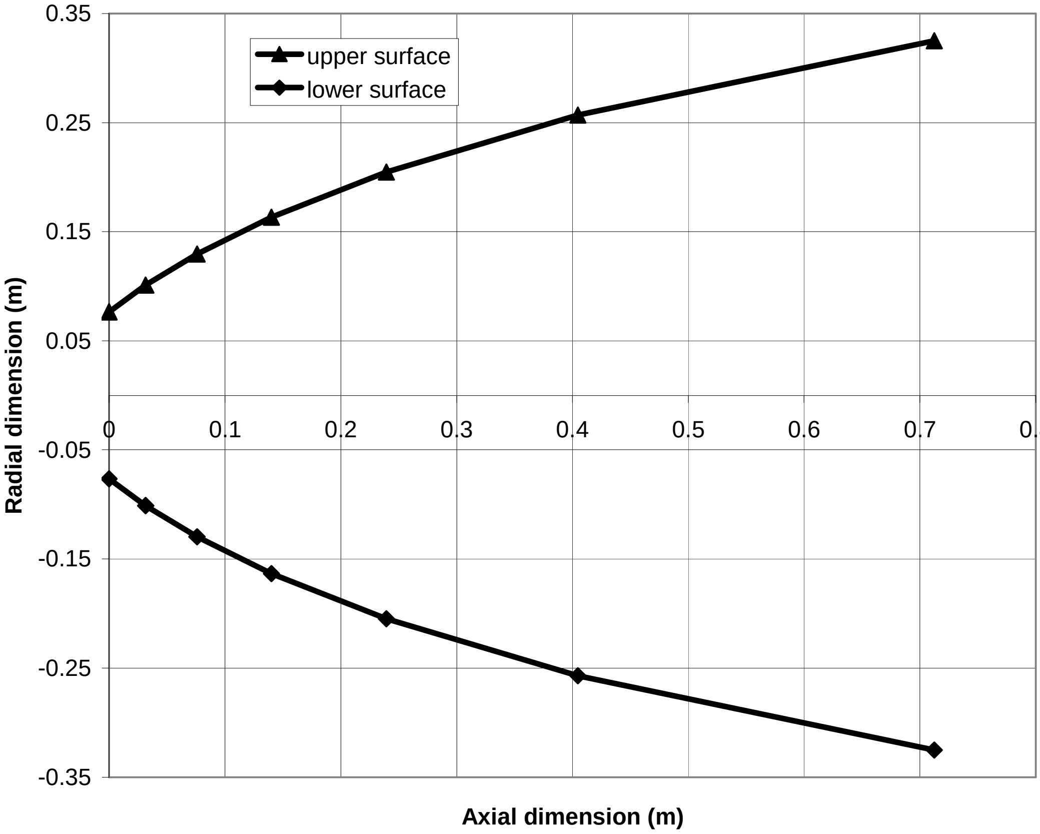

Fig. 1. 16:1 CPC cross-section

The circle was approximated by a dodecahedron (12 sided polygon), following [3].

2.2. Selection of reflective surface

Prior to the ray-tracing analysis, it was anticipated that a significant amount of heat would be absorbed by the reflective surface of the CPC, the extent of which depended on the type of reflective material used. Conventional household soda lime glass mirrors are 3mm thick and have the reflective coating applied to the back of the glass (rear surfaced) with a suitable protective layer. For light to be reflected using such mirrors, the incident ray must travel through the glass before striking the reflective surface and then the reflected ray must leave through the glass again, incurring absorption losses twice (not including internal reflections), decreasing optical efficiency and increasing heat load in the glass.

Using a front surfaced mirror would provide a better optical efficiency by preventing the issue of bulk absorption in the glass. As a result, this would decrease the heat load and cooling requirements. In the same vein, a high polished aluminium surface could by chromed, eliminating the need for mirrored glass altogether. This may lead to a greater reduction in the heat load than front surface mirrors, but this approach has its own set of disadvantages, the major issues being reduced starting reflectivity and the unknown rate and nature of reflectivity degradation when exposed to the environment over time.

Ultimately the rear surfaced mirror was opted for since it posed the least risk and the behaviour in its intended environment was well documented. Ideally the mirror should have a silver reflector coating (superior reflectivity compared to aluminium), it should be low iron glass since this reduces bulk absorption and should be as thin as possible (1-2 mm).

In the absence of locally available low-iron thin mirror glass suitable for solar applications, a supplier of 2mm soda-lime glass mirror was found, Clean Cut Glass. First, the spectral transmission through the mirror glass was determined. The protective paint layer on the back of the mirror was removed using paint stripper and thinners. The mirror coating layer was then removed using nitric acid. The transmission through three 50 mm by 50 mm samples were measured in a Cary spectrophotometer. The mean transmission of these samples is shown in comparison to a regular 2mm soda-lime glass sample (non-mirror application) from PFG in figure 2 (left).

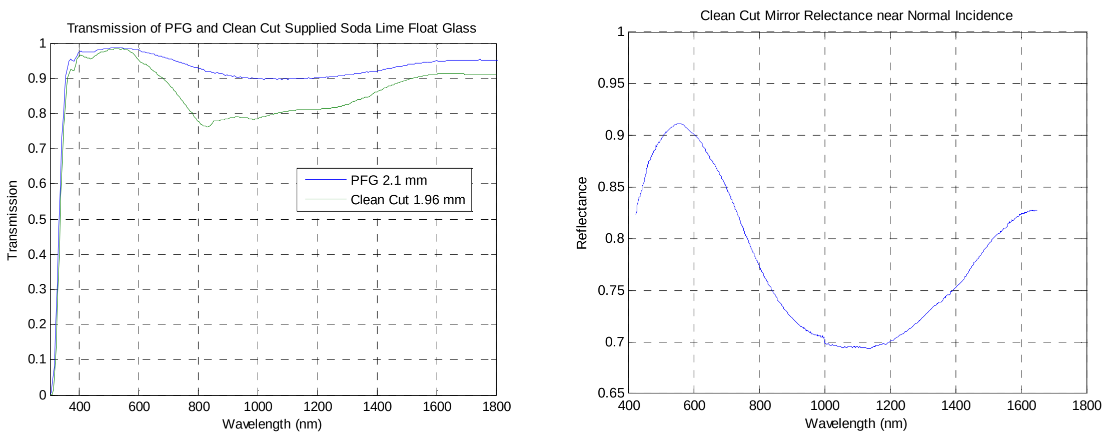

Fig. 2. Left: Comparison of transmissivity of PFG and Clean Cut Supplied Mirror Glass (300 nm to 1800 nm), Right: Measured reflectance of Clean Cut Mirror (420 nm to 1650 nm)

The reflectance of a 300 mm by 300 mm sample of the Clean Cut glass mirror was measured using a dual goniometer arrangement together with a uniform light source and an Analytical Spectral Devices (ASD) FieldSpec™ spectroradiometer. A 1° foreoptic was used on the ASD, and a large integrating sphere was used as the uniform light source. The measurement result for near normal incidence is shown in Figure 2 (right).

The required trapezoidal mirror geometries for the CPC were water-jet cut from 2mm sheets.

2.3. Heat load and cooling

2.3.1. Ray Tracing

The optical performance of the CPC design was modelled with a Monte Carlo raytrace using Zemax™. A flux tube of rays travelling from the heliostat to the secondary concentrator aperture was generated at a discrete set of wavelengths. The number of rays at each wavelength and the power carried per ray was chosen on the basis of a typical solar spectrum derived from the SMARTS [3] model. The solar spectrum and spectral transmission of the glass was used to determine the absorbed power in each facet, separately in the bulk of the material and at the reflective coating on the back of the facet. The overall efficiency of the concentrator was also determined using the raytrace data, and found to be 68.7%, and the flux absorbed in the mirror panels 28.9% (the remainder is rejected out of the entrance aperture as skew rays). The power distribution expected on the hemispherical calorimeter [6] could be determined by extending the raytrace through the exit aperture of the secondary concentrator to the absorbing surface of the calorimeter, and are shown in figure 3.

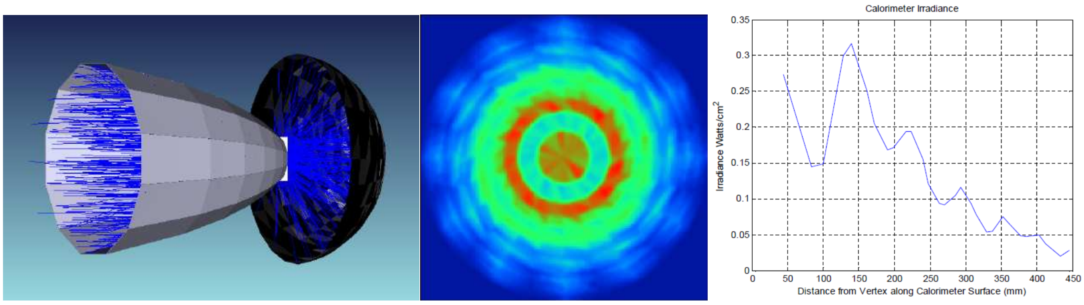

Fig. 3. Results of ray tracing analysis performed on the CPC - Left: CPC, calorimeter and light rays traced, Centre: irradiance distribution on calorimeter surface, Right: circumferentially averaged irradiance distribution per kW on calorimeter as function of distance from vertex

The predicted heat absorbed in each of the 6 facets is given in Table 1.

Facet no	W/kW	W total
1	8.9	211.4
2	5.4	128.3
3	3.6	85.5
4	2.4	57
5	1.8	42.8
6	2.1	49.9

Table 1. Predicted heat absorbed in each of the 6 facets

2.2.2. Cooling concept

The design of the thermal management system was inspired by the WIS [2, 3], and the 1st of the DLR [4] CPCs, where cooling channels were created by drilling holes into aluminium backing plates, 19mm and 20mm thick respectively. The CSIR approach was slightly different since one of the design constraints was that the CPC must be as light as possible (the 2nd DLR CPC concept with thin mirror glued to curved substrates was not regarded as a viable option until experience had been developed). This led to a sandwich construction concept, where a serpentine channel was cut into the centre 4.5mm aluminium sheet. The initial design was based heat loads on each facet assumed to vary in inverse proportion to the CPC cross-sectional area at each facet station. The criticality of these figures was soon realised and a more accurate method of attaining the expected heat load was required. As a result ray tracing was performed on the system .

A crucial aspect affecting the ultimate temperatures seen by the mirror facets is the selection of an adhesive to bond the mirror to the aluminium sandwich containing the cooling channel. A highly specialised adhesive was required, one that had a high enough thermal conductivity to result in a small enough temperature gradient across the adhesive layer and therefore acceptable mirror temperatures for a given coolant flowrate, preventing thermal stress and breakage. Two investigations were conducted simultaneously:

- a search for a commercial adhesive with suitable conductivity
- an investigation into the possibility of manufacturing a suitably conductive adhesive

Research in this field has been conducted although not widely published. It is suggested [8] that a high conductivity adhesive can be made by mixing aluminium shavings into an epoxy using a vacuum oven with mechanical mixing. The problem was that a simple issue such as the rotational speed of the mixer could be detrimental to the characteristics of the adhesive due to air ingress. Specific information of this nature could not be found in literature. Another problem to which there is no definite solution is the difficulty of attaining a uniform solids packing density. If this is not consistent, the thermal conductivity would be inconsistent which would be detrimental to the secondary concentrator. Furthermore, neither the thickness nor the thermal conductivity was guaranteed with this process.

From the ray tracing, the percentage of incoming radiation absorbed on each facet was obtained. It was also noted that the most critical area was the last two segments before the exit aperture since they experienced the highest absorbed flux. This implies that the highest temperatures would be experience here and the cooling requirements were most crucial in this region. Using the absorbed flux data generated, the cooling parameters of the thermal management system were recalculated. Sensitivities were carried out on the effect of the cooling water flowrate and the thickness and thermal conductivity of the adhesive on the glass temperature. It was found that the thickness and the thermal conductivity had the greatest effect and thus became criteria for selection of an effective adhesive. Ultimately an adhesive in the form of a double sided tape was found with a guaranteed thickness of 100 microns and a thermal conductivity that ensures a mirror temperature comfortably below its threshold.

2.4. CPC mechanical design and construction techniques

It was initially decided that a sandwich type approach would be taken in the assembly of the CPC but a number of possibilities still existed in putting together the constituent components of the concentrator. One example was the decision either to have the metal cut into individual facets and welded together or to have entire segments cut and kinked (mechanically bent) to the required angles. Another area where complications were envisaged was the alignment of the various layers, from the stainless steel backing plate to mirrors. It was initially decided that guide holes would be drilled in order to align each piece. However, that would have raised the issue of sealing these holes and this option was therefore abandoned.

Instead it was decided to specify the length and width of each facet such that the edges meet. Therefore, for the mirrors to sit precisely in place leaving no gaps between facets, the lengths and widths of preceding sections needed to be cut exactly to specification to ensure that they aligned precisely.

For the general construction technique, it was decided that the best method with the least risk would be to construct the secondary concentrator from the outside in. The stainless steel ribs, flanges and backing plates were laser cut with the ribs having the required angles within a tight tolerance. The ribs were welded together to form a frame. The stainless steel backing plate was cut into segments and kinked (folded) to the specified angles, and welded to the ribs. This was most critical since the rib dictates the shape and proper alignment of the subsequent sections. Figure 3 illustrates the abovementioned.

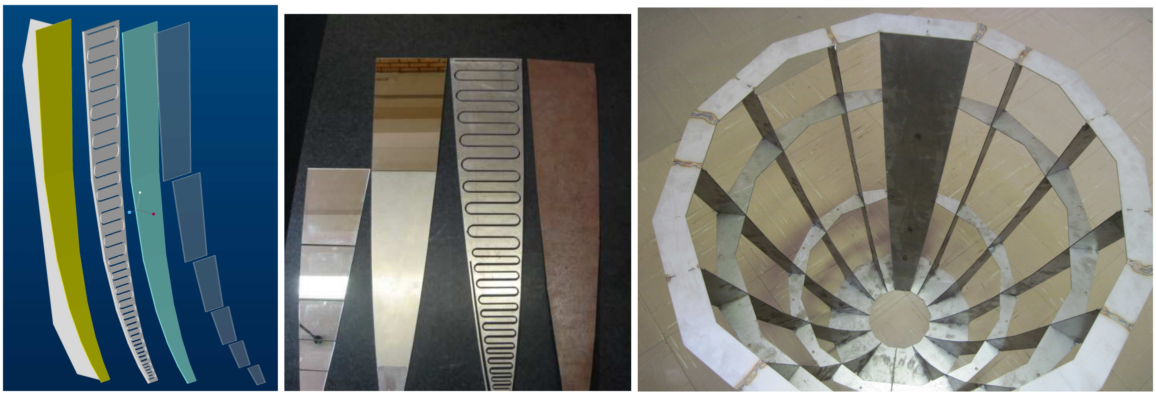

Fig. 3. Left: conceptual layup; Centre: mirror facets, thermal spreader plate, cooling plate and backing plate; Right: ribs welded into frame with 1 backing plate

The cooling channels were water-jet cut, since a trial done using laser cutting exhibited thermal deformation of the metal. This would make sealing problematic due to the inconsistency of the metal surface. A Loctite product was chosen to bond the cooling channel to the backing plate which also forms a seal. This was also used to bond the front of the cooling channel to the aluminium plate.

Pressure tests were conducted on a separate single segment. This was done to test the adhesive used to bond the stainless steel plate to the cooling channel. The concern here was that the very small adhesive bond surface area on the first and second facet of the cooling channel would not provide an effective seal. The test segment was found to leak under pressure. This problem was solved by using a specialised aluminium tape covering both sides of the cooling channels, thus:

- effectively sealing the coolant channel, and
- increasing the surface area for adhesion.

No leaks were found on testing.

It was decided that each of the twelve cooling segments would operate independently. The first facet (exit aperture) sees the highest concentrated solar flux inside the CPC, and possible significant thermal reradiation from the target (volumetric receiver or solar fuel reactor). The circular coolant inlet manifold cannot therefore be close to the exit aperture (otherwise the coolant water would be preheated). As a result, the cooling system was designed such that the inlet would be situated at the top of the fourth facet, flowing down to the first segment and all the way up to the entrance aperture.

Fig. 4. Left: Complete frame and backing plates, Right: CPC view from above with all mirror facets temporarily in place

2.4. Outstanding work

To bond each of the layers in turn, use is to be made of laser-cut wooden forrners which will force each layer with adhesive in turn against the previous outer layer until the adhesive is dry. Each of the different layers have been laser-cut and “kinked”, bonding will proceed shortly. Thereafter the cooling manifolds will be added and the CPC will be tested in a beam-down facility containing the calorimeter.

5. Conclusion

Mirror characterisation, ray tracing, adhesive selection and construction procedures development have been completed for the first South African CPC. Experimental testing will prove to be the final validation of the design.

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