A METHOD OF INCREASING COLLECTOR APERTURE IN LINEAR FRESNEL SOLAR CONCENTRATORS AT HIGH ZENITH ANGLES

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Abstract

Concentrating solar power (CSP) has been recognised as one of the most appropriate renewable energies to help alleviate the energy shortage in South Africa as well as move the country towards a green economy. In particular, Linear Fresnel Reflectors (LFR) have great potential in southern Africa due to the low cost and increased percentage of local manufacture inherent in the technology. LFR systems have traditionally suffered from high levels of shading by adjacent mirrors at early hours of the morning and late afternoon. This has increased the amount of time needed for plant start-up during the morning as well as penalised the time to which the plant can operate into the evening. A method of reducing the shading effect and thereby increasing collector aperture at high zenith angles was investigated. This has the potential to increase the level of irradiation received daily which would increase the energy production of such a plant. Increased energy production at these times of day would either reduce an installation's use of supplementary firing when used as a thermal source for factories or increase electricity production at peak hours which would improve revenue for such a plant.

Keywords: linear Fresnel; collector; aperture; concentrating; optical; ray trace

1. Introduction

A number of previous studies have investigated the effects of various aspects of linear Fresnel design on the overall efficiency of the system [1][2][3]. Many of these have employed ray tracing methods of some form to analyse the optical performance of the system. Some common causes of losses in the modelled systems become apparent and various alternative designs have been proposed to mitigate particular losses [4][5]. An analytical and graphical model was developed in MATLAB that allowed a number of these losses in LFR systems to be analysed. Some of these losses include:

- *Shading*: Adjacent mirrors shade each other from incoming sunlight
- *Blocking*: Adjacent mirrors block outgoing reflected rays from mirrors to the receiver
- *Spillage*: Due to diverging reflected beams or narrow receivers, a portion of the

beam misses the receiver

- *Specular losses*: Inconsistencies in mirror surfaces
- *Transmissivity losses:* Impurities in glazing
- *Tracking errors:* Mechanical and manufacturing tolerances
- *Receiver shading*: shading of mirrors below the receiver
- *Edge losses*: Declination of the sun causes losses at the ends of collector arrays

2. Simulation of collector

2.1. Design variables

The MATLAB model was coded in such a way as to allow various input design variables to be entered that would model a particular LFR design. For example, variables included: number of mirrors, width of mirrors, spacing of mirrors, receiver height, receiver width etc. Another input was a file containing Direct Normal Irradiance (DNI) data for the specific location that an LFR array was to be evaluated at. This allows the potential power production for any particular LFR design to be calculated. The power production can also be used as the function value when using optimisation algorithms such as particle swarm on the input variables.

2.2. Simplified ray trace model

The ray trace model used is a basic geometric model similar to methods used in other studies to calculate concentration ratios [6][7]. The azimuth and zenith angles of the sun are transformed onto an East-West plane so that the North-South facing collector may be approximated as a two-dimensional slice. A ray from the centre of the sun disk to the centre of the mirror is designed to be reflected to the centre of the receiver. The edge rays of the mirror are then reflected to a horizontal plane through the receiver which is modelled as the receiver aperture. These rays diverge due to the sun's subtend angle as well as specular irregularities as shown in figure 1.

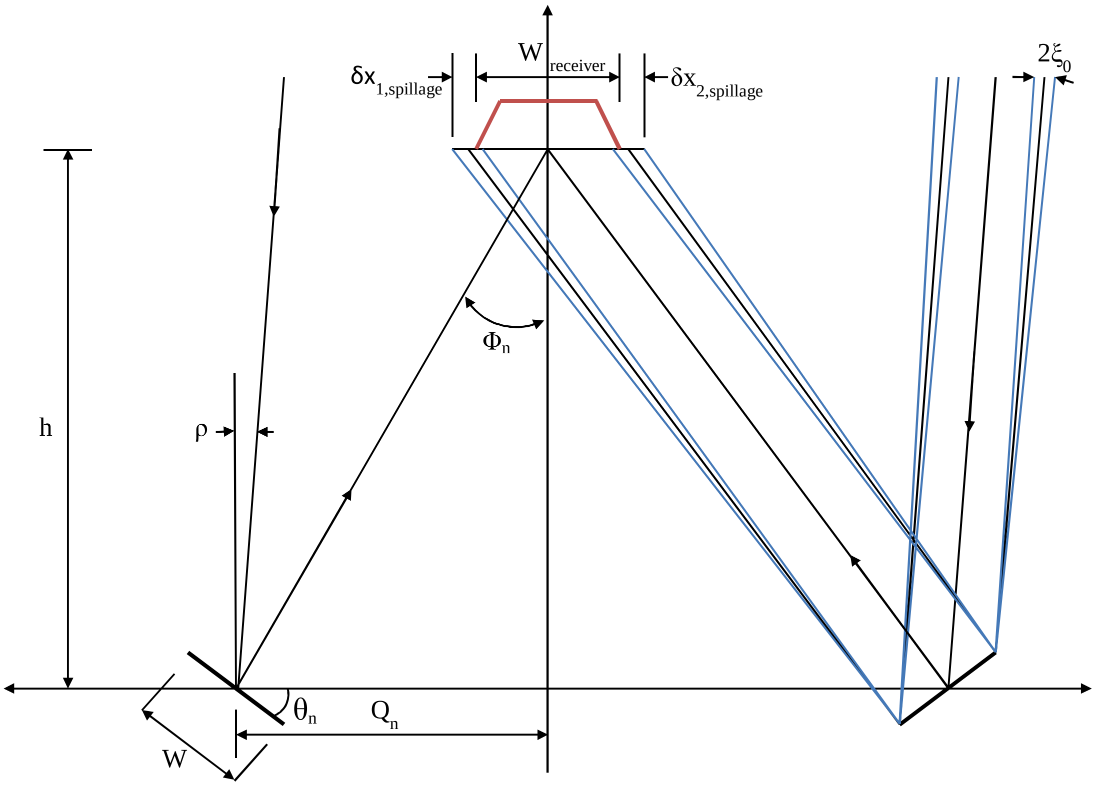

Fig. 1. Ray trace layout and variables

For a specularly reflective mirror, the tilt angle for the Nth mirror is a function of the sun-angle and its position relative to the receiver:

$$\theta_n = \frac{\varphi_n - \rho}{2}$$

The concentrated flux is then calculated as the sum of the reflected flux from all the individual mirrors. The contribution from each mirror will not be equal as shading, blocking and receiver shading will result in different apertures for the different mirrors.

$$Concentration\ of\ reflected\ beam\ of\ Nth\ mirror = \frac{LA}{LP}$$

where: LA = Aperture length of incoming ray to Nth mirror after blocking and shading effects have been taken into account.

LP = Length of projection of the divergent reflected beam onto the horizontal receiver aperture (can be smaller than LA if mirrors are bent)

The concentration ratio of the reflected beam will not be constant over the width of the receiver due to the effect of the sun's subtend angle on the edges of the mirrors. This was taken into account as well as the effects of spillage beyond the receiver's width, as indicated by $\delta x_{1,spillage}$ and $\delta x_{2,spillage}$ in figure 1.

3. Investigation of new concept

In an attempt to reduce the effects of shading, an alternative method of mounting the collector mirrors was investigated. This method aims to increase the aperture of the collector at high zenith angles by pivoting mirrors around an axis of rotation instead of merely rotating on an axis through the centre of the mirror. The principle is shown in the figure below. Mirrors are offset to different directions on either side of the centre of the collector.

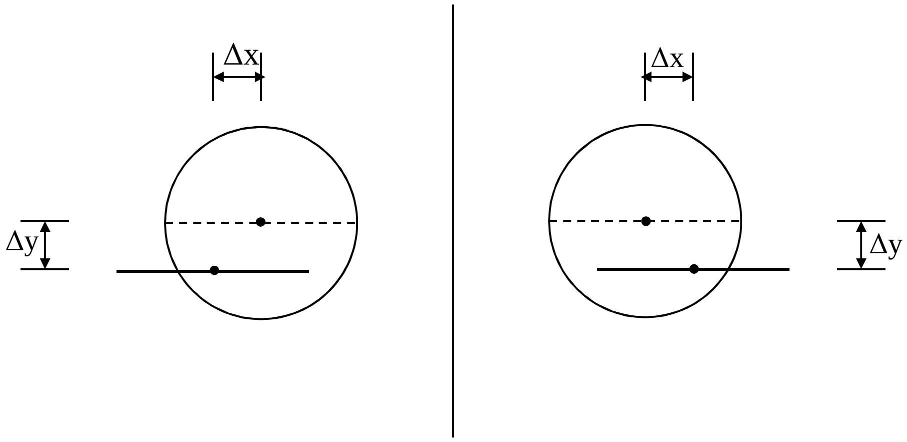

Fig. 2. Offset pivoting concept

3.1. Modelling the concept

Calculating the tilt angle θ_n for standard Fresnel is a basic exercise as only the sun-angle changes for a particular layout. For the offset pivot, the relative x and y offsets from the centre of the mirror to the fixed centre of rotation are constantly changing. Only when a mirror is horizontal or vertical are the offset coordinates equal to the fixed Δx and Δy design values as shown in figure 2. In all other instances, the x and y coordinates shown in figure 3 below must be calculated.

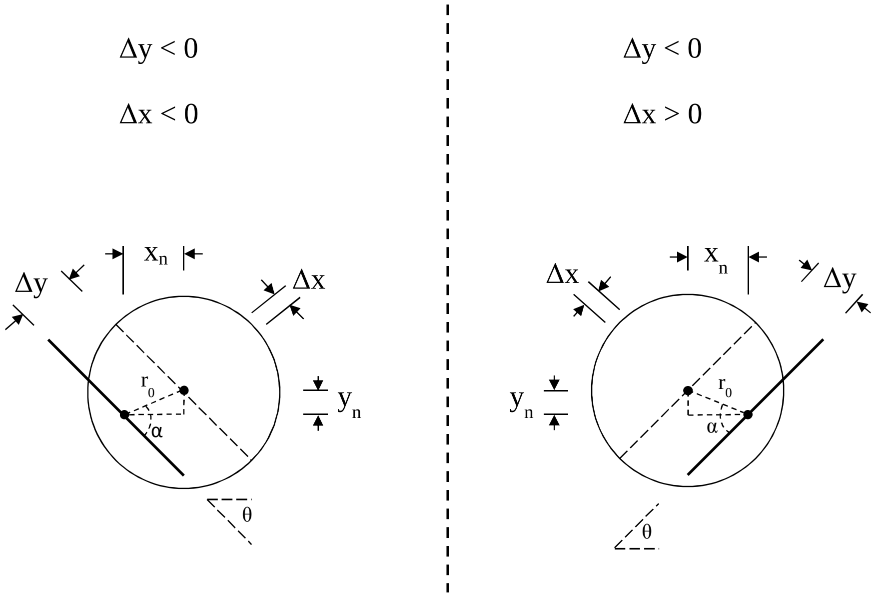

Fig. 3. Offset coordinates

The offset radius is simply:

$$r_0 = \sqrt{(\Delta x)^2 + (\Delta y)^2}$$

And the angle between r_0 and the mirror surface:

$$\alpha = tan^{-1}\left(\frac{\Delta y}{\Delta x}\right)$$

The offset coordinates x and y are then:

$$x_n = r_0 \times cos(\alpha - \theta_n)$$

$$y_n = r_0 \times sin(\alpha - \theta_n)$$

The altered geometry of the offset pivot results in:

$$tan(\varphi_n) = \frac{Q_n + x_n}{h + y_n}$$

Assuming specular reflection and rearranging equation, then substituting in x_n and y_n:

$$tan(2\theta_n + \rho) = \frac{Q_n + r_0 \times cos(\alpha - \theta_n)}{h + r_0 \times \sin(\alpha - \theta_n)}$$

In the above equation, θ_n is the only unknown however it must be solved either through an iterative process or using a solver function such as those available in MATLAB.

4. Results and Discussion

The offset pivot concept does show a noticeable increase in aperture over the traditional method of pivoting around the centre of the mirror. At early morning, the east side of the collector drops below the horizontal plane while the west side raises up slightly. The reverse is true for late afternoon as shown in figure 4.

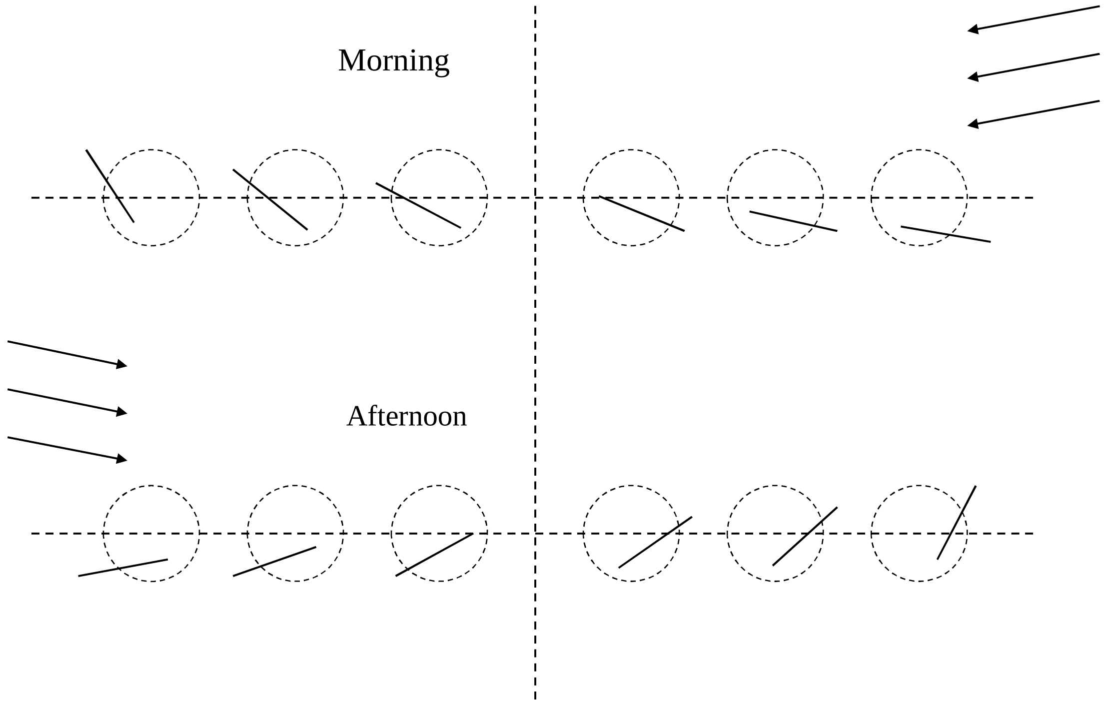

Fig. 4. Collector mirror positions at high zenith angles

The actual gain in aperture at high zenith angles is a function of the distances offset from the central pivot in both the x and y direction. It was found that the maximum increase in aperture was gained when the offset in both x and y was incremented in the direction of the edge of the array. The mirrors directly below the receiver were then very similar in pivot to standard Fresnel while the outer most mirrors had the most noticeable offset pivot.

The aperture gain for a particular system is shown in figure 5. The design variables for the system analysed are included in table 1. Only the offset variables were changed to alter the model to an offset pivot.

Number mirrors	Mirror width	Receiver height	Receiver width	Spacing	Offset increment
16	0.2 m	2 m	0.3 m	10 mm	20 mm

Table 1. Example simulation variables

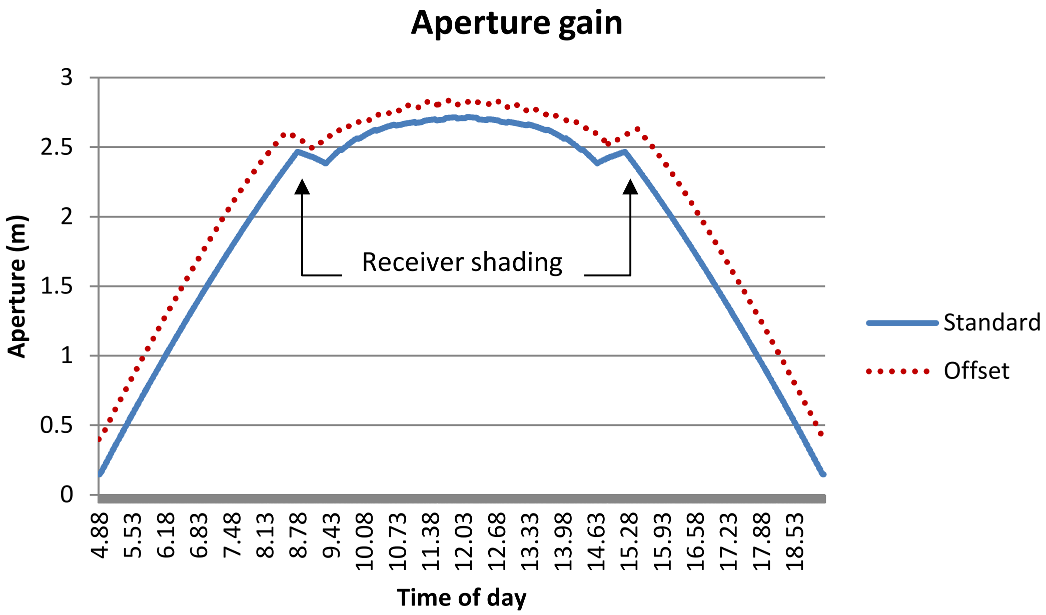

Fig. 5. Aperture of test setup over the course of a day

The increase in aperture over standard Fresnel is noticeable over the entire day. At high zenith angles, this increase is usually in the order of 100%. This doubling of aperture however is the doubling of an already small aperture and does not contribute dramatically to the power production over the course of the day. This fact can be seen in figure 6 where the power curves of the two cases are very close at early morning and late afternoon. The gap does widen however when the DNI starts to increase. The sharp dips in aperture evident at mid-morning and mid-afternoon are caused by receiver shading taking effect.

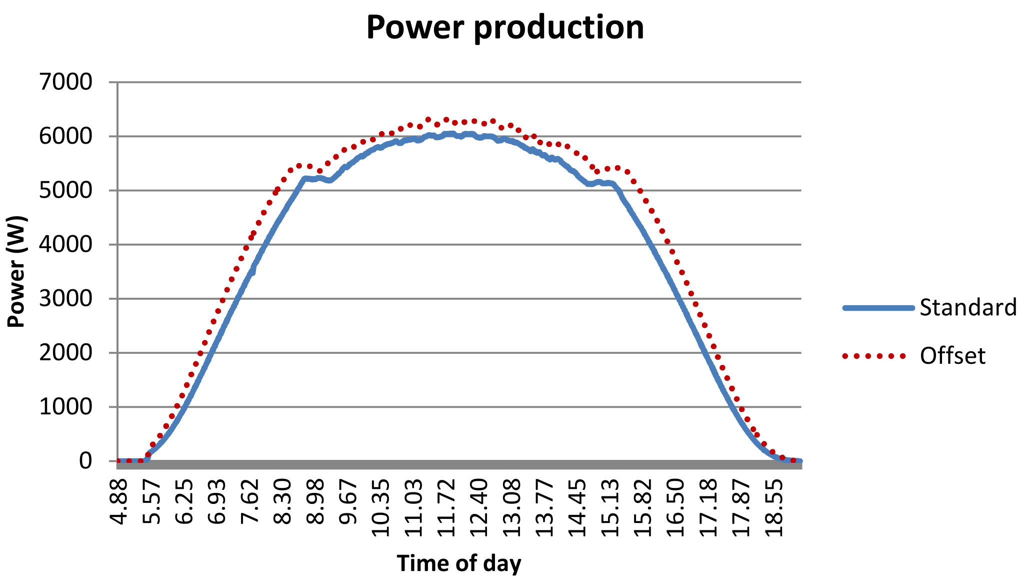

Fig. 6. Power production on average summer day

The power production shown in figure 6 is based on a collector of 3 m long by roughly 3.5 m wide which relates to the design of the test prototype to be built on the Stellenbosch University solar roof. The DNI data used was an average summer day derived from the DNI data of Stellenbosch, South Africa. The power is the thermal energy entering the receiver and does not include losses from the receiver onwards in order to focus on only the optical optimisation of the system.

5. Conclusion

Whilst the offset pivot idea does show promise in increasing the efficiency of LFR systems, a detailed economic and feasibility study will need to be conducted to determine its true potential. For example, the above instance shows an 8.9% increase in power in summer and a 9.5% increase in power in winter. This corresponds with a 10.5% increase in the footprint of the system. Therefore the trade-off between increased efficiency and increased land use will need to be evaluated. The complexity of the offset pivot as well as the increased load on bearings and drive systems due to moments will drive up costs.

A LFR test rig will be built in order to verify the aperture gains predicted by the model and to test new concepts proposed by later studies.

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