The design and testing of a small scale solar flux measurement system for central receiver plant

Sebastian-James Bode,

Paul Gauche and Willem Landman

Stellenbosch University

Centre for Renewable and Sustainable Energy Studies

Abstract

In concentrating solar power systems radiant energy from the sun is directed onto a target using a collection of reflecting surfaces. The flux arriving at the target is then converted into usable form energy. This paper discusses a method developed at the University of Stellenbosch used to measure the incident flux on a target from a point focus, central receiver system. Details of the experimental apparatus and method are discusses and results of a number of preliminary experiments are provided. The system is loosely based on flux measurement systems found at larger central receiver plants. However, challenges faced by a smaller research facility differ to those of the larger plants and thus measurement system needs to be designed accordingly.

Keywords: *Ray tracing, heat flux measurement*, *CMOS camera*

1. Introduction

Concentrating solar power (CSP) offers a viable, green energy alternative to South Africa heavy reliance on coal. Unfortunately, all current CSP technologies are not yet cost comparative with traditional power generation systems, particularly coal. In order to realize the potential of CSP over all costs need to be bought down, which requires significant research and development.

One CSP technology, which has great potential for further research is central receivers. In central receiver systems a group of mirrors, called heliostats, concentrate sunlight onto a central target. For a central receiver research it is important to have a proper understanding of the heat flux incident on the receiver. The heat flux (simply referred to as flux) is the amount of energy transfer through a given area. In solar applications the flux can be related to the total power incident on a receiver and thus the total power available to the plant.

A number of flux measurement techniques have been developed for large scale receivers (Marc Röger, 2011). However, requirements such as cost, accuracy, spatial resolution and measurement speeds differ between small and large plants. More importantly incident flux and temperature temperatures differ greatly between large and small plants.

In larger fields higher temperatures are developed and damaging measuring equipment is a concern. In contrast, in smaller plants, low flux and temperatures are a concerned as the measuring equipment is more easily affect by ambient influences. For example the diffuse radiation reflected from the roof of a nearby building may only be fractionally less than the reflected radiation from a single heliostat. Therefore a method needs to be specifically developed which can handle small-scale flux measurements.

This paper begins with description of the apparatus used in the experiment as well as a as well as the limitations of the apparatus and sources of error (Section 3). The experimental procedure is then discussed and how the error is accounted for. Finally results of an experiment are provided and discussed.

2. Objectives

Develop a means which is capable of measure the flux reflected from a number of heliostats onto a target. The method should be sensitive enough to measure the flux from a single heliostat but flexible enough to be used for multiple heliostats. The output of the method should be a complete, continuous map of the flux on the target. The method should also be fast as to not be affected by the changes in sun position.

3. Flux measurement apparatus

Flux measurement can be classified into direct and indirect measurement. Direct method use mechanisms to directly measure incident flux, while indirect methods commonly measure solar radiation reflected off the target.

Common direct methods include colorimeters (Mouzouris, Roberts, & Brooks) (Roos, Plessis, Klein, Bode, & Landman, 2011) or flux sensors (J. Ballestr, 2003). Due to their easy construction and the fact that they can be locally purchased or produced calorimeters are a good choice to measure flux on a target. Unfortunately calorimeters offer little or no spatial resolution. Flux sensors are also a common direct measurement system.

Flux sensors are commonly based on the thermocouple principal and deliver a measurement signal proportional to the irradiance flux striking them. Flux sensors can only be used to measure flux at discrete points. To marginally improve spatial resolution several flux sensors can be used and data between measurement points can be interpolated.

Indirect methods are capable of developing a continuous flux map. Digital cameras are often used for indirect flux measurement. In a digital camera a sensor, made up of millions of smaller photosensitive sensors (pixels), outputs a voltage directly to the amount of photons which strike it. For camera is aimed at a target the amount of photons hitting the each pixel is directly proportional to the flux incident on a target. Digital cameras give very good spatial resolution but with no means of quantifiably determining the flux.

The method developed at Stellenbosch University uses a combination of direct and indirect measurements to generate a continuous calibrated flux map. Images are first captured using a digital camera. These images are then calibrated using a flux sensor position in the middle of the target. The following sections describe the experimental apparatus and the procedure is explained in **Error! Reference source not found.**.

1.1 Direct solar flux measurement

Direct measurements are conducted with a Vatell Corp. TG-1000 circular foil gauge. The circular foil gage, also known as a Gardon gage was invented by Robert Gardon to measure radiation heat transfer, schematic is illustrated in Figure 3-1.

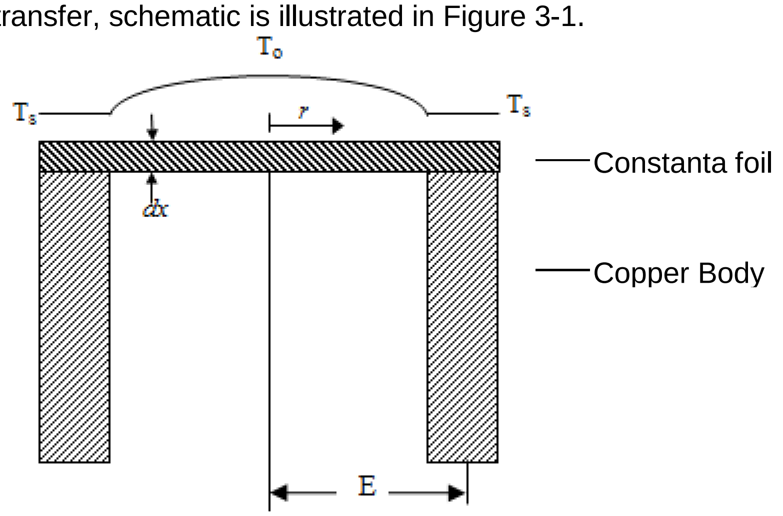

Figure 3-1: Circular foil heat flux sensor

A Gardon type gauge is based on a thermocouple principal. A thin foil made of one thermocouple material, usually constanta, is attached to a hollow cylinder made of second type of thermocouple material, usually copper. A wire from the second type of material is attached to the centre of the thin foil. This sets up a differential thermocouple pair between the centre and the edge. Heat flux incident on the gage causes a radial temperature distribution.

The gauge outputs a voltage which is directly proportional to the flux on the gauge. The gauge has been calibrated and a calibration constant is used to calculate the flux. For very low flux measurements a signal amplifier is used. The Gardon type gauge is very accurate in reading the direct irradiative flux and is therefore very suited for low flux measurements.

1.2 Indirect measurement

Indirect measurements are conducted with digital camera and a Lambertian target.

1.2.1 Camera

The indirect measurement is done with a Nikon D-5100 CMOS camera. In digital still photography two sensors are widely used: charged couple device (CCD) and complimentary metal-oxide semi-conductor (CMOS). Traditionally due to their superior image quality CCD cameras were used for scientific purposes (Bausch, 2011) and previous work on flux measurement has been conducted with a CCD camera (Marc Röger, 2011), (J. Ballestrín R. M., 2004) (Ho, Khalsa, Gill, & Sims, 2011). With modern technology however, CMOS sensors have reached image parity with CCD. Furthermore CMOS offers more chip functionality, lower power dissipation and smaller system size and are therefore favoured in newer cameras.

In a CMOS chip each pixel has its own charge-voltage conversion and the sensor often includes other circuitry such as noise-correction and amplifiers. As in all real systems there are limitations to the hardware used to capture an image. These limitations cause imperfections which manifest themselves as image imperfections or noise. Noise is any additive, unwanted measurement that is generated by the sensor independently of incoming light. Two types exist: random noise and correlated noise. Random noise cannot be predicted and varies from one image to another. Correlated noise, on the other hand, can be predicted and is compensated for. The major sources of correlated noise which can be compensated for are; bias, vignetting and imperfect sensors.

Bias

Taking a dark frame image (an image generated in the absence of any incoming light) should give a zero reading for each pixel as no light is falling on the pixel. However, zero values in a dark frames are purposefully avoided in camera design as any value below zero will also be read as zero. Therefore to account for the uncertainty digital cameras manufactures deliberately bias an offset value to a value above zero. ~~Thus, all pixels in a~~

Vignetting

Vignetting is a radially dependent illumination strength falloff due to the camera lens and optical properties of the system. All lens systems have light ray spread which increases as the light rays are further from the centre. Vignetting results in a radial shadowing effect towards the image periphery (Kelcey & Lucieer, 2012)

Imperfect sensors

The third influence of noise is due to the fact that the sensor pixels are not perfectly manufactured. This imperfect manufacturing shows up as per-pixel noise.

1.2.2 Lambertian Target

A Lambertian target is perfectly diffuse surface which has the same apparent brightness when view from any direction. In contrast, a glossy surface such as plastic has areas of varying brightness depending on the view angle. Lambertian surfaces are the theoretical limit and practically only approximate diffuse surfaces are available. Lambertian surfaces are important for the experiment as the camera's position and angle relative to the target and heliostats can never be adequately known. With a diffuse surface a photograph of the target taken from any viewing angle will accurate represent the image of the reflected flux.
For price considerations a Lambertian surface could not be acquired. Instead a number of paints were tested and it was found that Prominent Paint Wall Primer has the best diffuse properties. Similar test at CSIR Pretoria also found Prominent Paint wall primer to have the best diffuse properties (Griffith, 2011).
For the experiments a 1mx1mx4mm mild steel target was sprayed with several coats of paint and sanded smooth. The flux sensor was positioned in the centre of the target.

4. Methodology

Test can be divided into three stages; the setup, which mainly involves camera noise reduction, the experiment and post processing. The following describes the steps involved in the experiment.

1.3 Camera noise reduction

To correct for both vignetting and errors associated with imperfect pixel sensors a *flat field* image is captured. Flat fields are fields which exhibit even illumination. Flat field images were generated by portion of a cloudless sky. Exposure time is set long enough to be close to saturation of the sensor to ensure a significant signal level is recorded.
Flat field images under the effects of vignetting exhibit radial deviation away from a uniform condition. In CCD cameras the brightest pixel within the flat field image exhibits the correct flat field measurement (Mansouri, Marzani, & Gouton, 2005). As vignetting is an optical error, as appose to measurement error, it was assumed that the same applies to the CMOS cameras. The flat field image is bias corrected and normalized and a correction factor is then determined to correct each pixel value to the brightest pixel. Several flat field images were captured and the mean correction factor determined.

In order to account for bias a dark frame or *bias frame* is removed from all experimental images. A bias frame effectively removes the incoming signal component from the measured data, thus providing a sample of the per-pixel bias component. Several images are taken and the average per-pixel sensor noise is estimated. As a camera's bias is a set value a bias frame was only created once and used in all experiments.

1.4 Experimental procedure

A huge advantage of the experimental method is that after is has been successfully setup and the camera has been calibrated, the actual flux measurement is relatively straightforward and quick. For each experiment, two simultaneous images are captured; a reference image, without any image cast on the target and an experimental image , with the heliostat(s) concentrating flux onto the target. As the actual experiment is rapid several images can be captured. Once an image has been captured it is stored post processing.

1.5 Post processing

The image processing was performed in the free software Python, but the algorithms were later converted to be used in MATLAB due to MATLAB's advantages in speed in handling large matrices.
In MATLAB an image is represented by a three-dimensional matrix, that is, three matrices representing the red, blue and green light spectra. Each element in the matrix represents

a single pixel. Higher matrix entries indicate higher voltage outputs and thus more photons which hit that pixel.
The first stage of the post processing is to convert all images to gray scale. The following equation is then used to determine the actual pixel intensity value of the reference image and experimental image.

$$\begin{aligned} &Actual\ Intensity\ value_{ij} \\ &\qquad = (flat\ field\ conversion\ Factor) \\ &\qquad \times Measured\ Intensity\ Value_{ij} - Bias_{ij} \end{aligned} \tag{4-1}$$

Where the subscripts i, j represent the matrix elements.

Finally to scale the image, the reference image is then subtracted from the experimental image. This exaggerates the difference between the highest and lowest pixel value as it eliminates the effects of ambient illumination. This final stage is not necessary but helps for flux visualization. The image is then ready to be calibrated.
To calibrate the image it is assumed that flux immediately adjacent to the flux sensor is equal to the flux incident on the sensor. This assumption is possible with no loss in spatial accuracy as very distinct flux contours are present and it is possible to determine within which contour the sensor falls. The entire image is then normalized according to this flux contour. Each pixel now has pixel value (*PV*) which correlates to a specific flux measurement. All that is required to determine the flux at a specific pixel is to multiply this pixel value by the flux correction (F_c) value.

$$I = F_c \times PV \tag{4-2}$$

5. Results

The following results are taken from an experiment conducted with single mirror facet on the 12th October 2012 on the solar roof laboratory at Stellenbosch University.

Figure 3-1 shows the original, cropped image of the flux on the target. The image may appear darker than expected. This is because a neutral density filter was used with the camera in order to prevent sensor saturation.

Figure 5-1: RAW image captured with ISO 100, f Number f/29, exposure time 1/800

The processed flux map is given in Figure 5-2. The flux measured on the sensor was 6.35W/m^2. An enlargement of the flux sensor is given in Figure 5-3.

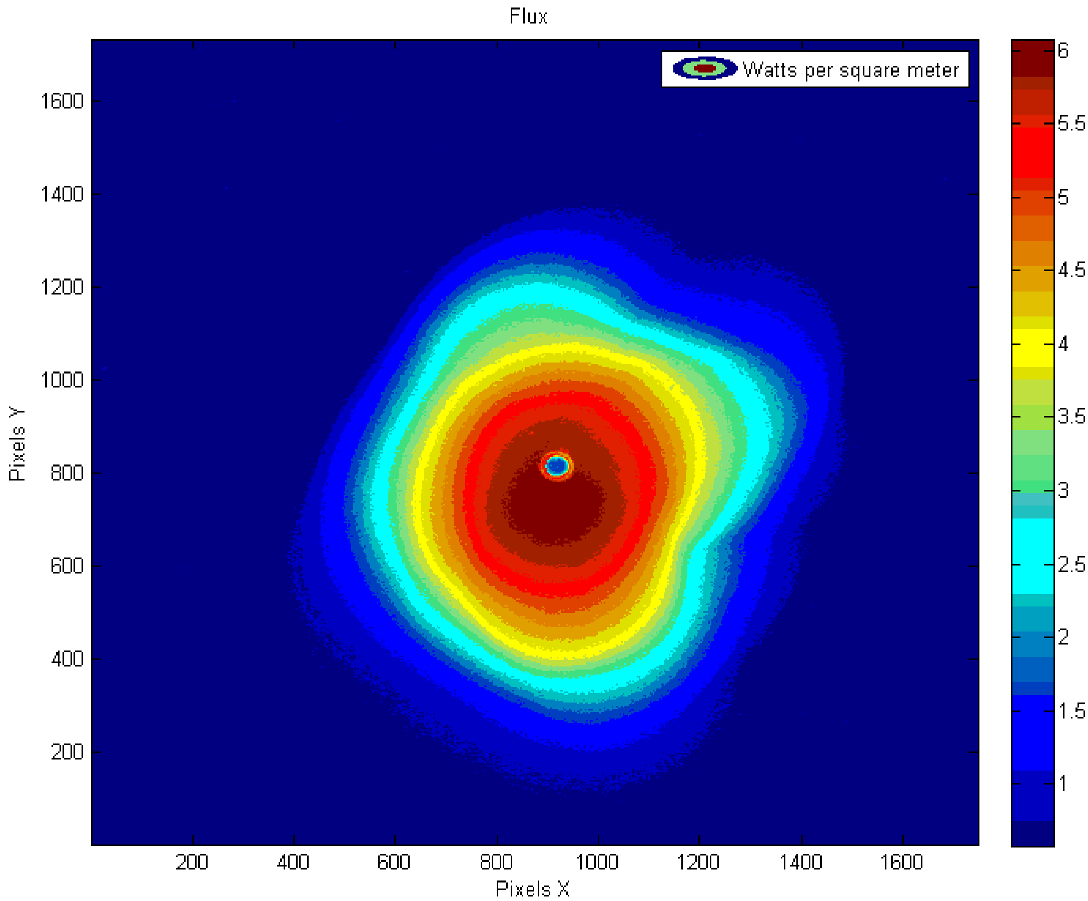

Figure 5-2: Image of the flux incident on a target

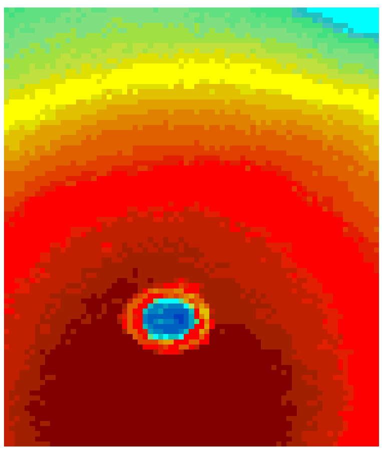

Figure 5-3: Enlargement of flux sensor

Comparing Figure 5-1 and Figure 5-2 the importance of flux mapping can be illustrated. Examining just Figure 5-1 it is almost impossible to determine the area of highest flux whereas in Figure 5-2 it can clearly be seen that the maximum flux situated just below the sensor. Images such as this can be used in mirror shape design, field lay out, tracking and receiver design.

The sensor recorded a flux of 6.35W/m^2 and the rest of the image was calibrated using this value.

Also evident in the images is there is not a smooth transition between flux contours, but instead the edges appear jagged. This can be contributed to the target. At the time of the experiment the target had a protective undercoat sprayed below the Prominent Primer. This undercoat was not applied smoothly which results in a bumpy surface of the target.

6. Conclusions and recommendations

A processed has been developed which can accurately measure the flux reflected from a heliostat onto a receiving target. Indirect methods, using a CMOS camera, provide a method to determine the flux at any point on a target, with a resolution only limited to the camera's pixel size. Images captured using indirect methods are then calibrated with a flux sensor located at the centre of the target. Images of flux maps can be used to validate numerical flux predictions, determine total power reaching a target and determine the overall shape of the image cast.

Further work has been conducted to smooth out all bumps in the target which shall give better visualization of the flux maps. As only one flux sensor is available, it is recommended that further validation be performed. This can be done by moving the flux image over the target while a series of images are captured in close succession.