DESIGN CHALLENGES IN POINT-FOCUS SOLAR COLLECTORS: OPTICAL ERROR ANALYSIS AND THERMAL PERFORMANCE VALIDATION

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Abstract

This paper addresses the challenges involved in constructing inexpensive point-focus solar concentrators and validating their performance. Construction errors in low-cost point-focus concentrators result in optical and pointing errors. A principle design challenge is minimizing these errors so as to reduce the spread at the focal point and optimise the concentration ratio. A supplementary challenge lies in the characterisation of thermal performance at the concentrator's focal point, which may be addressed using calorimetric and/or radiometric techniques. Further complexity is introduced when two-dimensional characterisation of the focus is required to determine the peak flux position and the sharpness of the resulting hot spot. This paper will address the issues of optical error characterisation in point-focus solar concentrators as well techniques to validate thermal performance.

Keywords: point-focus; construction; slope errors; performance characterization; calorimeter

1. Introduction

An important factor affecting the performance of a point-focus solar collector is the accuracy of the reflective paraboloidal surface. While a range of construction methods may be followed in producing reflective surfaces, the lower cost approaches inevitably lead to a reduction in performance due to the use of non-specialised equipment. A limited performance reduction may be acceptable if the trade-off against mass or cost is justifiable. A supplementary challenge is the development of accurate and inexpensive high-flux measuring devices. This paper aims to discuss the difficulties involved in the construction of inexpensive point-focus concentrators and high-flux measuring devices.

The complex geometries of point-focus concentrators constrain the methods available for accurate construction. To date, parabolic dishes have dominated point-focus developments using expensive CNC lathe construction processes such as diamond turning of aluminum [1, 2]. Advantages of using such methods are the proven accuracies in the region of 0.1 mrad and good rigidity properties [3]. Other, inexpensive dish construction methods include using flat mirrors with composite materials to form a segmented paraboloidal concentrator [4]. Alternative research in point-focus technologies, such as the ring-array concentrator, has demonstrated accurate construction techniques comparable to that of parabolic dishes. The ring array configuration comprises a set of nested paraboloidal elements, each designed to reflect incoming solar rays to a common focus (Figure 1). The developers of the ring array used a centrifugal forming process to construct the reflective elements [5]. This is a preferred method owing to the axisymmetrical geometric properties of the resulting elements, however it is expensive and requires complex construction techniques. The Sustainable Energy Research Group (SERG) at the University of KwaZulu-Natal (UKZN) demonstrated an inexpensive, composite material ring array concentrator construction technique discussed in this paper [6].

Another field of solar research in need for development is the measurement of high-flux concentrations. The measurement of energy flux is required to characterise the performance of a point-focus solar concentrating system. Several devices have been developed for high-flux solar measurements, including calorimetric and radiometric techniques [7,8]. Calorimeters use energy balance methods to obtain estimated flux concentrations incident on the receiving surface. The methodology includes determining the heat absorbed by a heat transfer fluid flowing through the calorimeter body, by measuring the change in temperatures at inlet and outlet [9]. Considerations for this technique include minimizing uncertain measurements pertaining to mass flow rate of the fluid and rise in temperature at calorimeter exit. Estimated modeling of heat losses due to convection and radiation is needed when the receiver plate does not approximate ambient temperature. Other more expensive instruments used for measuring heat flux are CPV cells [10] and radiometers, such as the Gardon gage [11]. Operating principles of the Gardon gage include measuring the radial temperature difference of a circular foil disk using a differential thermocouple. The disk is machined from constantan and attached to a cylindrical copper heat sink. Material properties of the assembly produce a 10mV maximum output that is directly proportional to the absorbed heat flux. The advantage of using the Gardon gage for high-flux solar measurements is its short time response of less than one second which makes it an attractive device for experimental procedures. In comparison the inexpensive approach of using calorimeters requires processing of the experimental results before obtaining flux measurements.

This paper focuses on addressing the challenges in developing inexpensive point-focus concentrators, with particular emphasis on ring array technology. In addition this paper looks at previous developments for the inexpensive measurement of high-flux solar energy and gives potential improvements to increase the efficiency and accuracy of the results.

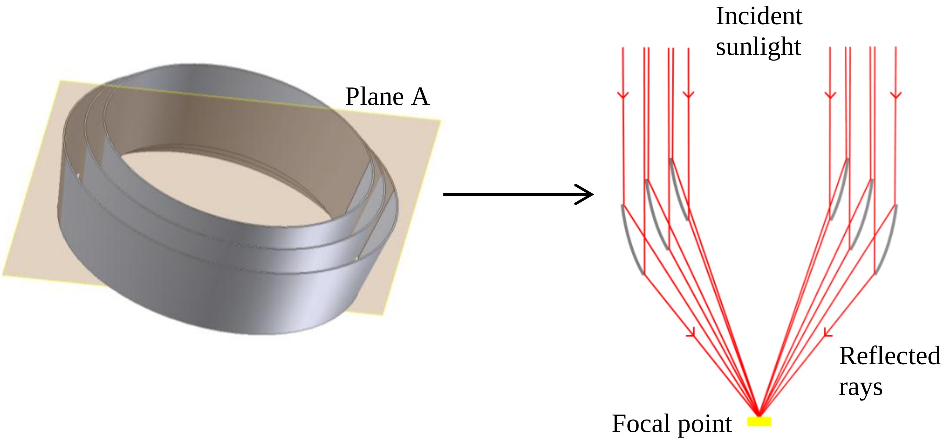


Fig. 1. Typical paraboloidal elements of a ring array concentrator with plane A illustrating the cross-sectional profile of three elements and single stage reflection to a common focal point.

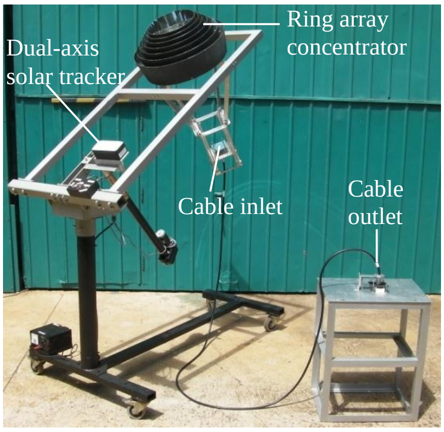
2. Previous work on inexpensive point-focus concentrators

2.1. Point-focus concentrator: ring array configuration

A point-focus concentrator in the form of a ring array configuration has been demonstrated to provide high-flux concentrations [6]. The study aimed to design and construct a concentrator to inject concentrated thermal energy into a fibre optic cable for high-flux applications. The solar thermal concentrating system is known as the Fibre Optic Concentrating Utilisation System, (FOCUS) and has been developed at the University of KwaZulu-Natal (UKZN) to provide thermal input to high temperature processes. The system is intended for use in a university ISRU program, primarily to demonstrate the melting of a lunar regolith simulant at 85 W/cm^2 for oxygen production. The optical system consists of three key components; the ring array concentrator, fibre optic cable and a solar tracking system (Figure 2).

The construction aim of this research was to construct a prototype low-cost solar concentrator of the ring array design. Polymer matrix composites in the form of fibre reinforced plastics (FRP) were used as the materials for construction of the reflective elements. A composite material hand lay-up method was employed for the construction of each element, which is formed from a matrix material and two reinforcement materials to produce a FRP composite. The matrix material is a thermosetting polymer and distributes the stress to the reinforcement materials, providing the final shape of the element [13]. The detailed construction method is documented by Mouzouris and Brooks [14]. Each reflective element was constructed using a pre-machined paraboloidal mold in conjunction with a composite material vacuum-bagging process to allow the reflective surface to form the shape of the paraboloid (Figure 3). The concentration of sunlight with a completed reflective FRP element is illustrated in Figure 4.

A slope error analysis of the ring array concentrator was conducted to confirm the match between the ideal geometry required and the realised geometry obtained through the composite material construction process. Results yielded slope errors ranging between 2.90 mrad – 5.67 mrad with a direct correlation between the size of the reflective ring and the scale of surface slope error. Several factors can cause surface errors in the constructed elements, as well as variation in error between individual elements constructed using the same method. For one, the manual hand lay-up, vacuum bagging process permits variation in the nature and extent of distortion, and can explain the range of slope error results. Resin and fibre volume fractions characterise the quality of each laminate and although a low resin laminate was desirable, the quality of the resulting part depends on the skills and consistency of the laminators. Due to the unique nature of hand lay-up processes it was difficult to produce high fibre volume fractions for the seven separate vacuum bagging processes, which potentially caused the range of errors between elements. Improved slope error results in the smaller ring elements suggests that due to the decreasing curvature, smaller elements require less shaping and pressure forming of the flat reflective aluminum to form a paraboloid. In addition the characteristic double curvature of the paraboloidal surface creates a complex manufacturing geometry in which material fibres are less likely to adhere accurately to the mold shape. The slope error results suggest that ring array designs should ideally comprise reflective elements with reduced curvatures if hand lay-up, vacuum bagging methods are employed. A thorough analysis of structural distortion during curing of the composites could lead to better lay-up design and material selection. These and other improvements could reduce surface slope errors and increase overall optical efficiency of the concentrating system.



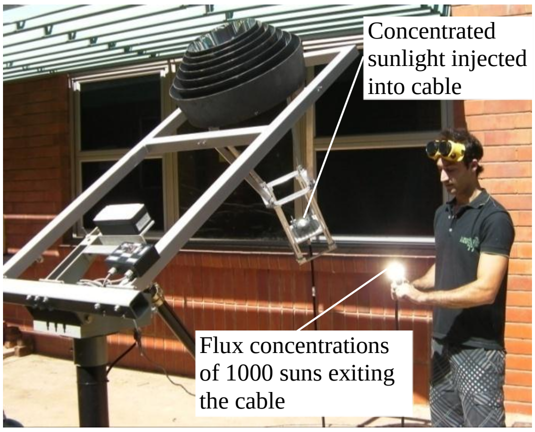


Fig. 2. FOCUS consisting of a ring array concentrator integrated with a fibre optic cable to provide high-flux levels remote from the collector (left). FOCUS in operation, concentrating incoming solar rays into a fibre optic cable (right).

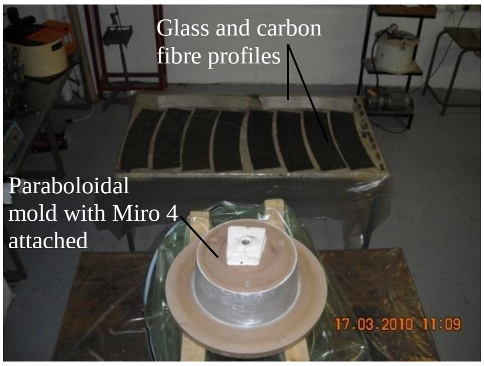


Fig. 3. Pre-vacuum bagging process showing the Miro 4 aluminum attached to the paraboloidal mold. Glass and carbon fibre profiles were hand impregnated with resin for the hand lay-up process (left). A vacuum bag is applied to improve consolidation and allow for additional pressure forming of the aluminum on to the paraboloidal mold.

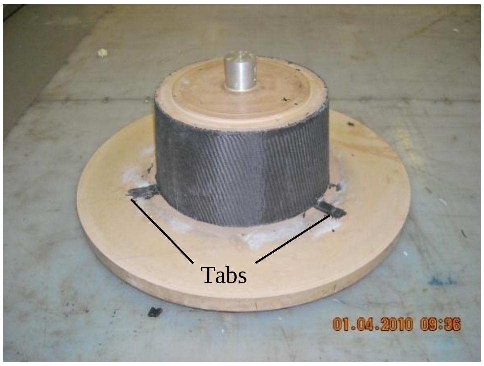


Fig. 4. After the vacuum-bagging process is completed the completed FRP element is detached using tabs (left). A completed reflective element focusing incident rays to a point (right).

2.1. Point-focus concentrator: dish configuration

A common practice for the construction of inexpensive parabolic dishes includes using uniform flat mirror facets attached to a paraboloidal framework. This segmented construction method has been demonstrated by Johnston [4] who designed and constructed a 20m^2 parabolic dish using composites to achieve a surface slope error of 2.0 mrad. The concentrator consists of 2300 flat mirrors glued on to a fiberglass shell that was cast on a paraboloidal mold. Performance results at beam irradiances of 1000 W/m^2 showed power levels of 14.8 kW intercepted at the focal point with a peak concentration of 970 suns. The flux map showed an expected non-Gaussian distribution with a flat, uniform peak concentration area due to the segmented flat mirrors reflecting uniform beam concentrations at the focal plane. This provides uniform concentrations with dimensions dependent on the flat mirror sizes. Possible optimization to increase the concentration ratio includes using thinner, pliable reflective surfaces to form an approximate continuous paraboloid surface. This should minimise surface slope errors and generate a characteristic “bell curve” flux map.

Further research has been documented on the effect facet size has on the performance of point-focus collectors [16]. The research showed a ray tracing analysis, based on a convolution technique, has been developed to optimize the radiative flux distribution at the focus. The results showed for a set area, maximizing the amount of facets increases concentration ratios. The concentrator optimization model was applied in designing a high radiative flux furnace to achieve maximum peak concentrations with cost considerations [17]. The geometry for the concentrator framework was chosen considering different configurations of flat, parabolic and spherical shapes. Simulations for a spherical framework configuration demonstrated similar performance characteristics to a parabolic shape with potential reduced construction costs. The proposed optical design comprises 409 hexagonal mirrors, each with 40 cm apothem, mounted on a spherical frame to generate a power of 30 kW with concentration levels exceeding 10 000 suns. The research demonstrates a mirror-facet concentrator optimization tool for point-focus optical systems considering construction limitations and expected performance results.

3. Previous work on inexpensive thermal performance characterisation

3.1. Calorimetric techniques

A high-flux solar measuring device, in the form of a calorimeter, was constructed at UKZN to validate performance results of an optical system with cost savings estimated at one tenth the price of existing commercial radiometers [6]. The flat plate calorimter comprises a cylindrical outer casing machined from stainless steel which houses a nylon insulator, radial flow distributor and a copper receiver (Figure 3). The insulation material is Ertalon 66SA Polyamide which has a low thermal conductivity of 0.25 W/(m.K) to minimise heat transfer between the calorimeter body and water flow. The radial flow distributor threads into the cylindrical water passage and allows water to diffuse evenly on to the copper disc. A copper plate fastens on to the insulation and concentrically covers the distributor with a gap that allows water flow. The copper surface exposed to the concentrated energy is painted with NS7, a black matt paint which creates a rough surface to increase energy absorption. NS7 paint was assumed to have similar properties to the well characterised coating of Zynolyte paint due to their use in similar applications [15]. Six K-type thermocouples were used to obtain temperature distribution results in the copper plate and two T-type thermocouples for the water inlet and outlet measurements.

The use of the calorimeter allowed validating the high-flux concentrations entering a fibre optic cable with an inlet aperture of 6 mm diameter. The results were compared with a comprehensive ray trace analysis which incorporated the solar half-angle (0.265°), realistic specular reflection, misalignment errors and mirror slope inaccuracies. Experimental results of the inexpensive high-flux measuring device are showed in Figures 4 and 5. Measurements recorded were processed in an energy balance model to determine the realized flux concentrations entering the 6 mm diameter fibre optic cable. Figure 4 shows a representative set of steady-state temperatures reached in the copper plate and water passages after 3 minutes of testing, allowing the assumption of a constant source of beam irradiation. Results show a peak flux level of 1528 kW/m^2 at an irradiance of 850 W/m^2 corresponding to a concentration of 1798 suns (Figure 5). Test results approximate the ray trace model, however neglect to show peak flux levels possibly due to insufficient testing methods. A need to further develop and optimise inexpensive, calorimetric techniques is needed to accurately determine peak flux levels. A proposed method includes constructing a miniaturized calorimeter to potentially increase measurement sensitivity, accuracy and heat losses. In order to obtain 2D and 3D flux maps, the proposed calorimeter must be positioned incrementally along multiple cross-sections of the focal spot.

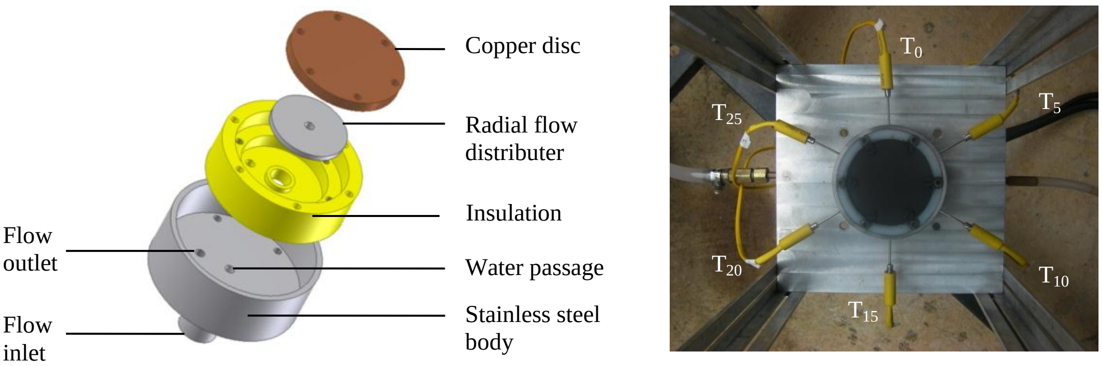


Fig. 3. The calorimeter consists of a cylindrical stainless steel outer casing that houses a nylon insulator, a radial flow distributor and the copper receiving plate (left). The assembled calorimeter with six radially positioned thermocouples in the copper plate, starting with T_0 at r = 0 mm, increasing anti-clockwise in increments of 5 mm, ending with T_{25} at r = 25 mm.

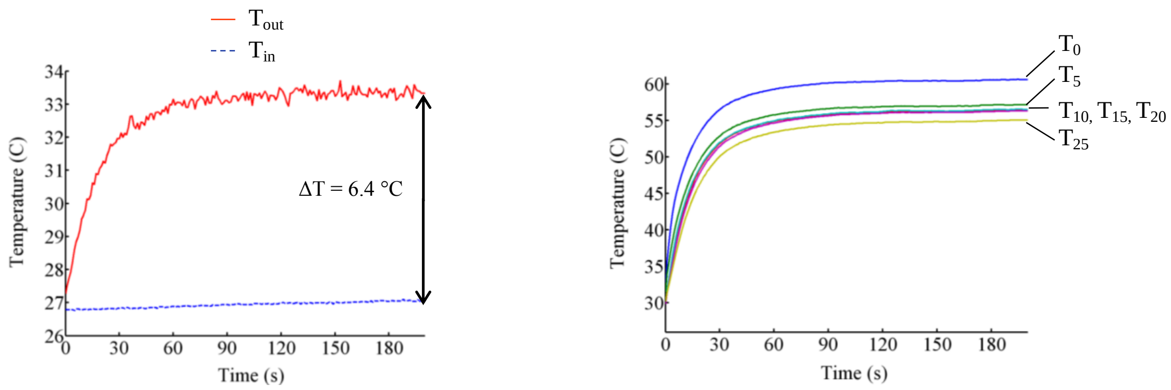


Fig. 4. Representative experimental results, showing a water temperature difference ($\Delta T = T_{out} - T_{in}$) of 6.4°C (left) and temperature measurements midway in the copper plate (right). The experimental procedure was conducted for three minutes allowing the temperatures to reach steady-state conditions.

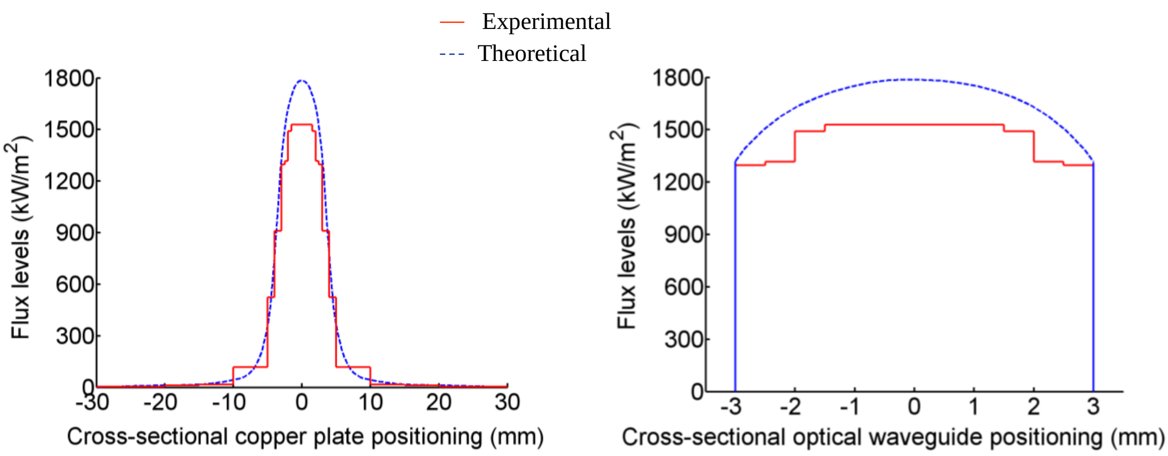


Fig. 5. Performance results at concentrator focus showing flux levels striking the full copper plate (left) and a magnified view of the 6 mm diameter fibre optic cable inlet (right). Theoretical and experimental results illustrate performance levels at 850 W/m^2.

3.2. Optimized calorimetric techniques

Supplementary calorimeter research for thermal performance characterisation is being conducted at the University of Stellenbosch. The calorimeter is intended for use with a small-scale 1.5 kW heliostat field. The optical system comprises an array of 150 mirror facets (100 x 100 mm) mounted onto a dual-axis rotating framework (Figure 6). The design of the flat-plate calorimeter differs from its predecessors [6-9] in that the rear body is solely made from Nylon PA6 C insulation with thermal conductivity of 0.26 W/m.K. This aims to further reduce the internal losses of the high-flux solar measuring device. A calibration procedure including a uniform electric power input device (mica resistance heater) was constructed to characterise the performance of the calorimeter (Figure 7). The experimental procedure included applying the flat mica resistance heater onto the copper receiver with the rear backing plate insulated with typical Rockwool insulation. Preliminary experimental results approximated a two-dimensional heat conduction model. On-sun testing using the small-scale heliostat field yielded a power of 900 W striking the calorimeter at a beam irradiance of 1000 W/m^2. A comprehensive energy balance was developed to model radiation and convection losses for estimating the incoming solar flux. A detailed description of this research is documented by Kretzschmar et al. [18].

Fig. 6. Experimental layout of the small-scale 1.5 kW heliostat field, comprising 150 flat mirrors mounted on a manual, dual-axis rotating framework.

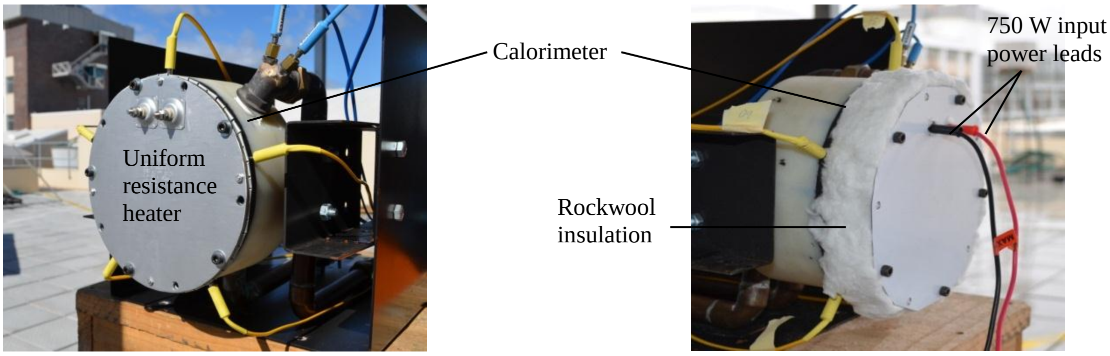


Fig. 7. Experimental setup for calibrating the calorimeter. The device was calibrated with a flat mica resistance heater and 750 W electric power supply which allowed characterizing the internal heat losses.

5. Conclusion

The successful construction of inexpensive point-focus solar concentrators has been demonstrated using composite materials and flat mirror facet techniques. Further work is needed to optimize construction methods aimed at decreasing optical errors and increasing concentration ratios. A supplementary challenge exists to characterize the incoming solar flux striking a receiver. Previous and current developments show that energy balance calorimetric techniques can be used as high-flux solar measuring devices.

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