Abstract

The uniformity of the radiation flux profile along the focal line of a linear parabolic concentrator is typically dependent on factors such as the mirror shape accuracy, gaps between mirrors and shading due to receiver supports. For a photovoltaic trough concentrator, small regions of low radiation flux can have a large impact on the entire system performance. Radiation flux profiles have been measured on the Combined Heat and Power Solar Collectors developed at the Australian National University. The results for the first prototype showed significant variation in the radiation flux intensity along the length. The effect of imperfections in the mirror shape has been studied using ray tracing techniques and the software package Opticad. The simulations allowed the individual effects of mirror shape imperfections, gaps between mirrors and shading to be examined. It was found that small variations from the ideal mirror shape could cause large variation in the longitudinal radiation flux profile. Finally, techniques to minimise the drop in performance of a PV concentrator due to flux non-uniformities are discussed, including use of bypass diodes, and choice of solar cells.

INTRODUCTION

The Centre for Sustainable Energy Systems (CSES) at the Australian National University (ANU) has developed a photovoltaic/thermal (PV/T) collector with geometric concentration ratio of 37x. The so-called Combined Heat and Power Solar (CHAPS) collectors consist of glass-on-metal mirrors that focus light onto high efficiency monocrystalline silicon solar cells to generate electricity. Fluid flowing through a conduit at the back of the cells removes most of the remaining energy as heat, which can then be used for building heating and domestic hot water. The CHAPS collectors track the sun on a single axis, and may be oriented in any direction.

One of the main challenges in designing a concentrator PV system is to achieve an acceptable radiation flux distribution. Because the CHAPS system is a linear concentrator, the impact on flux profile due to gaps between mirrors and receiver support posts is not confined to a particular area, but shifts along the receiver as the incidence angle of the sun’s radiation changes as the sun moves across the sky. Non-uniformities are compounded by mirror shape error, which, though the errors are small in magnitude, has a significant effect on the flux profile, and the electrical performance of the array. The passively cooled EUCLIDES™ array in Tenerife (Sala et al., 2000) is the only other large scale PV concentrating parabolic trough system. The effect of optical imperfections on the EUCLIDES™ array performance is discussed by Anton et al. (2000), and was significant enough to warrant trials of a secondary concentrator.

Focal region measurement is mostly carried out using videographic flux mapping techniques, whereby a charge coupled device (CCD) video camera takes images of the focal flux projected onto a target. Johnston (1998) gives an excellent technical summary of this technique and previous work in the area. Another technique for measurement of the flux profile of a parabolic trough was recently developed by Riffelmann et al. (2003) using an array of photodiodes. This sensor has been used to assess the performance of the EUROTRough parabolic collectors at the Plataforma Solar de Almería. The radiation flux distributions presented in this paper have been measured using a custom built device that uses a calibrated photovoltaic solar cell to measure short circuit current in the focal line of a
An investigation of non-uniformities in the longitudinal radiation from a parabolic trough, from which the flux profile can be determined. This technique has the advantage for a PV concentrator that the cell has the same dimensions of the cells mounted in the receiver. Therefore, less post-processing is required and as the current is measured directly, a more accurate result could be expected.

The impact of the longitudinal flux non-uniformity on the performance of a PV concentrator is discussed, and investigated further through focal region modelling using ray-tracing techniques in OptiCAD.

MEASUREMENT OF THE LONGITUDINAL RADIATION FLUX PROFILE

A device, known as the ‘Skywalker’ module, was designed and built for measuring the illumination flux profile along the focus of a receiver. The Skywalker module consists of a calibrated concentrator solar cell mounted on an aluminium block and encapsulated with silicone and glass. The short circuit current of the solar cell is measured across a resistor, mounted on the back of the block. Water flows through channels milled into the block to keep the cell at a consistent temperature (figure 1), which is measured by a thermocouple mounted in the aluminium behind the cell. Using results from the solar cell calibration, the radiation flux intensity at the cell can be calculated.

![Skywalker cell mounting block, showing the 5mm deep cooling channels.](image)

The block is mounted on a trolley that is moved along the focal line of the collector by a motor and pulley system (figure 2). A potentiometer measures the position of the trolley. LABVIEW™ is used to move the trolley, collect position and short circuit current data, and process and display the results.

![The so-called ‘Skywalker’ module (left), mounted on a trolley at the focus (right).](image)
RESULTS FROM THE SKY WALKER MODULE

In the case where radiation is incident upon the mirror at an angle away from the surface normal, the effect of the gap between mirrors and the receiver support arms becomes significant. This has been investigated for a range of incidence angles using the ‘skywalker’ device. The results are shown in summary in figure 3.

The salient features of the flux profile are seen to move along the focal line as the angle of incidence changes. This is one of the most difficult aspects of single-axis tracking linear PV concentrators. It is not possible to isolate the problem areas and treat them specially. For example, if the region of low illumination were always at the end of a receiver, then it is likely that overall efficiency would be improved by the absence of solar cells in this region. However, while the deepest dips in the flux profile occur near the ends of the receiver when the sun is near perpendicular, at other times the dips are near the middle of the receiver, and solar cells at the ends do contribute significantly, as can be seen in figure 3.

The cause of the deepest dip in the flux profile is a combination of shading due to the receiver supports, the small gap between the mirrors, and the high slope error at the ends of the troughs. The relative significance of these factors is discussed later in the paper.

Attenuation of peaks and troughs

The magnitude of peaks and troughs in the illumination profile at the focus could be expected to be attenuated somewhat due to the single short-circuit current reading for the 50mm long solar cell
effectively averaging the illumination. This was investigated experimentally by masking the solar cell at the focus of the ‘skywalker’ device, all bar a narrow slit of 1.5mm.

Figure 4. Comparison between ‘skywalker’ results with a 50mm long cell and a 1.5mm long cell.

Figure 4 shows the close similarity between the full cell data and the masked cell data with a moving average over 50mm, and confirms the flux profile is the same for the two measurements. Significant variation in the illumination profile is observed, particularly in the region under the influence of the mirror gap and support post shading (seen close up in the bottom graph in figure 4). The peaks and troughs in illumination are deep, and it is therefore fortunate that the 50mm long cells used in the receiver do provide some illumination ‘smoothing’.

ANALYSIS OF THE FLUX PROFILE USING OPTICAD

Geometric ray tracing can be used to simulate an optical system such as a parabolic trough collector. OptiCAD, a commercial computer program for ray tracing (Opticad Corporation, 2001), has been used to simulate the flux profile at the focus of a GOML similar to that analysed in the previous section.

Preliminaries

The sun source is modelled in OptiCAD as a ‘pillbox’ shape, with half-angle set to 4.65 mrad. This means that all radiation coming from within solar disc is assumed to be of equal intensity, and that no radiation originates from outside the solar disc. Figure 2 shows a comparison between the flux profile at the focus of a trough from a ‘pillbox’ sunshape and a real sunshade at a circumsolar ratio of 5%. The OptiCAD studies focus on the flux profile longitudinal to the receiver, and for these purposes the pillbox profile is adequate.
OptiCAD allows three-dimensional surfaces to be defined then positioned and oriented in a global coordinate system. Predefined shapes such as parabolic troughs and rectangular films can be used to simulate a geometrically ideal concentrator. Individual objects may have surface properties defined, such as the degree of reflectivity or the amount of radiation scattering. A non-dimensional study has been carried out, and therefore properties that affect just the magnitude of the reflected flux profile are not important, and are set to the OptiCAD default values.

To simulate the measured mirror shape, a multifaceted mirror (called a polynet in OptiCAD) has been defined. The polynet is made up of continuous groupings of individual triangular polygon facets. The number of facets is determined by a tradeoff between the desired optical accuracy and the processing time and software limitations of the program. Figure 3 shows the radiation flux profile for a range of faceted mirrors. It was decided that at least 150-200 facets across the width of the mirror are required to give a flux profile that matches the ideal case with suitable accuracy. For 200 facets, 80% of radiation flux falls underneath the pillbox shaped flux profile and over 90% within the ±7mm width of the pillbox shape. The remainder of radiation falls within ±12 mm, which is well inside the ±20mm width of a cell.
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Method developed by Johnston (1998), with accuracy estimated to be 20-40 microns. Figure 4 shows the shape error of one of the troughs, which is the difference between the measured z-coordinates and those calculated for a parabolic trough fitted to the data using a least squares technique.

![Figure 4. Deviation from a perfect parabolic trough.](image)

Maximum deviation from the ideal shape is in the order of 1 mm, and the majority of the mirror surface is within 0.4 mm. Due to constraints in the photogrammetry process, the mirror is measured at around 70 points across the width and 60 points along the length, and therefore some interpolation is required. Two interpolation schemes were assessed: linear interpolation (first interpolating across the width of the trough, then across the length) and a triangle based cubic interpolation, performed using Matlab. It was found that the difference between the two interpolation schemes was minimal, and therefore the simpler linear interpolation was employed. Another constraint in the photogrammetry process meant that it was not possible to measure a row of points right at the very end of the mirror. Unfortunately, the ends of the mirror have the largest slope error, and it was found that the last 50mm at either end of the mirror has a significant effect on the flux profile in the critical area of lowest flux.

To extrapolate right to the ends, the slope of each row of points in the longitudinal direction was used. The extrapolated data was compared to intermittent measured data at the ends to check the accuracy of the extrapolation. No smoothing scheme is employed for the mirror shape data, as the salient features, specifically the noticeable troughs and peaks, are outside the error expected by the photogrammetric measurement. The intervals between points are split into three in both the longitudinal and transverse directions. Therefore the trough is modelled by a polynet with around 210 points across the width and 180 points across the length. A cell target 40mm wide is placed at the focal point, and a further sheet simulating the receiver cover is placed slightly above the focal point. The gap between the mirrors has kept as small as possible, but there remains a 19mm gap between the mirror glass. The receiver support arms are made from 10 x 25 steel bar, supported from outside the mirror, shown in figure 5.

![Figure 5. Support arm geometry](image)
Validation of the ray tracing

A comparison is made between the flux profile predicted by ray tracing and the measured flux profile for a GOML mirror, as shown in figure 6.

![Diagram showing comparison between measured and predicted radiation flux profiles](image)

Figure 6 demonstrates that there is a significant difference between ray tracing from a perfect parabolic mirror and from a ‘real’ mirror. Where there is a dip in the ‘perfect’ trough profile, there is a peak in the ‘real’ trough profile. The dip in the ‘perfect’ trough profile corresponds to the position where you would expect a dip based on the position of the sun and the gap between mirrors. However, as both the measured data and the modelled data using the ‘real’ trough shape show, there is a peak. The reason for the peak is that the significant slope error at the ends of the troughs creates a kind of ‘pseudo concentrator’, as shown diagrammatically in figure 7. The flux profile created by ray tracing using the ‘real’ mirrors shows reasonable agreement with the measured profile. The magnitude of the peaks are not perfectly matched, however given the sensitivity of this area to the mirror shape at the ends of the mirror, the error is to be expected. Importantly, the peaks and dips coincide in position for the simulated and measured data, and the magnitude of the deepest dip is reasonably well predicted. It can be concluded that the ray tracing is a useful tool for predicting flux profile if the measured mirror shape is used, but not if a perfect mirror is used.
Analysis using ray tracing results

The aim of the ray tracing simulation was to identify the cause of the non-uniformities in the measured flux profile, and in particular, to determine what causes the deepest trough, as this has the most effect on the overall electrical performance of a PV concentrator. Figures 8a-d show the results of comparisons between a perfect parabolic trough (the dotted lines) and the simulated 'real' trough for all combinations of receiver supports and gaps between mirrors. The first 600 mm from the end of the mirror is shown, in order to focus on the region affected by the gap and the receiver support.
Figure 8a shows the flux profile that could be expected if there was no gap between the mirrors and no receiver support. For all angles, a pronounced hump can be seen in the flux profile for the position corresponding to the end of the mirror (i.e. for 0°, 4°, 8°, 12°, 16°, 20° the positions are 0, 59, 119, 180, 242 and 308 mm from the end of the receiver respectively). This further confirms the result discussed in section 0. However, a very interesting corollary can be drawn by direct comparison of figure 8a and 8c, as shown in figure 9. In all cases the illumination at the point corresponding to the gap between the mirrors is not the minimum. Moving the mirrors apart has the effect of reducing the peak at this point. Eventually, of course, if the gap is large enough then there will be a corresponding gap in the flux profile. Modelling indicates that for the mirrors measured, a further 10mm gap would be possible before the concentrating effect of the pseudo-focus due to the sloped mirror ends is negated. However, while the general shape of the curve on either side of the hump in figure 9 is similar for the gap and no gap cases, there is a slight decrease in the magnitude of the lowest dip when there is a gap. Therefore there remains some advantage in further minimising the gap.

The effect of the receiver support can be seen in figures 8b and 8d, but is a little obscured by the interference due to the mirror end effects. Unlike for a 'perfect' mirror, the shading due to the support for 'real' mirrors is significant, particularly for incidence angles around 4° to 8°. An unavoidable consequence of the 'pseudo-focus' at the mirror ends is that there will be a region on either side of the hump that has lower illumination than average. The radiation has to be 'stolen' from somewhere, and in effect light that is incident on this curved section at the end of the mirror is spread out along a greater length of the receiver, and hence the concentration ratio is reduced where there is no superposition of light from the adjacent mirror. When there is no receiver support, the dip is larger on the side nearest the mirror end (figs 8a & 8c). When there is a receiver support, for incidence angles up to about 10° the coincidence of the position of the dip on the side of the hump furthest from the mirror end and the shade due to the receiver support causes the minimum radiation in the flux profile (figs 8b & 8d). For larger angles, the impact of the receiver support shading ‘smears’ along the focus and becomes less significant, and the largest dip occurs on the other side of the hump closer to the
mirror end.

Figure 9. Comparison between flux profiles with and without a gap both without shading from the receiver support (left) and with the receiver support (right).

IMPROVEMENT OF THE FLUX PROFILE

The results of the ray tracing indicate that further reduction the gap between mirrors would marginally improve the electrical performance of the CHAPS collector. However, the mirrors are held in shape at their ends by tabs stamped into sheet metal, and it is therefore not possible to reduce the distance between mirrors with the current design. The EUCLIDES™ system supports the mirrors from behind, and is therefore able to achieve an average of 4mm spacing between mirrors (Anton et al., 2000). However, the stamped tab rib design is integral to the low cost and high optical accuracy design of the mirrors. The results above show that some convexity in the mirror shape improves the flux profile around the mirror gap (when compared to the perfect mirror), but that the convexity is a little too severe. Investigations continue into methods of optimising the mirror shape in the manufacturing process to more precisely compensate for the mirror spacing.

MITIGATION OF THE EFFECT OF AN UNEVEN FLUX PROFILE

One possibility for mitigation of the effect on electrical performance of regions of low illumination is to use higher quality solar cells in these areas. Figure 8 shows that the lowest dips in illumination occur at small incidence angles in the region close to the end of the receiver. Therefore, cells with higher than average maximum power currents should be installed in these regions. In the early production runs of the ANU solar cells it has been found that the maximum power current at 30 suns and 65°C has roughly a normal distribution with an average current of 18.6A and a standard deviation of 0.35A. The distribution is not very wide, however the best cells at the ends of the receivers are compared to the worst cells in the centre, and therefore there should be a few cells at either end of the receiver around 5% better than the worst cell in the centre.
USE OF BYPASS DIODES TO IMPROVE PERFORMANCE

Bypass diodes are usually applied to protect shaded solar cells from breakdown under reverse bias. Woyte et al. (2003) presents a literature review of work in the area of optimising PV module design and determining the maximum number of solar cells per bypass diode to avoid the formation of hot spots. For the CHAPS collector, it would be feasible to use a single bypass diode to protect all 28 cells in a receiver. However, bypass diodes may also be used to optimise the overall performance of the collector by shunting sections of a receiver that are adversely affected by shading and therefore limiting the current of the rest of the collector. As was shown in figure 8, the region of a receiver with the lowest illumination tends to be near the end. Therefore a diode has been incorporated across three cells at either end to allow this region to be bypassed if the overall performance is significantly affected. The maximum power point tracker determines the operating current and voltage for the array. If the end cells have significantly lower than average current, the it is possible that the maximum power current will be closer to the current of the unshaded cells, and hence the end diode will switch on. However, while there is an increase in current, there is a reduction in voltage due to the missing cells and the bypass diode voltage drop, and therefore in practice, the diode only comes on if the minimum illumination on these cells is significantly lower (~12.5%) than the least illuminated cell in the remainder of the receiver.

Due to the geometry of a single axis tracking concentrator, for much of the day, the receivers at the end of the array will be partially illuminated. Rather than lose the output of a whole receiver, it is better to have bypass diodes positioned across smaller groups of cells. A diode plan with five diodes is used for the CHAPS receivers (3-7-8-7-3 across the 28 cells), which allows a standard manufacturing technique for each receiver, and a reasonable balance between performance and cost.

CONCLUSION

Detailed analysis of the radiation flux profile of the CHAPS system has revealed that a small shape error in each mirror can have a significant impact on the system performance of a PV concentrator. Ray tracing studies showed that pronounced convexity near the ends of the mirrors causes a peak in illumination in the region where a dip might be expected because of the gap between the mirrors. However, while it is an advantage that the light spreads out across the gap, in the two regions adjacent to the peak where there is no superposition of light from the adjacent mirror, dips in the flux profile occur. One of these dips is always the minimum point in the radiation flux profile for the receiver (which one depends on the incidence angle). To slightly offset the impact of the lower flux, cells with higher maximum power current can be located at the ends of the receiver where the largest dips occur.

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REFERENCES


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