Performance Analysis of Low Concentrating PV-CPC Systems with Structured Reflectors

Sylvester Hatwaambo
University of Zambia
Zambia

1. Introduction

The conventional sources of energy such as coal, oil, natural gas, etc are undoubtedly dwindling on a world scale at the current rate of consumption. Other sources of energy like nuclear power have a nuclear waste disposal problems and the creation of large water reservoirs for hydro-electricity generation brings about migration and a disturbance in the general ecosystem. It is for this reason that alternative sources of energy are being sought. One of the promising sources of energy is the solar energy. Solar thermal collectors can easily harness the heat from the sun while photovoltaic systems can convert solar energy directly into electricity. The major problem with solar energy is that it is not evenly distributed over the globe and that its conversion efficiency is generally low.

In concentrator photovoltaic systems, highly specular (high reflecting) materials are used to concentrate radiation on the module solar cells. Ultimately, this increases the temperature of the module solar cells. Module solar cells made from silicon show a drop of 0.5% in power for each degree rise in temperature [1]. High grade silicon solar cells have been used in space applications but these are too expensive for conventional use. These specular materials are not only expensive but also cause un-even illumination in certain geometries of solar collectors. One way of going round this problem of un-even illumination is to use diffuse reflectors that have a potential to scatter the radiation flux onto module solar cells.

Non-imaging static concentrators have been tested using converging (Fresnel) lenses as refractive elements [2, 3, 4]. On the other hand, non-imaging static concentrators with reflective elements for low concentration have been tested for high latitudes [5, 6, 7]. Specular reflectors have shown to have a long life but the problem of non-uniformity of illumination has been prominent [6]. Low cost and partly diffuse reflectors have a great potential for overall cost reduction in photovoltaic-thermal hybrids provided the problem of non uniform irradiance could be solved [8, 9].

2. Specific objectives

In this chapter, we analyze the performance of a photovoltaic concentrator system with structured reflectors. These material reflectors are anodized aluminium (oxide layer of Al_2O_3

forms on aluminium during anodization), rolled aluminium foil (lacquered rolled aluminium foil, laminated on plastic PET or mylar, and miro (commercial aluminium sheet coated with $TiO_2/SiO_2/Al$). The overall objective was to test whether a reflector with low-angle anisotropic scattering in one direction and specular in the other could be characterized for use in low concentrators.

In the second case, we investigate one alternative of improving the performance of a low concentrating photovoltaic system using semi-diffuse rolled reflective elements. Our results indicate that rolling marks on the reflector aligned parallel to the plane of the solar module cell improve the performance of the photovoltaic system.

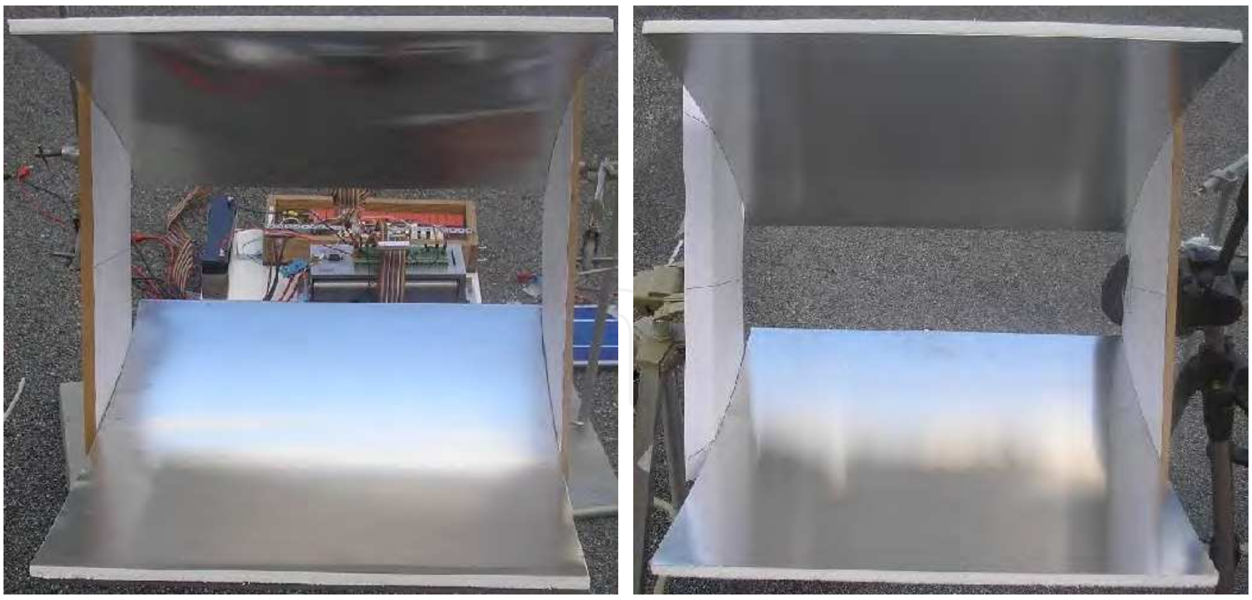
3. Methodology

3.1 The compound parabolic concentrator (CPC) geometry

The studied symmetrical compound parabolic concentrator is shown in figure 1. The acceptance half angle θ_c and the geometrical concentration ratio C_g were 15^o and 3.6 respectively. The optical properties of the reflector materials in terms of their integrated specular reflectance were analyzed using the Perkin Elmer Lambda 900 spectrophotometer. In the second analysis, two identical CPCs were constructed as shown in the figures 2(a) and 2(b). In figure 2(a), the diffuse rolled aluminium sheet had its rolling grooves aligned parallel (HG) to the plane of the solar module cell and in figure 2(b), we show the same rolled aluminium sheet with the rolling marks aligned perpendicular (VG) to the plane of the solar module cell.

In both CPCs, the half acceptance angle was 15^o, the exit and the entrance apertures were 12.5cm and 42cm respectively, making a geometrical concentration ratio of 3.36. The CPCs were truncated to a height of 49cm and a total length of about 61cm. The solar cell used was a standard, high grade mono-crystalline silicon solar cell with dimensions of 12.5cm x 12.5cm inserted at the base of CPC.

Fig. 1. Truncated CPC with 10 cell module string



2(a) 2(b)

Fig. 2. Photograph of CPCs with horizontal grooves(HG) in 2(a) and vertical grooves(VG) in 2(b). module string

4. Current-voltage curve measurements

The current-voltage (I-V) curves were measured using an electronic load instrument [10] by adjusting the voltage through a logging system of potentiometers, operational amplifiers and power transistors as shown in the background of figure 2(a). The CPC was tilted manually below and above normal incidence *(0^o)* in one degree intervals to ± 20^o. At every angle of incidence, an I-V curve was plotted for each reflector material. The current values were compensated for irradiance at 950 W/m^2 and the voltage values were compensated for temperature increase on the module at 25^oC. From each plotted I-V curve, the short-circuit current I_{sc}, the open circuit voltage V_{oc}, the maximum current I_{max} and the maximum voltage V_{max} were extracted. Subsequently, the maximum power P_{max} and the fill-factor FF were calculated at each angle of incidence.

The effective specular reflectances (R_{eff}) for each material was also estimated from the short-circuit current equation (1) at normal incidence.

$$I_{sc}^{conc} = \left[1 + (C_g - 1)R^{eff}\right]\frac{I_b}{I_t} I_{sc}^{ref} + \left[\frac{1 + (C_g - 1)R^{eff}}{C_g}\right]\frac{I_d}{I_t} I_{sc}^{ref} . \quad (1)$$

The first expression on the right gives the current contribution from beam radiation with reflectance losses and the second expression accounts for the current contribution from diffuse radiation. The parameter I_{sc}^{conc} is the short-circuit current measured under concentration, I_{sc}^{ref} is the short-circuit current measured on a reference module placed at the entrance aperture of the CPC, I_b is the beam radiation, I_d is the diffuse radiation and I_t is the total radiation. The parameter C_g = 3.6, is the geometrical concentration ratio of the used CPC. The ratio of the beam radiation to the total and the ratio of the diffuse radiation to the total on a typical blue sky day are 0.9 and 0.1 respectively.

In the second scenario, a standard current-voltage (I-V) plotter [10] was used to generate a series of I-V curves at each angle of incidence (tilt). From each I-V curve and at a particular angle of incidence, short-circuit current I_{sc}, open-circuit voltage V_{oc}, maximum power P_m, maximum current I_m, and maximum voltage V_m were extracted and the fill-factor (*FF*) was evaluated from equation (2).

$$FF = \frac{P_m}{I_{sc}.V_{oc}} \cong \frac{I_m}{I_{sc}}\left(1 - \frac{I_m R_s}{V_{oc}}\right) \tag{2}$$

Where R_s is the series resistance of the module. The corresponding cell efficiency may be calculated from equation (3).

$$\eta = \frac{FF.I_{sc}V_{oc}}{I_N A_m} \cong \frac{I_m V_{oc}}{I_N A_m}\left(1 - \frac{I_m R_s}{V_{oc}}\right) \tag{3}$$

Where I_N is the incident solar radiation and A_m is the active solar module area.

5. Un-even illumination profile measurements (Flux distribution)

The non-uniform illumination profile apparatus used in the measurements is shown in figure 3. The rotation of the motor also rotates the potentiometer which in turn moves the wiper and the attached photo-diode in the clockwise direction.

A small hole of 1 mm diameter was used to increase the resolution of the Photo-diode measurements. The flux distribution profile measurements were averaged at four regular intervals along the length of the CPC to minimize errors due to non-linearity of the CPC geometry. The non-uniform illumination was compared for the three reflectors in terms of their local concentration ratios *(C_L)* from the flux distribution measurements.

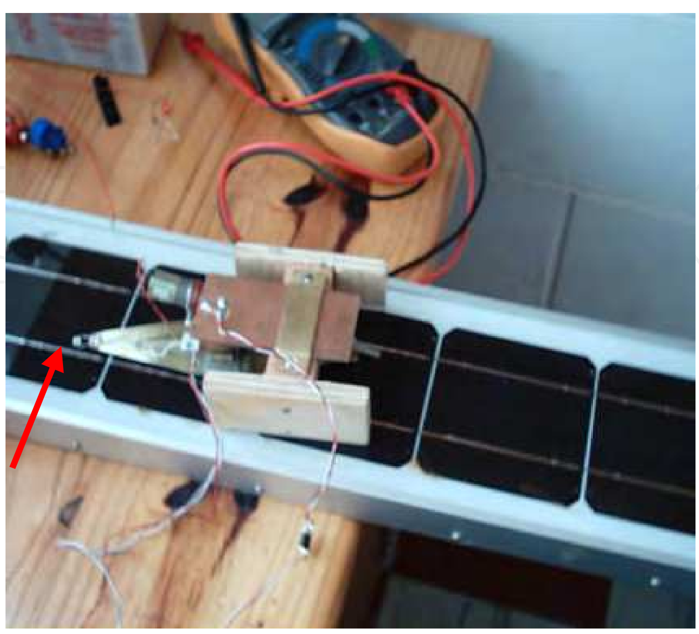


Fig. 3. Flux distribution profile apparatus resting on module string.

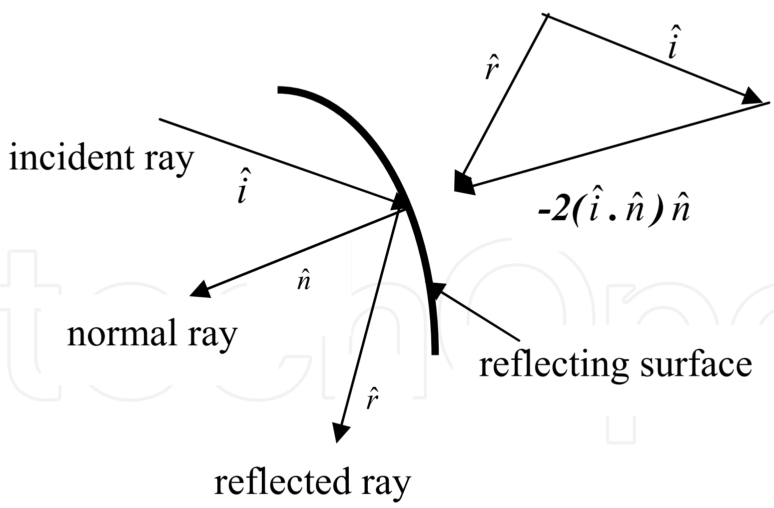


Fig. 4. Vector representation of light reflection for a specular surface.

6. Ray-tracing techniques

The ray-tracing was performed using commercial Zemax software [11] and the Matlab programmes. If we denote the incident unit vector $\hat{i}$, the normal unit vector $\hat{n}$ and the reflected unit vector $\hat{r}$, we may make a representation of ray-tracing profile for a specular surface as shown in figure 4. If the incident ray is known, the reflected ray may be calculated from the standard reflection equation (4).

$$\hat{r} = \hat{i} - 2(\hat{i} \cdot \hat{n})\,\hat{n} \tag{4}$$

A known number of rays were sent through the aperture of the CPC and monitored statistically the fraction of rays that hit the absorber directly f_0, the fraction of those that hit the absorber after the first reflection f_1 and the fraction of those that hit the absorber after the second reflection f_2 etc. From these statistics, the effective specular reflectance (R_{eff}) for each reflector material was estimated from equation (5). Note that equation (5) was evaluated for normal incidence only as was the case for equation (1) as a comparison.

$$\frac{C_L}{C_g} = f_0 + f_1 R_{eff} + f_2 . R_{eff}^{\ 2} + ... \tag{5}$$

6.1 Goniometric measurements

A photograph of the reflected light distribution from the reflector surface on to the screen is shown in figure 5. The incident beam was entering through a small hole on the screen and was reflected by the sample with the rolling grooves aligned vertically (y-direction). A goniometer instrument was then used to obtain the angular distribution of the reflected radiation along the x- and y-directions as defined in the figure. We observed the relative intensity of the detector signal as the alignment of the rolling grooves were either perpendicular to the scattering direction (scattering plane) or parallel to the scattering plane.

A photo-detector was used to record the relative signal intensity at each scattering angle.

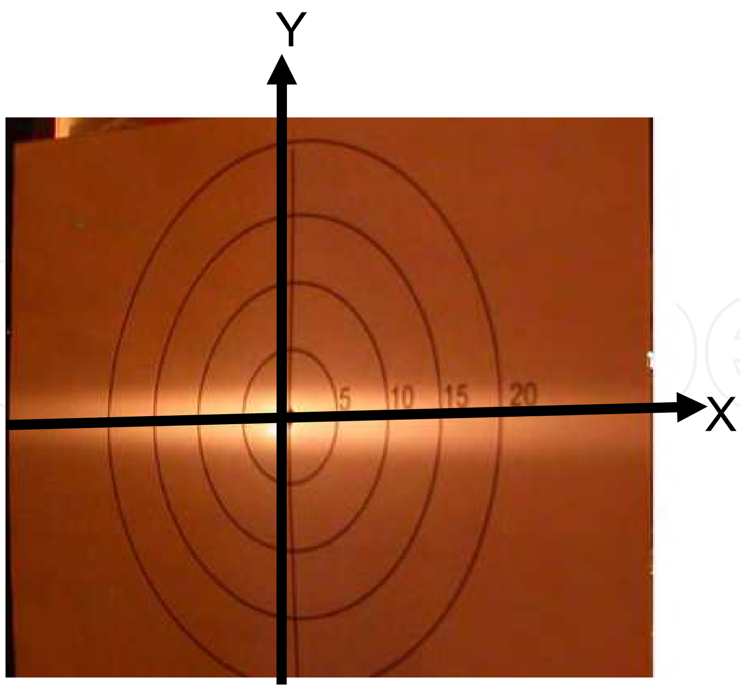


Fig. 5. Screen showing the reflected intensity. White band indicates direction of more scattering, hence anisotropic.

7. Experimental results

7.1 I-V characteristic curves

The dependence of the short-circuit current as a function of angle of incidence were analyzed as shown in figure 6 for the three materials.

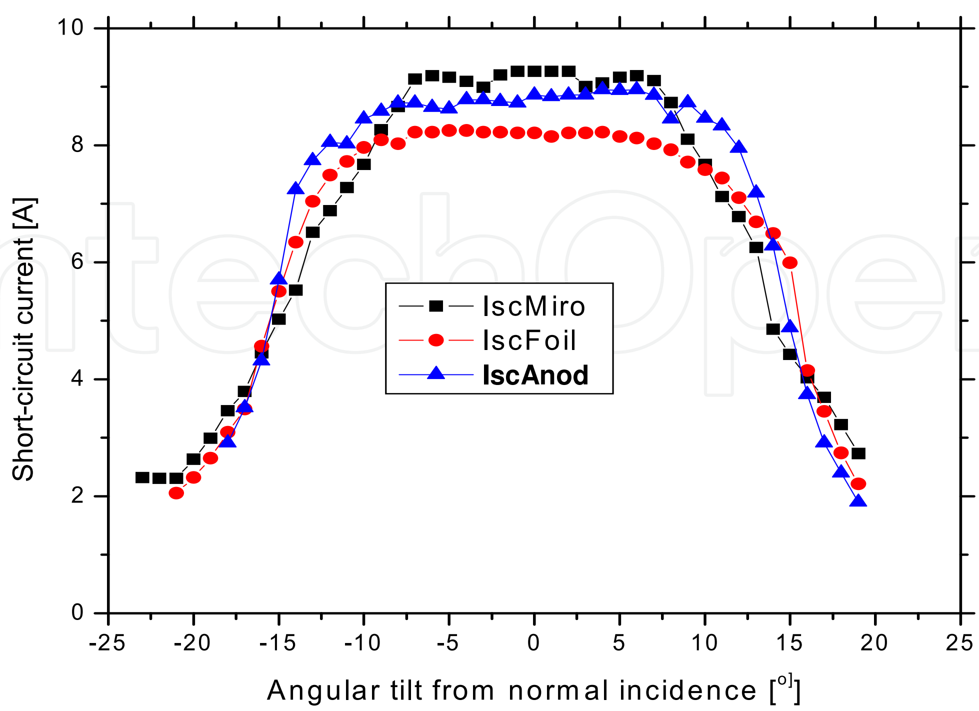


Fig. 6. Angular dependence of short-circuit current for three reflector materials.

The increase in the short-circuit current was proportional to the increase in irradiance on the cells. The short circuit current curve for anodized material followed the ideal optical behaviour because it was used as the base reflector. The miro and the rolled foil short circuit current curves show narrower angles of acceptance due to loose binding to the reflector geometry.

The reduction in short-circuit current at angles of incidence less than the acceptance half angle were due to optical imperfections of the reflector.

The fill factor for each material seemed to be fairly constant within ±10^o of angular tilt as shown in figure 7. The fill factor for the anodized reflector dropped sharply at ±14^o because all the rays fell on the edge of the cells and hence increased resistive losses. The increase in fill factor outside these angles of incidence were due to the decrease in generated current. Figure 8 shows typical current-voltage curves for the different groove orientations on the diffuse aluminium reflector sheet. The calculated fill-factor values at normal incidence are shown in the inset. It is observed that the percentage drop in the fill-factor for horizontal orientation of the rolling marks was about 1.6% and that for the vertical rolling grooves was about 2.4%. The smaller drop in the fill-factor for horizontal grooves was due to uniform illumination of the solar flux causing an even distribution of currents within the solar cell. The larger the fill-factor, the larger the power output and hence the efficiency from a solar cell as seen in equations (2) and (3).

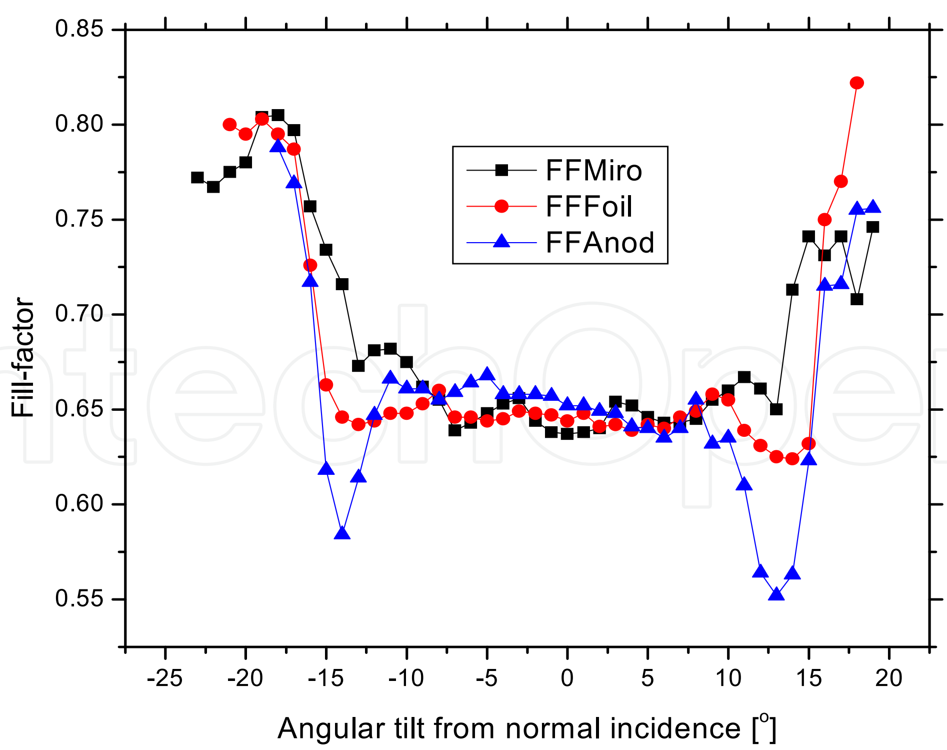


Fig. 7. Angular dependence of fill-factor for three reflector materials.

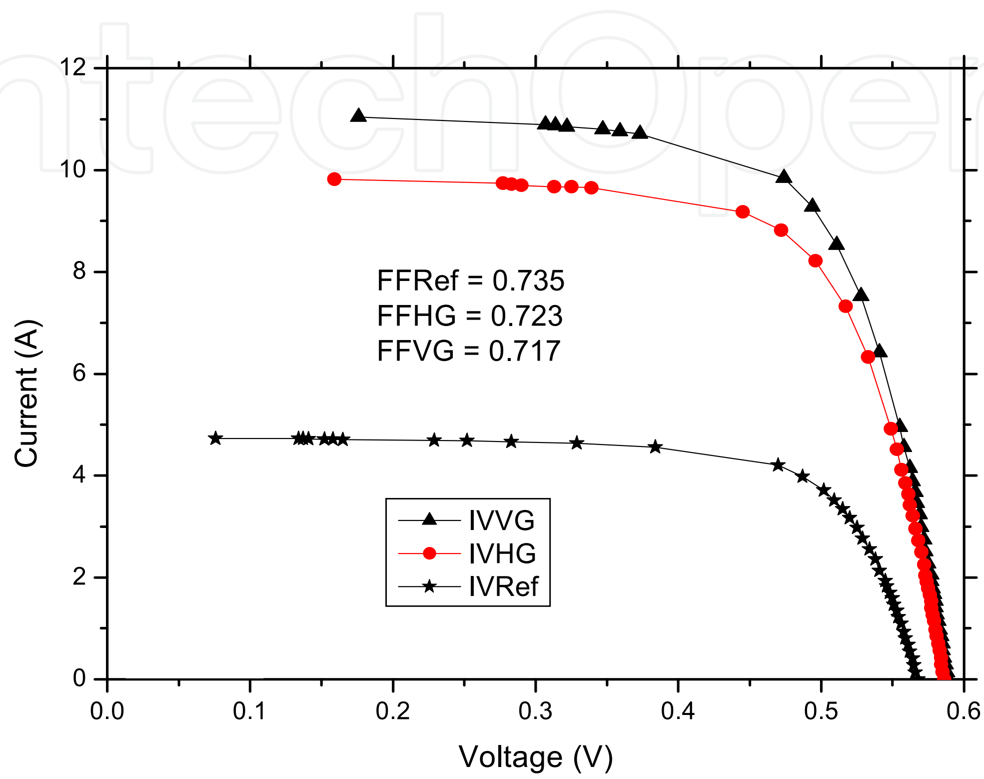


Fig. 8. I-V curves for different groove orientations at normal incidence.

Figure 9 shows the variation of short-circuit current *(I_{sc})* for the two groove orientations as a function of the angular tilt of the CPC. It is observed that short-circuit current for the rolling marks vertical was higher than the short-circuit current for the horizontal grooves within the acceptance angle. The vertical grooves behaved similar to a specular material.

High short-circuit currents generated with vertical grooves are not desirable in low concentrating systems as they induce high intensity peaks caused by local heating.

Figure 10 shows the variation of the fill-factor *(FF)* as a function of the angular tilt of the CPC within the acceptance angle (15^o). We observe that the fill-factor for the horizontal rolling marks was better than the corresponding fill-factor for the vertical grooves. The moderate short-circuit currents generated from the horizontal grooves tended to lower the heating effect by spreading the illumination flux.

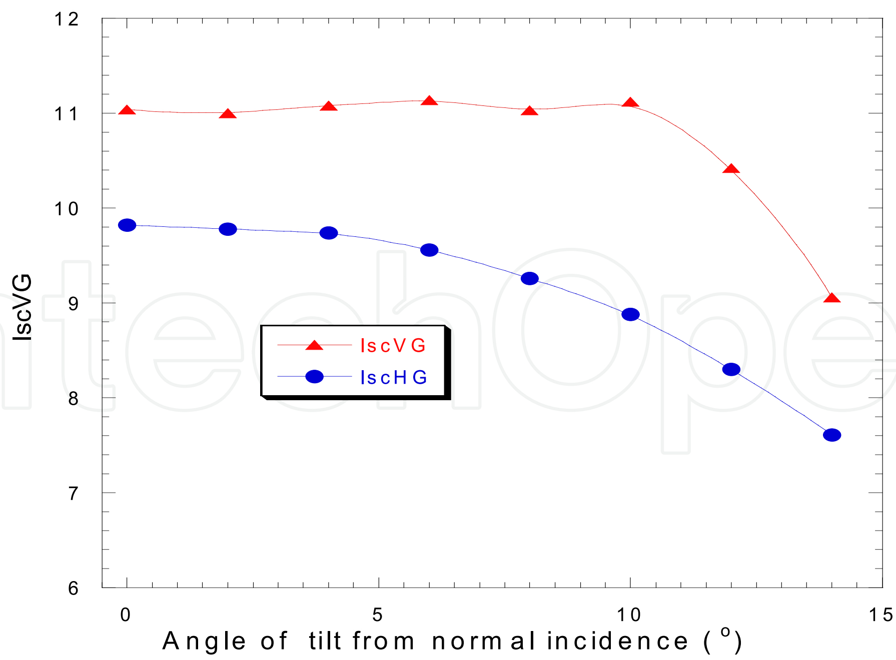


Fig. 9. Comparison of short-circuit currents for horizontal and vertical grooves.

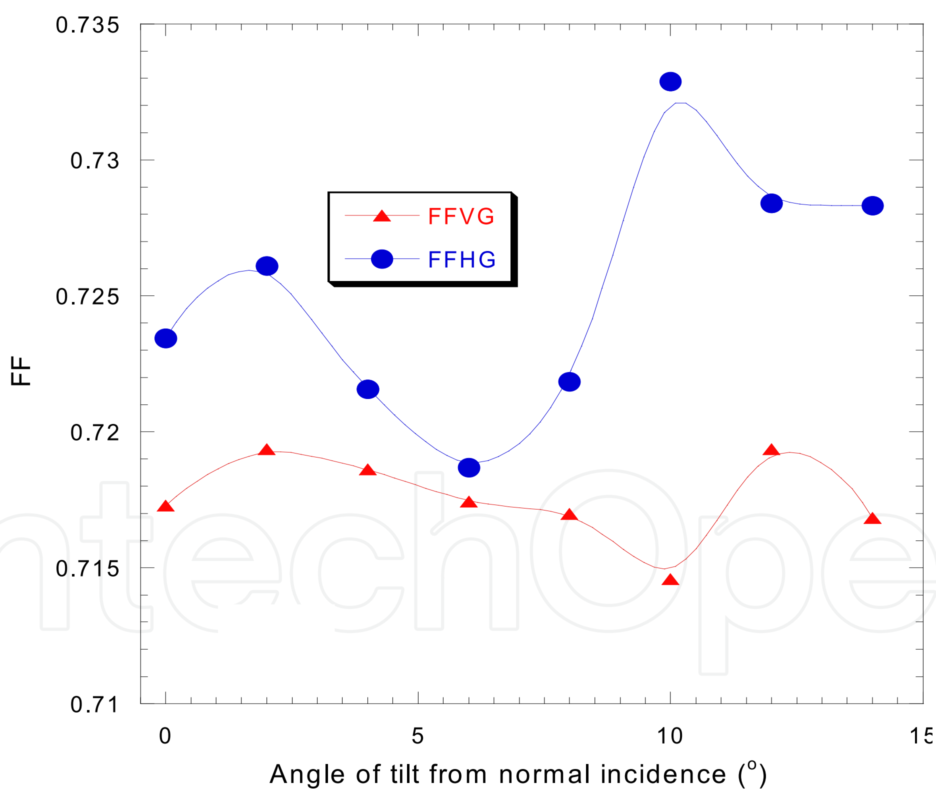


Fig. 10. Comparison of fill-factor for horizontal and vertical grooves.

8. Flux distribution and ray-tracing results

The local concentration ratios (C_L) and the ray-tracing results are shown in table 1. The effective specular reflectance (R_{eff}) is also compared as shown in table 1.

Reflector material	C_L ratio (From flux measurements)	R^{eff} (From flux and Ray-tracing Eqn. 4)	R^{eff} (From I-V measurements Eqn. 1)	Integrated specular reflectance
Miro	2.72	0.73	0.74	0.86
Rolled Foil	2.59	0.68	0.61	0.55
Anodized Aluminium	2.70	0.72	0.69	0.85

Table 1. Comparison of the local concentration ratios for the different reflector materials and the ray-tracing results.

Figure 11 shows the comparison of the local concentration ratio *(C_L)* of the solar cell illumination for the different groove orientations on the reflector as a function of the position along the solar cell width at normal incidence. It is observed that vertical orientation of the rolling marks give high concentration peaks along the surface of the solar cell, which is an indication of high heating. The horizontal rolling marks on the other hand give reduced peaks across the solar cell width an indication of an even illumination of the solar flux *(C_LHG curve on the figure)*. There is no concentration at the centre of the solar cell because all the rays reach the solar cell directly without any reflection *(C_LVG curve on the figure)*.

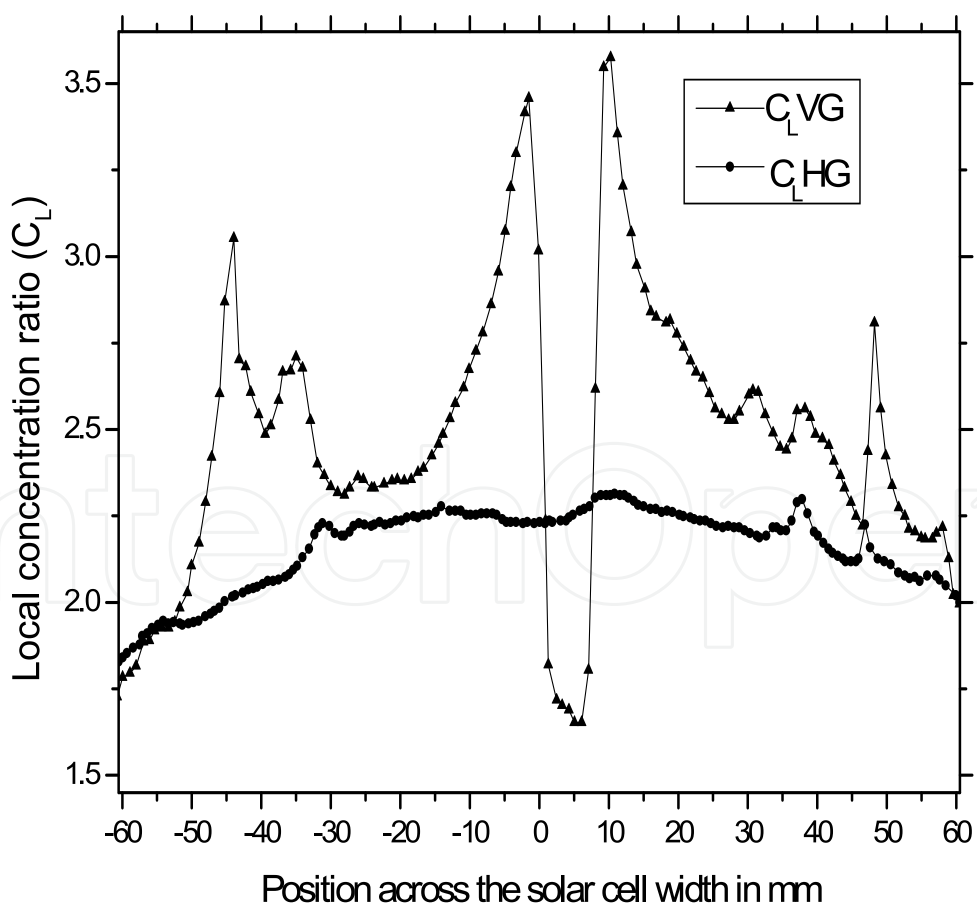


Fig. 11. Comparison of the local concentration ratio for the different groove orientations measured by the flux distribution apparatus. currents for horizontal and vertical grooves.

9. Conclusions

The CPC element with a geometrical concentration ratio of 3.6 has been analysed with different reflector materials. The short circuit current increased within a factor of 2.4 and 2.7. The fill factors decreased from 0.72 for the reference module to 0.65 under concentration, giving a percentage decrease of about 10%. The decreased fill factor during concentration was a result of high and non-homogenous irradiance that increased the resistive losses during concentration. The rolled aluminium reflector did not perform as expected in the fill factor improvements although behaved relatively well with the flux distribution measurements. From the flux distribution measurements, the rolled aluminium could performance better with an improved CPC geometry. Concentrator geometry with a uniform intensity distribution would be desirable since the cell with the lowest irradiance limits the power output from a module.

The effective specular reflectance values from the short-circuit current and those from the ray-tracing techniques were comparable to within 10% at normal incidence.

However, the rolled aluminium reflector has a potential for use as PV-CPC reflector for cost reduction. The cost of rolled aluminium is 2 to 3 times less than the cost of anodized aluminium and 6 times less than the cost of the Miro reflector per square metre. It is recommended that further work be done on different groove sizes and different groove orientations in improved geometries. It is expected that reflectors with grooves parallel to the trough would give stronger scattering across the module and better performance in terms of fill factor.

We have further demonstrated that a semi-diffuse aluminium sheet reflector with rolling grooves oriented parallel (HG) to the plane of the solar cell module can improve the fill-factor as it scatters the solar flux evenly across the solar cell module. It is the even scattering that causes uniform distribution of currents within the solar cell and therefore reduces the heat spot formation. Although the differences in the fill-factor were minimal between horizontal grooves and vertical grooves, the Goniometric measurement results show remarkable differences in the angular scattering of the light flux across the solar cell. From the Goniometric results, larger scattering angles are observed from the rolling grooves aligned perpendicular to the direction of scattering or the plane of scattering.

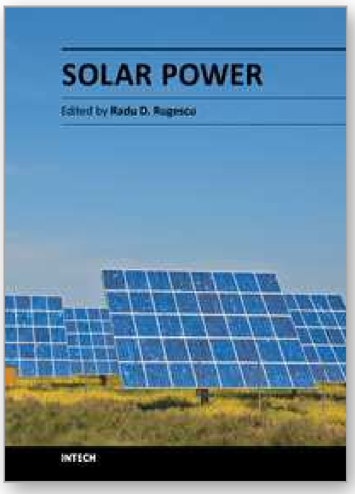
10. Acknowledgements

This work was sponsored by Uppsala University through the financial support of the International Science Programme (ISP). The hospitality at Lund University is highly acknowledged. The University of Zambia through the Dean, School of Natural Sciences and the Head, Department of Physics are acknowledged for their logistical support.

11. References

[1] Wenham S. R., Green M. A, and Watt M. E (1994): Applied Photovoltaics. Centre for Photovoltaic Devices and Systems, University of New South Wales

[2] Saitoh T. and Yoshioka K,; Preparation and properties of photovoltaic static concentrators: Renewable Energy 15 (1998) 566 – 571
[3] Goma S., Yoshioka K and Saitoh T.; Effect of concentration distribution on cell performance for low-concentrators with a three dimensional lens.: Solar Energy Materials and solar cells 47 (1997) 339 – 344.
[4] Luque A., Sala G. and Arboiro J. C.: Electric and thermal model for non-uniformly illuminated concentration cells: Solar Energy Materials and Solar Cells 51 (1998) 269 – 290.
[5] Perers B., and Karlsson B., External reflectors for large solar collector arrays, simulation model and experimental results. Solar Energy 51(5) (1993) 327 - 337
[6] Ronnelid M., Perers B., and Karlsson B: Construction and testing of a large-area CPC collector and comparison with a flat-plate collector; Solar Energy 57 (1996) 177 – 184.
[7] Karlsson B., A large bifacial photovoltaic-thermal low concentrating module. 17th PVSEC, Munich, Germany, 2001.
[8] Brogren M., Nostell P., and Karlsson B., Optical Efficiency of a PV-thermal hybrid CPC module for high latitudes: Solar Energy, 69(6): (2001) 173 – 185
[9] Brogren M., Karlsson B., and Hakansson H.: Design and modeling of low- concentrating Solar Energy Systems and investigation of irradiation distribution on modules in such systems, in 17th EUPVSEC 2001. Munich, Germany.
[10] Hatwaambo S., H. Hakansson, J. Nilsson and B. Karlsson: Angular characterization of low concentrating PV-CPC using low cost reflectors, Solar Energy Materials and Solar Cells 92 82008) 1347-1351
[11] Nilsson J., Optical design and characterization of solar concentrators for photovoltaics, Lund University, Licentiate Thesis, 2005.



Solar Power
Edited by Prof. Radu Rugescu

ISBN 978-953-51-0014-0
Hard cover, 378 pages
Publisher InTech
Published online 15, February, 2012
Published in print edition February, 2012

A wide variety of detail regarding genuine and proprietary research from distinguished authors is presented, ranging from new means of evaluation of the local solar irradiance to the manufacturing technology of photovoltaic cells. Also included is the topic of biotechnology based on solar energy and electricity generation onboard space vehicles in an optimised manner with possible transfer to the Earth. The graphical material supports the presentation, transforming the reading into a pleasant and instructive labor for any interested specialist or student.