

DESIGN AND EVALUATION OF A LOW-COST CONCENTRATOR
PHOTOVOLTAIC (PV) SYSTEM USING SEMI-DIFFUSE
STRUCTURED ALUMINIUM REFLECTORS

By

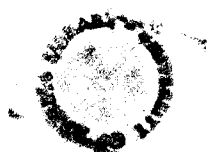
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A dissertation submitted in partial fulfilment of the requirement for the
degree of Master of Science in Physics

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DECLARATION

I, Joseph Simfukwe, hereby declare that this dissertation is my own work and that it has not been submitted and is not being currently submitted in part or in whole for the award of a degree at any other University.

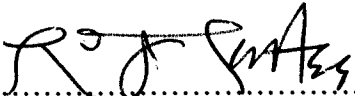
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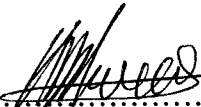
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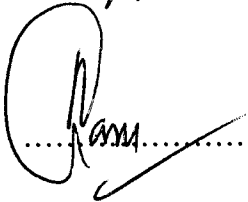
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ABSTRACT

The production of energy from fossil fuels and nuclear materials has environmental drawbacks. These drawbacks include the creation of nuclear waste and the pollution associated with fossil fuels which lead to global warming and climate change. It is apparent that alternative and sustainable sources of energy must be found. A potential solution to this problem is solar electricity. Currently, solar panels are expensive and hence uneconomical for most consumers. The use of solar concentrators creates a potential for less expensive electricity because concentrators raise the amount of incident radiation over a relatively small area of the absorber. The reduction in cost is achieved by reducing the module area and by the use of low-cost reflectors. However, specular reflectors cause highly concentrated heating and form hot spots on the solar module cells. These hot spots are a result of uneven concentration of radiation. The overall effect is a reduced fill factor and reduced overall efficiency of the system. In this dissertation, we investigate an alternative solution to the problem of non-even illumination which uses locally available low-cost semi-diffuse reflectors with four different groove orientations scribed on them so as to scatter the radiation flux onto the module. The groove orientations were plain sheet (NG), horizontal (HG), vertical (VG), and criss-cross (CG). Our results show that locally purchased semi-diffuse aluminium structures can be used as booster reflectors with a performance comparable with that of commercial high specular reflectors. The results also show that the criss-cross grooves (CG) gave the highest fill factor followed by the horizontal grooves (HG) and then the vertical grooves (VG). The plain sheet with no grooves (NG) had the smallest fill factor. The results also show that the drop in the fill factor from the reference value was about 3% for CG and HG, while the drops for vertical grooves

(VG) and the plain sheet were about 8% and 12% respectively. The power output increased by 33% for the CG and 52% for the HG orientations. The VG and the NG had 65% and 64% increases in power output respectively. Although the VG and NG orientation had high power output, they had high currents which caused hot spots and an overall reduction in the performance of the module. CG and HG orientations were the best materials, as these scattered the radiation flux and produced higher fill factors. The better the fill factor, the better the performance and the longer the life span of the photovoltaic (PV) system.

DEDICATION

To my beloved wife **Mushabase**

and

Children **Mapalo, Chiyembekezo and Nataizya.**

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Many people have contributed to this dissertation in one way or another. I would like to express my gratitude to them all. However, a few deserve special mention:

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I would like to thank my mother **E. Namfukwe** and my father **J. Simfukwe**, who constantly prayed for me to succeed. I am grateful to my in-laws, **Mr. G. D. Zulu** and **Mrs. E. Zulu** for encouraging me to pursue higher education.

My beloved wife **Mushabase** earns special honor and thanks for taking on family responsibilities during my absence. Her patience and understanding of my absence from the family gave me peace of mind and strength to carry on the study. My sincere apology to our children, **Mapalo, Chiyembekezo** and **Nataizya** who missed fatherly love in their critical moments of growth and development. To them this work is dedicated.

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List of symbols and abbreviations

a	half width exit aperture of CPC	[m]
ac	alternating current	[A]
A	half width entrance aperture of CPC	[m]
A_m	active area of module cells	[m ²]
A_a	entrance aperture area	[m ²]
A_{ab}	absorber area	[m ²]
C	concentration ratio	[--]
C_g	geometrical concentration ratio	[--]
C_m	maximum concentration ratio	[--]
dc	direct current	[A]
C_L	local concentration ratio or brightness factor	[--]
D	entrance aperture diameter of a concentrator	[m]
d	size of the exit aperture of a concentrator	[m]
E_g	band gap	[eV]
f	focal length	[m]
FF	fill-factor	[--]
G_{sc}	solar constant	[W/m ²]
h	Planck's constant	[J-s]
I_m	current maximum	[A]
I_{sc}	short-circuit current	[A]
I_0	dark saturation current	[A]
I_N	solar intensity incident on area A_m	[W/m ²]
k	Boltzmann constant	[J/K]

MPP	maximum power point	[--]
P_m	power maximum	[W]
q	absolute value of electric charge	[C]
R_s	series resistance	[Ω]
R_{sh}	shunt resistance	[Ω]
V	voltage	[V]
V_m	maximum voltage	[V]
V_{oc}	open-circuit voltage	[V]
V_{mp}	voltage at maximum power point	[V]

GREEK SYMBOLS

θ_i	angle of incidence on a given surface	[°]
θ	angle of incidence on a given surface	[°]
θ_c	acceptance half angle	[°]
θ_z	zenith angle	[°]
η	overall efficiency	[--]
η_o	optical efficiency	[--]
η_{Th}	thermal efficiency	[--]
η_E	electrical efficiency	[--]
σ	Stefan-Boltzmann constant	[W/m ² /K]
ϕ	geographic latitude of a place, north positive	[°]
Φ	the angle subtended by the axis of the parabola and the absorber normal	[°]

CHAPTER ONE

INTRODUCTION

The world energy demand has been increasing rapidly as a result of population increase and rising standards of living especially in rural and developing nations. On the other hand, climate change as a result of man-made emissions of carbon dioxide, methane and other gases is now recognized as a major threat facing the planet. Acid rain from sulphur and nitrogen oxides is damaging waterways and fisheries as well as contributing to the damage of forests, crops and buildings in various places in the world. It is apparent that alternative and sustainable sources of energy must be found to mitigate some of the mentioned effects.

A potential solution to these problems is solar electricity. The earth receives 5.4×10^{24} J of solar energy annually through radiative transfer [1]. This energy is only about $4.55 \times 10^{-8}\%$ of the total energy emitted by the Sun. Yet this is roughly 10^4 times the global annual energy consumption [1]. Putting this energy to use would reduce the reliance on environmentally unfriendly sources of energy. However, the costs of solar panels compared to the amount of power they produce make them uneconomical for most end-users. The use of solar concentrators creates a potential for producing less expensive electricity by reducing expensive solar cell area with inexpensive optical materials such as refracting plastics or metal reflectors. Currently, mirror-like reflectors (specular materials) are used for solar thermal applications while lenses are used in photovoltaic (PV) systems. The use of lenses in photovoltaic systems may not reduce the cost of electricity to affordable levels because they are expensive.

Highly specular materials have high reflectance and are good in imaging optics for high concentration, whereas semi-diffuse reflectors are preferred in non-imaging optics for flux scattering. The module cost can be reduced if low-cost materials are used to concentrate the solar energy flux across a small module area. The other problem in concentrating photovoltaic systems without active cooling is the formation of hot spots on the solar module cells. These hot spots are the result of uneven concentration of radiation over the solar module cells. The overall effect of concentrated heating is the reduction in the fill factor of the solar module and the subsequent decrease in the overall efficiency of the system. Fill factor is a key parameter in evaluating the performance of solar cells. It is defined as the ratio of the actual maximum power obtainable to the theoretical power.

The aim of this dissertation is to address the problem of uneven illumination of concentrating photovoltaic systems. This is achieved by designing, constructing and evaluating a low-cost concentrator system using locally available semi-diffuse aluminium reflectors with four different groove orientations scribed on it to improve the fill factor (FF) of the module. The problem of module cost is addressed by using a module string to reduce the amount of silicon material in comparison with conventional module.

The fill factor is an important parameter that measures the overall performance of the solar module. A solar module with a high fill factor is able to produce high power for a long period of time. Therefore by improving the fill factor of the module, both the power output and the durability of the module are increased. We use four different groove orientations on the reflector to determine a better fill factor improvement for

the solar cell module. Literature [2] points out that the use of rolling grooves oriented parallel (horizontal grooves) 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.

1.1 Objectives

The objectives of this research are three fold:

- To design a concentrator system.
- To construct a concentrator system from locally available low cost materials such as plywood and semi-diffuse aluminium structures.
- To evaluate the performance of the concentrator system based on the groove orientations.

1.2 Statement of the Problem

The most expensive component in a conventional solar photovoltaic (PV) system is the solar module. The primary aim of a concentrator is to significantly reduce the cost of electricity by replacing expensive solar cell area with inexpensive optical materials. Currently, mirror-like reflectors (specular materials) are used for solar thermal applications while lenses are used in photovoltaic systems. The use of lenses in PV systems may not reduce the cost of electricity to affordable levels because they are expensive. The module cost could be reduced if low-cost materials are used to concentrate the solar energy flux across a small module area. The other problem in concentrating photovoltaic systems without active cooling is the formation of hot spots on the solar module cells. These hot spots are a result of uneven concentration of radiation falling on the solar module cells. The overall effect of concentrated heating is a reduction in the fill factor of the solar module and a subsequent decrease in the

overall efficiency of the system. This dissertation seeks to address the problem of non-even illumination in low concentrating photovoltaic systems by designing, constructing and evaluating a low cost concentrator system, using locally available low-cost semi-diffuse aluminium reflectors with four different groove orientations scribed on them so as to improve the fill factor.

1.3 Significance of the Study

The importance of this study derives from the fact that the solution of the problem of non-uniform irradiance on the concentrating photovoltaic (CPV) system will lead to the production of cheap solar electricity and hence increase the accessibility of solar power. This will reduce the demand for energy from fossil fuels and nuclear materials, whose use results in a number of environmental hazards.

1.4 Outline of Dissertation

The dissertation is organised as follows: We give a background to our research and objectives in Chapter One. In Chapter Two we review the physics of solar cells and concentrator systems. In Chapter Three we describe the method, the measurement techniques, and the instruments used in this work. We present and analyse the experimental results in Chapter Four and finally in Chapter Five we give the conclusions and suggest the main recommendations for future work.

CHAPTER TWO

PHYSICS OF SOLAR CELLS AND CONCENTRATOR SYSTEMS

2.1 The Photovoltaic Effect

The photovoltaic effect is the process by which solar energy is converted directly into electrical energy when light falls on a semiconductor device. The photovoltaic effect was first reported by Edmund Becquerel in 1839 when he observed that light falling on silver coated platinum electrode immersed in electrolyte produced an electric current [3,4,5].

Sunlight is composed of photons or "packets" of solar energy which contain different amounts of energy that correspond to different wavelengths of the solar spectrum. When photons strike a photovoltaic (PV) cell, they may be reflected or absorbed, or they may pass right through. The absorbed photons generate electricity. The energy of a photon is transferred to an electron in an atom of the semiconductor device. With its new found energy, the electron is able to escape from its normal position associated with a single atom in the semiconductor to become part of the current in an electrical circuit.

Photovoltaic cells have a built-in electric field which provides the voltage needed to drive the current through an external load. Figure 2.1 shows how a photovoltaic device generates electricity. Photons of light energy incident on the photovoltaic cell create an electron-hole pair. When a load is connected to the cell, the electron travels through the circuit, does work, and recombines with the hole.

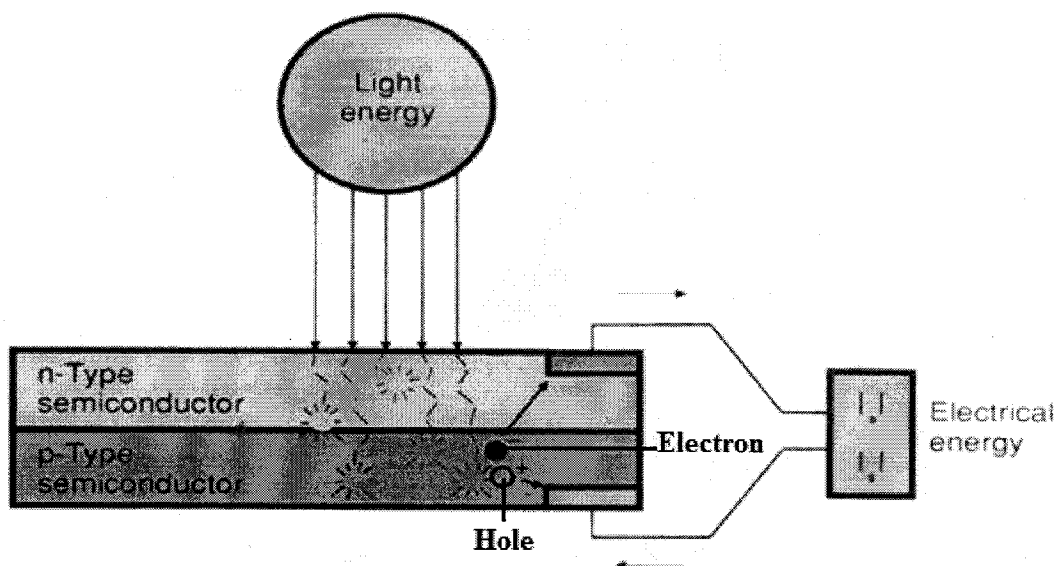


Figure 2.1 A photovoltaic device

(Source: <http://photovoltaics.sandia.gov/docs/PVFEffIntroduction.htm>)

2.2 Solar Cells

2.2.1 Photovoltaic cells and power generation

The solar cell is the basic building block of solar photovoltaic systems. The cell can be considered as a two-terminal device which conducts like a diode when there is no light and generates a photo voltage when illuminated by the sun. Usually, a solar cell is a thin slice of semiconductor material about 100cm^2 in area. The surface is treated to reflect as little visible light as possible and appears dark blue or black. A pattern of wires is imprinted on the surface to make electrical contacts. When illuminated by the sun, this basic unit generates a dc photo voltage of 0.5V to 1.0V and a photocurrent of tens of milliamps per cm^2 [6, 7, 8]. Although, the current is reasonable, the voltage is too small for most applications. Therefore, to produce useful dc voltages, the cells are connected together in series and encapsulated into modules which may then be connected in series or parallel to meet the desired voltage and current. Figure 2.2

shows a solar cell made from a poly-crystalline silicon wafer and Figure 2.3 shows a solar module string made from connecting ten cells in series.

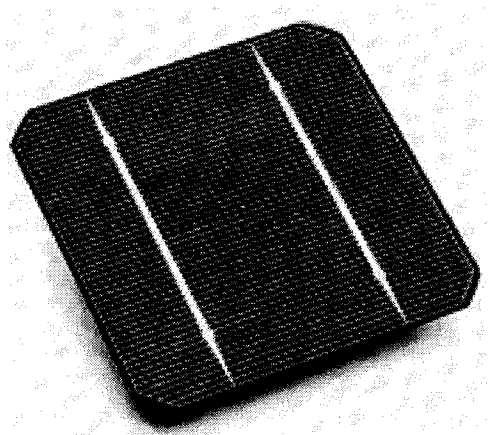


Figure 2.2 A solar cell made from a poly-crystalline silicon wafer.

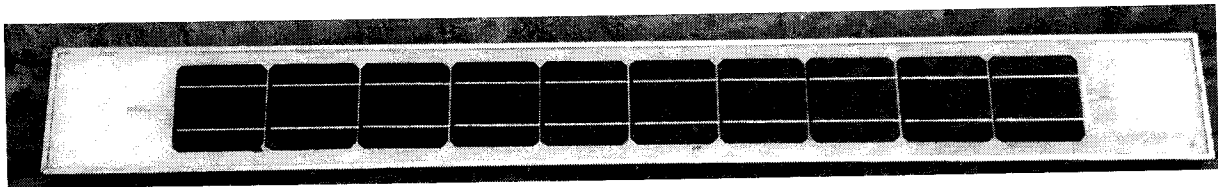


Figure 2.3 A solar module string with 10 cells in series

The modules are constructed with laminates and have a back sheet and a cover of low-iron glass which protects the front surface of the material while maintaining a high transmissivity. A structural outer casing is used to protect the glass and the solar cells.

A module typically contains 26 to 36 cells in series to generate a dc output of 12V under standard illumination conditions. Standard test conditions consist of an irradiance of 1kW/m^2 , a cell temperature of 25°C and standard reference AM1.5 spectrum (AM1.5 spectrum is the spectrum provided on a clear day by the sun when

its rays have passed through an average depth of atmosphere to the Earth's surface) [6,9,10]. The 12V modules can be used singly, or connected in parallel and series into an array with a large current and voltage output according to the power demanded by the application. Solar cells within a module are integrated with bypass and blocking diodes in order to avoid the complete loss of power which would result if one cell in the series failed. Figure 2.4 shows modules connected in series into strings and then in parallel to form an array in order to produce sufficient current and voltage.

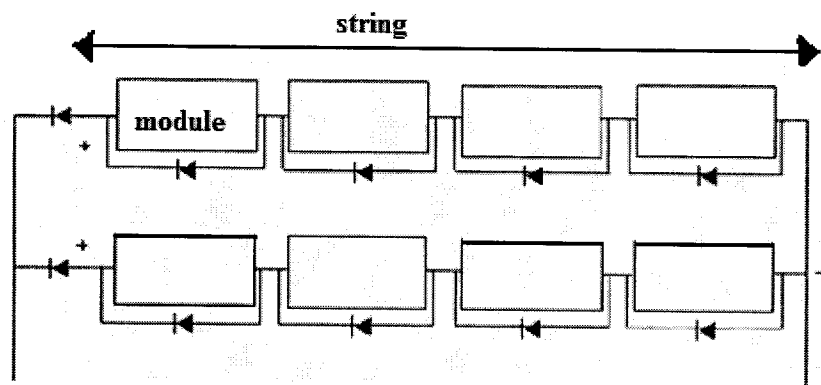


Figure 2.4 Modules connected in series and diodes fitted to a large array.

A photovoltaic generator is an array designed to generate power at a certain current and at a voltage which is some multiple of 12V under standard illumination. For most applications, the illumination varies too much for efficient operation and the photovoltaic battery generator must be integrated with a charge storage system (battery) and with components for power regulation (conditioner) as shown in Figure 2.5. The battery is used to store charge generated during sunny periods and the power conditioning unit ensures that the power is produced regularly and with less sensitivity to the solar irradiation. In order to power alternating current (ac) designed appliances and for integration with an electricity grid, the dc current supplied by the photovoltaic

modules is converted to ac of appropriate frequency using an inverter which is part of the power conditioning unit.

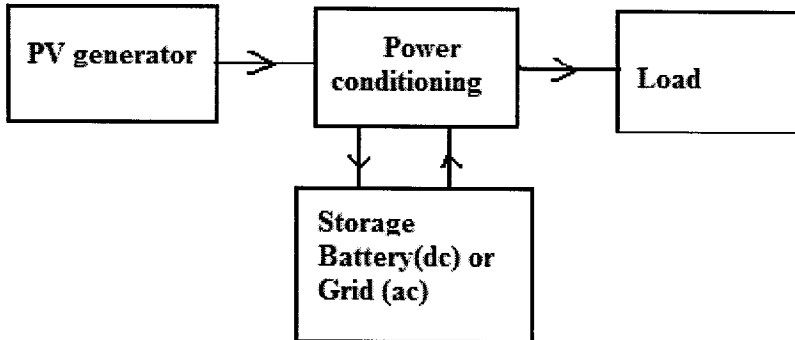


Figure 2.5 showing the integration of photovoltaic array with componets for charge regulation.

2.2.2 Solar cell materials and structures

Most solar cells are made from semiconductor materials that are deposited or arranged in various structures and designs using a number of manufacturing methods to reduce cost and to achieve maximum efficiency. Certain semiconductors such as amorphous or polycrystalline silicon, gallium arsenide, cadmium telluride and copper-indium-diselenide are suitable for photovoltaic conversion of solar radiation. Silicon is the most commonly used material and is available in various forms, viz, single crystalline, multi-crystalline and amorphous. Solar cells can be arranged in various ways; the four basic structures are homo-junction, hetero-junction, p-i-p, n-i-p, and multi-junction.

2.2.3 The p-n junction

In order to understand how a solar cell works, it is necessary to understand the *p-n* junction. A *p-n* junction is formed when an *n*-type semiconductor is put together with

a p -type semiconductor. The n -type semiconductor is doped with donor atoms that have more electrons than the surrounding material, and the p -type semiconductor is doped with acceptor atoms that have fewer electrons than the surrounding material. Atoms in the p -type semiconductor with fewer electrons than the surrounding material are said to have excess holes. These holes are thought of as positive entities much like electrons in that they can move throughout the material and contribute to the current. When a hole and an electron meet, they essentially annihilate each other in a process called recombination.

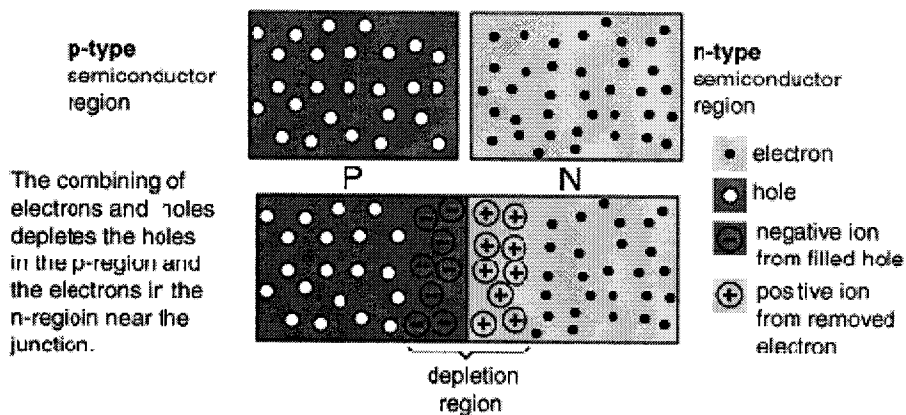


Figure 2.6 p - n Junction

(source: www.hyperphysics.phyastr.gsu.edu/hbase/solids/pnjun.html)

Putting an n -type semiconductor together with a p -type semiconductor creates an electron/hole concentration gradient. This concentration gradient causes a diffusion current with electrons diffusing to the p -side and holes diffusing to the n -side. The area in which this diffusion takes place is called the depletion region as shown in Figure 2.6. When electrons from the n -side diffuse to the p -side they meet with holes and recombine leaving negatively charged donor atoms on the p -side. The holes from the

p -side diffusing to the n -side create positively charged donors on the n -side. The ionized donors create an internal electric field in the depletion region [11, 12] as shown in Figure 2.7. The electric field in the region works as a barrier preventing more electrons from diffusing from the n -side to the p -side. Only those electrons with high enough energy to overcome the field can make the transition. In equilibrium there is no net current, and so the diffusion current and the drift current (due to the internal electric field) cancel each other.

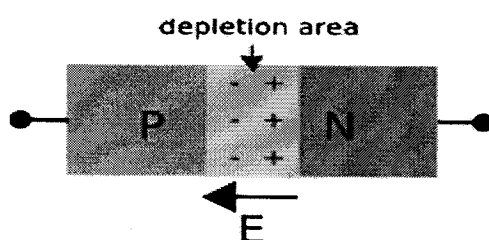


Figure 2.7 Creation of internal electric field

2.2.4 The p-n junction under an applied bias

When a potential is applied across a p - n junction, it can either increase or decrease the internal electric field. If the negative side of the potential is connected to the p -side, then the electric field is increased. This is called reverse bias. Alternately, forward bias, where the positive side of the potential is connected to the p -side, results in the reduction of the internal field. During forward bias, the number of electrons on the n -side that cross the depletion region to the p -side increase by a factor of $\exp(eV/kT)$. Here e is the electronic charge, V is the applied voltage, k the Boltzmann constant, and T the absolute temperature. The resulting electron current from the n -side to the p -side is $I_{eo} \exp(eV/kT)$. There is a small electron current I_{eo} from the p -side to the

n-side. This is due to the very few electrons (minority carriers) in the *p*-side. Thus the total electron current is:

$$I_e = I_{eo} \left(e^{eV/kT} - 1 \right) \quad (2.1)$$

The same relation holds for the hole current from the *p*-side to the *n*-side.

A forward bias results in a hole current:

$$I_h = I_{ho} \left(e^{eV/kT} - 1 \right) \quad (2.2)$$

where I_{ho} is the equilibrium hole current. Adding Equations (2.1) and (2.2) together gives the

total current I , also known as the diode current as

$$I = I_e + I_h = I_o \left(e^{eV/kT} - 1 \right) \quad (2.3)$$

I_o is sometimes called the dark saturation current [13, 14].

2.2.5 Solar cell principles

When photons of a high-enough energy are incident on a semiconductor, they create an electron-hole pair. This can be understood by looking at the energy band diagram of a semiconductor. Figure 2.8 shows the three distinct energy bands of electrons in a semiconductor. Valence band states are fully occupied by electrons and the first empty band (conduction band) is separated by a band gap. Electrons in the valence band cannot be involved in conduction because they possess energy lower than the band gap. When a photon with energy greater than the band gap is incident on a semiconductor, it gives an electron in the valence band enough energy to move to the conduction band. Both the electron in the conduction band and the hole that has been created in the valence band can be involved in the conduction of a current under an electric field [14].

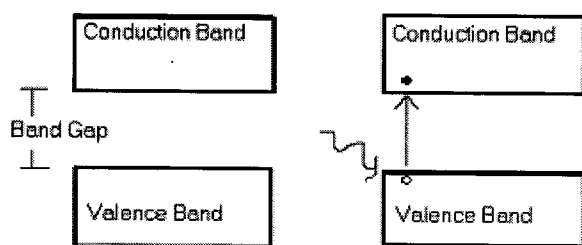


Figure 2.8 Band diagram and electron-hole pair production

A solar cell can be constructed by putting a very thin, heavily doped n -type layer on top of a thicker p -type layer. As can be seen in Figure 2.9, the depletion region is mostly on the p -side. Because the n layer is so thin, most photons penetrate into the depletion region or the p -side before creating an electron-hole pair. When an electron-hole pair is created in the depletion region the electric field moves the electron into the n -side and the hole into the p -side. This gives the previously neutral n -side a negative charge and the previously neutral p -side a positive charge. When a load is connected to the cell, the electron can travel through the circuit, do work, and recombine with the hole.

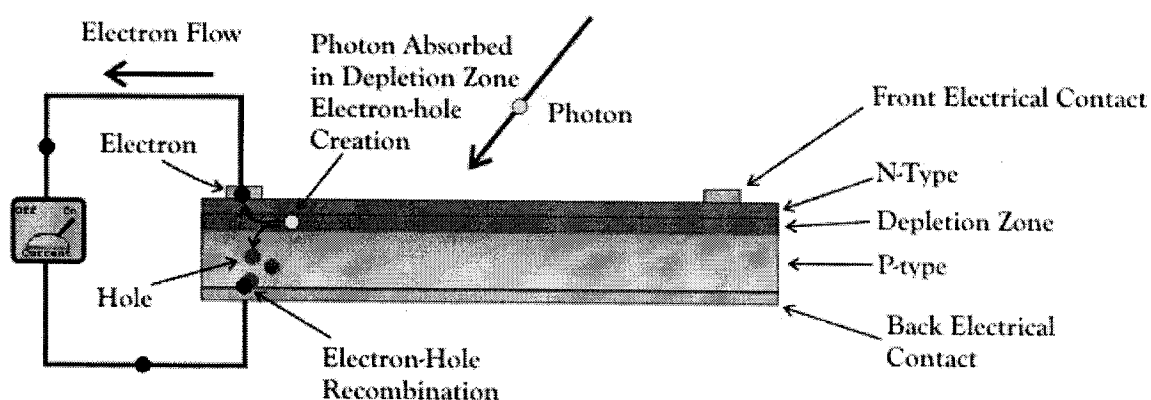


Figure 2.9 Electron-hole pair behaviour in solar cell

(Source: www.imagesco.com/articles/photovoltaic/photovoltaic-pg4.html)

If the light penetrates into the neutral p -side, then there is no electric field to separate the electron-hole pair. Instead the electron and the hole diffuse at random through the material and recombine if they meet. When an illuminated solar cell is short-circuited, a current flows through the circuit in the opposite direction to the photocurrent I_{ph} . The photocurrent is directly proportional to the intensity of the light. If the cell is in a circuit with some resistance, then there is a voltage across the junction and the total current under forward bias is given by

$$I = I_{ph} - I_0 \left(e^{eV/kT} - 1 \right) \quad (2.4)$$

2.2.6 Current-voltage (I-V) characteristic curve of the solar cell

The electrical output from a cell or a PV module is described by the I - V characteristic and it depends on the material properties of the semiconductor. The current-voltage (I-V) curve usually shows the possible combinations of current and voltage of the photovoltaic device. A typical I-V curve is shown in Figure 2.10. Two important parameters to note in a photovoltaic module are:

- *Short-circuit current* (I_{sc}) – This is the maximum current that the cell can provide and it occurs when the cell is short circuited. Unlike other small-scale electricity generating systems, PV cells are not harmed by being shorted.
- *Open-circuit Current* (V_{oc}) – This is the maximum voltage that exists between the cell terminals and is obtained when there is no load connected across the terminal.

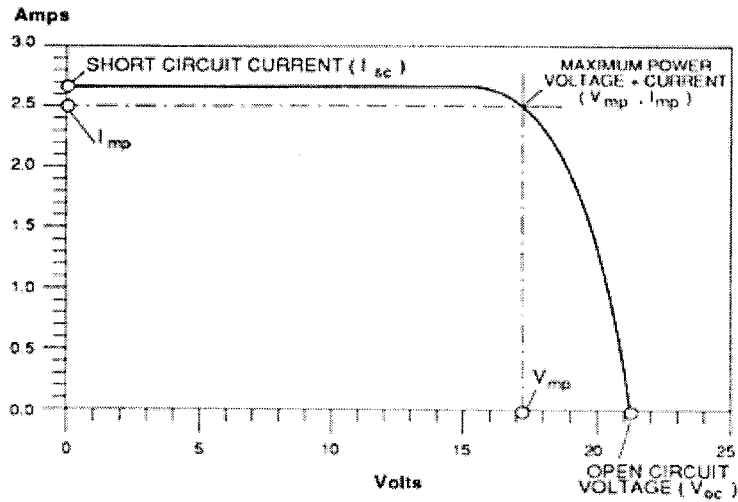


Figure 2.10 Typical I - V curve for a solar cell under illumination.

2.2.7 Maximum power point (MPP) and fill factor (FF)

The product of the maximum current and maximum voltage is the maximum power output for that operating condition and it occurs on the 'knee' of the I - V curve as shown in Figure 2.10. The power output at maximum power point under a light intensity of 1000 W/m^2 is known as the “peak power” of the cell or module and solar cells and modules are rated in terms of “peak” watts, W_p . The fill factor FF is a measure of the junction quality and the series resistance of the cell or module. It is an important characteristic in evaluating solar cell or module performance and is defined as the ratio of maximum power and the product of open circuit voltage (V_{oc}) and short-circuit current (I_{sc}) as

$$FF = \frac{I_{mp} V_{mp}}{I_{sc} V_{oc}} \quad (2.5)$$

Here I_{mp} and V_{mp} are the current and the voltage at the maximum power point on the I - V curve. Under non-concentrating conditions, the fill factor of the solar cell module drops slightly as the temperature of the cells gradually increases. This increase in

temperature becomes prominent under concentration and a further drop in the fill factor is observed under high concentration [2, 15]. The decrease in fill factor during concentration is a result of high and non-uniform irradiance that increases the resistive losses during concentration. One option for mitigating the high non-uniform illumination in low concentrating compound parabolic concentrators (CPC) is to use scattering reflective elements with rolling marks aligned along the plane of the module cells [2,15]. The rolling marks or grooves lead to strong anisotropic scattering of the reflected light. Previous studies using highly specular materials such as miro, anodized aluminium and rolled aluminium with horizontal grooves as reflective elements show a decrease in fill factor of about 10% [2]. It is expected that different reflector materials with grooves parallel to the trough would give stronger scattering across the module and better performance in terms of fill factor.

2.2.8 Efficiency of photovoltaic module

The conversion efficiency of a solar cell module is the ratio of electrical energy generated to the irradiation falling on it. The efficiency is dependent on the material properties, such as band gap energy (E_g) and on the spectral distribution of the incident light. The electrical efficiency of a solar cell module is given by the following relations:

$$\eta = \frac{V_{mp} I_{mp}}{I_N \cdot A_a} \quad (2.6)$$

or

$$\eta = \frac{FF \cdot I_{sc} \cdot V_{oc}}{I_N \cdot A_a} \quad (2.7)$$

where I_N is the irradiance on the cell or module and A_a is the surface area. The output of a PV module is limited by several factors and the following are some important ones:

- (i) A minimum energy of photon is required to create an electron-hole pair
- (ii) Optical losses
- (iii) Recombination losses

Optical and recombination losses reduce the module output. Optical losses occur due to the reflection of the incident radiation. Recombination losses occur due to several mechanisms and are of three types. In Auger recombination an electron recombines with a hole giving up the excess energy to another electron which then comes back to its original energy state releasing photons. Recombination also occurs through traps. Trap recombination occurs when an electron falls into a “trap” an energy level within the band gap caused by the presence of foreign atom or a structural defect. The third mechanism is the band to band recombination which occurs when an electron moves from its conduction band state to the empty valence band associated with the hole.

2.2.9 Effects of temperature on photovoltaic modules

The effect of temperature on the $I-V$ characteristics of a solar cell is shown in Figure 2.11. The solar radiation falling on a solar cell is not fully converted into electrical energy. The electrical energy is removed from the cell through the external circuit; however the thermal energy is dissipated by heat-transfer mechanisms. In a solar cell at a fixed irradiation level, increasing the cell temperature leads to decreased open-circuit voltage and a slightly increased short-circuit current I_{sc} . I_{sc} increases with temperature because the band-gap energy decreases and more photons have enough energy to create electron-hole pairs. But this effect is small. The main effect of

increasing the temperature of solar silicon cells is the reduction of V_{oc} and the fill factor. Therefore the overall effect is the reduction of the cell output voltage leading to reduction in the efficiency of the module. To improve the efficiency, heat transfer from the module should be maximized so that the cells operate at the lowest possible temperatures.

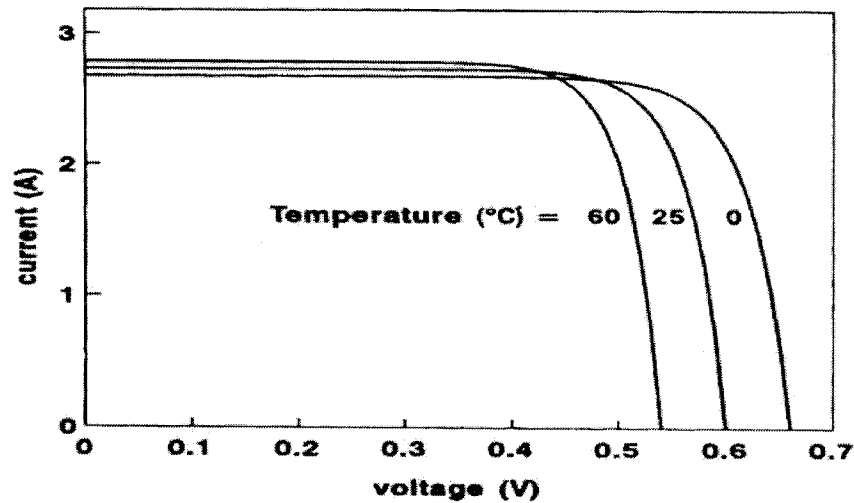


Figure 2.11 The effect of temperature on the I-V characteristics of a solar cell (Courtesy: www.powerfromthesun.net).

At high irradiation levels, the cell achieves higher temperatures, which reduces the output voltage. Therefore cooling is often required in concentrating solar systems.

2.2.10 Effects of irradiance on the I-V curve of PV cells

In a solar cell, the light-generated current is proportional to the flux of photons with energy greater than the band gap. The irradiation level is proportional to the photon flux and increasing the radiation level results in an increase in photon flux, which in turn generates proportionately higher current. Therefore, the short circuit current of a solar cell is directly proportional to the radiation level. The open-circuit voltage

increases logarithmically, and is usually neglected in practical applications. Solar cells respond to both diffuse radiation and beam radiation.

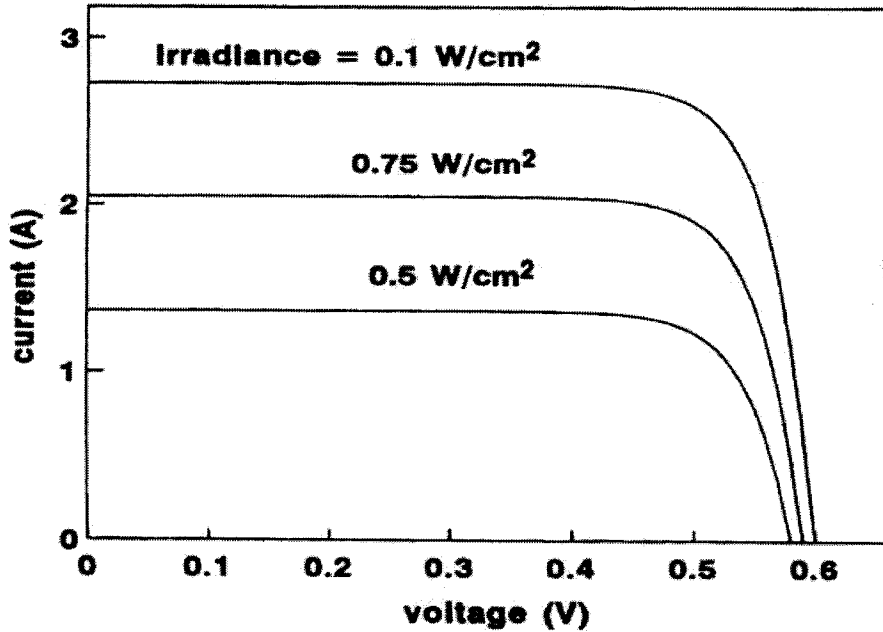


Figure 2.12 The effects of irradiance on the I-V curve of PV cells
(Courtesy: www.powerfromthesun.net)

2.2.11 Effects of parasitic resistances

Solar cells have inherent parasitic series and shunt resistance associated with them, both of which reduce the fill factor. The Series resistance R_s is due to the metal contact, particularly the front grid and the transverse flow of current in the solar emitter to the front grid. The Series resistance has no effect on the open-circuit voltage, but reduces the short-circuit current. The shunt resistance R_{sh} is due to the p-n junction quality and impurities near the junction. It has no effect on the short-circuit current, but reduces the open-circuit voltage. Figure 2.13 shows the equivalent circuit of a solar cell with both series and shunt resistances.

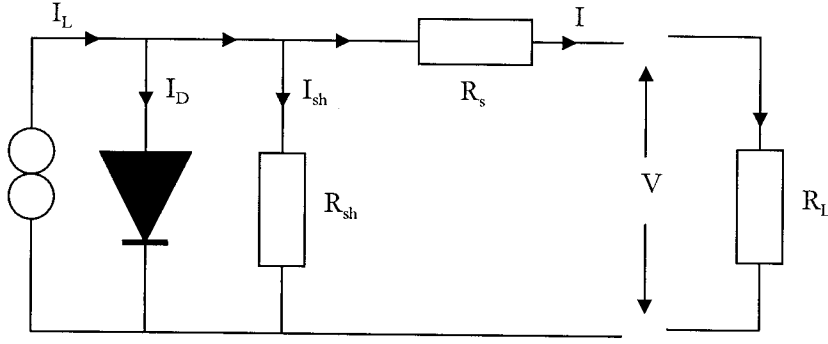


Figure 2.13 The equivalent circuit of a solar cell with both series and shunt resistances.

The governing equation for the current in Figure 2.13 is given by [6]

$$I = I_L - I_D - I_{sh} = I_L - I_0 \left[\exp\left(\frac{q(V + IR_s)}{nkT}\right) - 1 \right] - \frac{V + IR_s}{R_{sh}} \quad (2.8)$$

where I is the output current, I_L is the current generated by the incident light, I_{sh} is the shunt current, I_0 is the dark saturation current, I_D is the diode current, V is the output voltage, R_s is the series resistance, R_{sh} is the shunt resistance, n is the ideality factor, k is the Boltzmann constant, T is the absolute temperature and q is the electric charge.

2.3 Concentrators

2.3.1 Solar concentrators

The use of solar concentrators creates the potential for producing less expensive electricity when incorporated to high efficiency mono-crystalline or multi-crystalline solar cells. This is because both imaging and non imaging concentrators can be used to raise the amount of incident solar radiation on a relatively small area of the absorber [15]. In general, the materials used to build concentrators are less expensive than photovoltaic solar cells. The reflecting component takes up most of the area of a

concentrator system, and only a small amount of photovoltaic material is needed. Concentrating systems can reduce the unit cost (kWh/W_p) of solar electricity considerably the cost of solar cells is less than that of the power they produce.

However, the use of concentrators also has problems. Increasing the concentration ratio means also increasing the temperature at which energy is delivered to the absorber. This is undesirable in low-concentrating photovoltaic systems with conventional solar cells because the increase in temperature decreases the efficiency of the systems [15]. The other challenge faced with solar concentrators in photovoltaic systems without active cooling is the formation of hot spots on the solar module cells. These hot spots are the result of non-uniform irradiance of the solar module. Hot-spot heating occurs when there is one low-current solar cell in a string of several high-current solar cells, as shown in Figure 2.14.

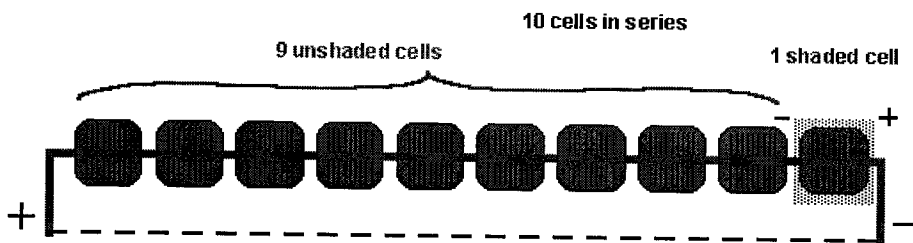


Figure 2.14 A shaded cell in a string of 10 cells reduces the current through the good cells.

One shaded cell in a string reduces the current through the good cells, causing the good cells to produce higher voltages that can often reverse bias the bad cell. If the operating current of the overall series string approaches the short-circuit current of the bad cell, the overall current becomes limited by the bad cell. The extra current produced by the good cells then forward biases the good solar cells. If the series string is short circuited, then the forward bias across all of these cells reverse-biases the shaded cell. Hot-spot heating

occurs when a large number of series connected cells cause a large reverse bias across the shaded cell, leading to large dissipation of power in the poor cell. Essentially the entire generating capacity of all the good cells is dissipated in the poor cell. The enormous power dissipation occurring in a small area results in local overheating, or "hot-spots", which in turn leads to destructive effects, such as cell or glass cracking, melting of solder or degradation of the solar cell [16,17,18]. As a result of this, photovoltaic cells need to be evenly illuminated, for otherwise the least-illuminated cell degrades the performance of the entire system. Figure 2.15 show cracks in a module due to heat dissipated in a shaded cell. A shaded cell is a least illuminated cell.

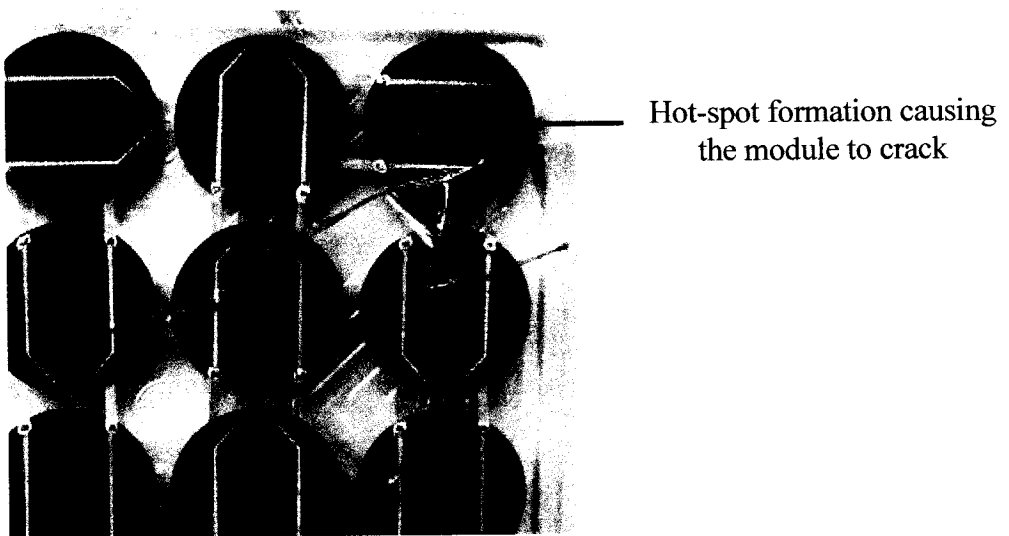


*Figure 2.15 Heat dissipated in a shaded cell causing the module to break
(Courtesy: <http://pvcdrom.pveducation.org/MODULE/Hotspot.htm>)*

The concentration of solar radiation can be achieved either by reflection (mirror-like reflectors) or by refraction (lenses) [19]. Currently mirror-like reflectors are used for solar thermal applications while lenses are used in photovoltaic systems. Thermal applications involve the conversion of solar energy to heat while photovoltaic systems convert solar energy directly into electricity. The most important reason why lenses are suitable for photovoltaics application is their ability to produce uniform

illumination when placed off focus [19]. Unfortunately, the refractive index of optical materials is highly dependent on the wavelength, which causes chromatic aberration. This aberration restricts the size of the solar cell and negatively affects its efficiency. This problem is solved by using achromatic refraction doublets but they are thick, heavy and require exotic glasses which make them expensive. Hence, the use of lenses as concentrators in photovoltaic system may not reduce the cost of photovoltaic electricity to affordable levels.

On the other hand, highly specular materials have very high reflectance and are good in imaging optics for high concentration. However, semi-diffuse reflectors are preferred in non-imaging optics for flux scattering so as to achieve an even illumination over the solar cell module. Diffuse reflectors have great potential for overall cost reduction in PV-thermal hybrids provided the problem of non-uniform irradiance can be solved or greatly minimized. Previous studies using highly specular materials such as miro, anodized aluminium and rolled aluminium foil as reflective elements [15] have shown that these materials could increase the short circuit current in photovoltaic cells from 2.4 to 2.7Amperes. However, the fill factor decreases to 0.65 from the reference value of 0.72, giving a percentage decrease of about 10%. The decrease in the fill factor was attributed to the high and non-homogenous irradiance that increased the resistive losses during concentration. Several design parameters such as the use of active or passive cooling mechanisms, the use of high-grade silicon solar cells, and/or the use of semi-diffuse reflectors such as rolled aluminium on existing CPC geometries have been tried and results show that though there has been an increase in the short circuit current, the problem of non-even illumination still exists. Literature [2] reveals that the use of rolling grooves oriented parallel (horizontal

grooves) 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 current within the solar-cell module.

2.3.2 Parameters characterizing solar concentrators

There are several parameters that characterize concentrating collectors; we give a brief description of some of them in this Section.

A generic concentrator as shown in Figure 2.16 consists of a concentrator entrance aperture of area A_a which is the area through which the radiant energy enters and an exit aperture area A_{ab} from where the radiation energy leaves the concentrating system.

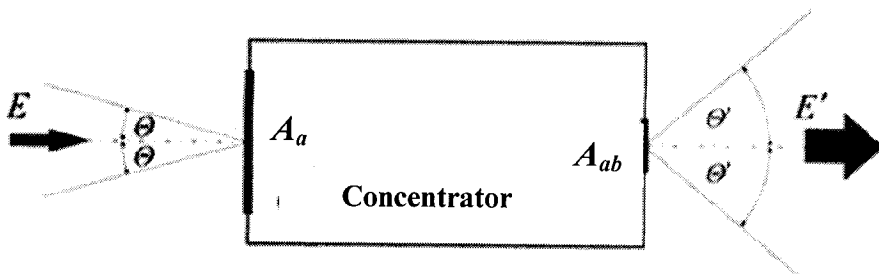


Figure 2.16 Scheme of a generic concentrator showing relevant aperture areas A_a and A_{ab} radiation densities E and E' and half angles of the radiation cones Θ and Θ'

- The *aperture area* A_a is the area through which the solar radiation energy is incident [20].
- The *absorber area* A_{ab} is the total area of the surface that receives the concentrated radiation. It is also the area from which useful energy can be obtained.
- The *acceptance angle* θ defines the angular limit to which the incident ray deviates from the normal to the aperture plane and still reaches the absorber/receiver. A concentrator with large acceptance angle needs only seasonal adjustment while a

concentrator with small acceptance angle is required to track the sun continuously and must be adjusted regularly.

- The *geometrical concentration ratio* C_g is the ratio of the aperture area to the absorber area.

$$C_g = \frac{A_a}{A_{ab}} \quad (2.9)$$

- The *local concentration ratio* C_L is the ratio of the solar radiation at any point on the absorber surface to the incident radiation at the aperture of the solar concentrator. This is the term used to describe non-uniformity of illumination and it is also known as the brightness concentration ratio [20].
- The *intercept factor* γ is the ratio of the energy intercepted by an absorber of given width to the total energy redirected by the focusing device. This is defined by Equation (2.10) where $I(x)$ is the solar flux at a certain position x .

$$\gamma = \frac{\int_{-w/2}^{+w/2} I(x) dx}{\int_{-\infty}^{\infty} I(x) dx} \quad (2.10)$$

- The *optical efficiency* η_o is the ratio of the energy absorbed by the absorber to the energy incident on the concentrator aperture. It includes the effect of the reflector/refractor surface, shape and reflection/refraction losses, tracking accuracy, shading, receiver-cover transmittance, and absorptance of the absorber.
- The *thermal efficiency* η_{th} is the ratio of the useful energy delivered to the system to the energy incident at the concentrating aperture. In a thermal conversion system, a working fluid is used to extract the energy from the absorber. The thermal performance of a solar concentrator is described by its thermal efficiency.

The incident solar energy consists of beam (direct) and diffuse radiation. However, the majority of the concentrating collectors can utilise only beam radiation.

- *The electrical efficiency η_E* describes the electrical performance of a solar concentrator and is defined as the ratio of the peak power to the total solar power received at the aperture.

$$\eta_E = \frac{P_m}{I_N \cdot A} \quad (2.11)$$

where P_m is the power maximum I_N is the solar intensity incident on area A .

2.3.3 The parabola

The parabolic shape is widely used as the reflecting surface for concentrating solar collectors. For an understanding of the design and the working of the compound parabolic concentrator, one has to understand the geometry of the parabola. A parabola is the locus of a point that moves so that its distances from a fixed line and a fixed point are equal. This is shown in Figure 2.17, where the fixed line is called the directrix and the fixed point F is the focus and the lengths FR and RD are equal. The line perpendicular to the directrix and passing through the focus F is called the axis of the parabola. The parabola intersects its axis at a point V called the vertex, which is exactly midway between the focus and the directrix.

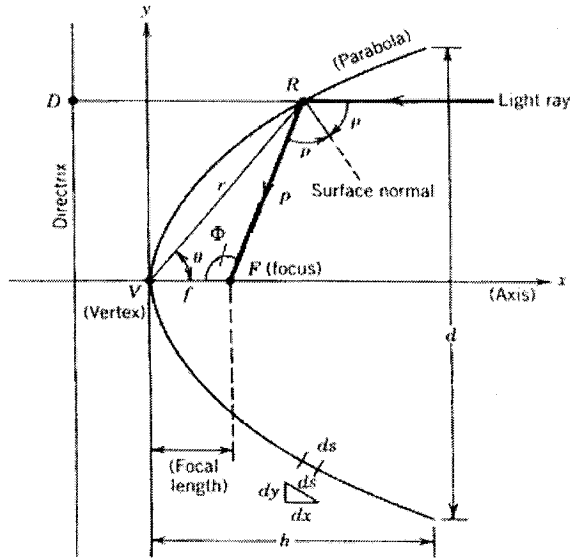


Figure 2.17 The parabola (courtesy: www.powerfromthesun.net).

If the origin is taken at the vertex V and the x -axis along the axis of the parabola, the Equation of the parabola is

$$y^2 = 4fx \quad (2.12)$$

where f , the focal length is the distance VF from the vertex to the focus. When the origin is shifted to the focus F as is often done in optical studies, with the vertex to the left of the origin by f , the Equation of the parabola becomes

$$y^2 = 4f(x + f) \quad (2.13)$$

In polar coordinates, using the usual definition of r as the distance from the origin and θ as the angle from the x -axis to r , we have for a parabola with its vertex at the origin and symmetrical about the x -axis as

$$\frac{\sin^2 \theta}{\cos \theta} = \frac{4f}{r} \quad (2.14)$$

Often in solar studies, it is more useful to define the parabolic curve with the origin at F and in terms of the angle Φ in polar coordinates. The angle Φ is measured from the line VF and the parabolic radius p , which is the distance from the focus F to the curve.

2.3.4 The compound parabolic concentrator (CPC)

Non-imaging optics is the branch of optics concerned with the optimal transfer of light radiation between a source and a target [21, 22]. Unlike traditional imaging optics, the techniques involved do not attempt to form an image of the source; instead an optimized optical system for optical radiative transfer from the source to the target is desired. In imaging optics designs like the burning glass, telescopes, microscopes or *parabolic shaped mirrors*, all rays leaving from a point on an object and entering into the aperture will be concentrated to a single point in the exit aperture independently of their path through the optical systems. That is how an image is generated. Imaging optics have inherent optical errors which do not allow them to achieve the maximum theoretical concentration ratio. For instance imaging optics can concentrate sunlight to a single point, producing at most the same flux at the surface of the sun. On the other hand non-imaging optics have been demonstrated to concentrate sunlight to 84,000 times the ambient intensity of sunlight.

Non-imaging systems only require that all rays entering the entrance aperture leave the exit aperture somewhere. It is not surprising that the fewer constraints of non-imaging systems lead to a higher flexibility concerning the concentrator design so that higher concentration ratios can be achieved. A simple example is a truncated cone with reflective inner surfaces, where the radiation enters through the larger opening and leaves through the smaller one. A very efficient design of a non-imaging concentrator

is a cone with a specific shape forming a segment of a parabola. Such a concentrator is called a compound parabolic concentrator (CPC) (see Figure 2.18).

Literature reveals that the compound parabolic concentrator was invented independently in the United States by Hinterberger and Winston [23], and in the Soviet Union by Baranov and Melnikov, as well as in Germany by Ploke [23]. The CPCs provide the highest concentrations permissible by thermodynamics for a given acceptance angle θ_c . The CPCs have large angles of acceptance and therefore require only intermittent adjustment towards the sun. Figure 2.18 shows a two dimensional (2D) CPC which consists of two distinct parabolic segments placed in such a way that the focus of one parabola is placed on the other. The axes of the two parabolic segments are oriented away from the CPC axis by the acceptance half angle θ_c . The slope of the parabolic reflector surface at the entrance aperture is parallel to the CPC's optical axis; therefore the solar rays entering the concentrator at the maximum acceptance angle are reflected tangentially to the surface of the absorber.

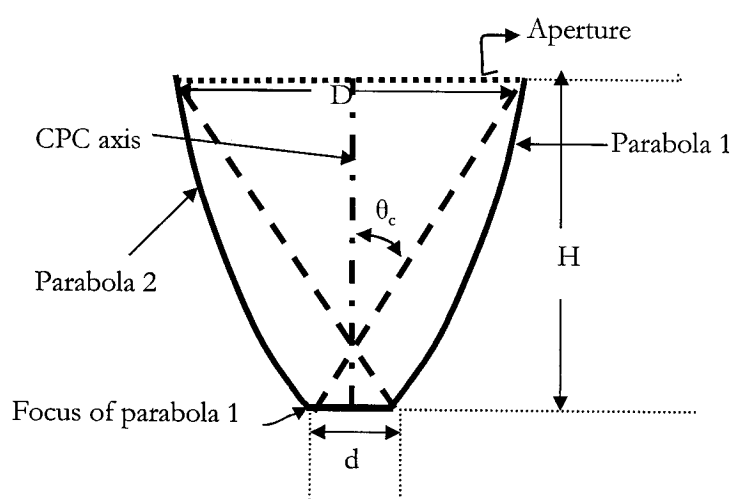


Figure 2.18 The geometry of the Compound Parabolic Concentrator.

From Figure 2.18, it can be shown that:

$$\tan \theta_c = \frac{D + d}{2H} \quad (2.15)$$

where D is the size of the entrance aperture, d is the size of the exit aperture, H is the height of the CPC and θ_c is the acceptance half-angle of the concentrator.

The height of the CPC may be given by: [20]

$$H = \frac{D + d}{2 \tan \theta_c} \quad (2.16)$$

The theoretical concentration ratio is given by: [20]

$$C = \frac{D}{d} = \frac{1}{\sin \theta_c} \quad (2.17)$$

Using Equation (2.15) and (2.17) the height of the CPC, H becomes:

$$H = \frac{D(1 + \sin \theta_c)}{2 \tan \theta_c} \quad (2.18)$$

or

$$\frac{H}{d} = \frac{1 + C}{2} [C^2 - 1]^{1/2} \quad (2.19)$$

Using Equation (2.19) we can determine the height of the concentrator having determined the values of d and C .

2.3.5 Designing of the compound parabolic concentrator.

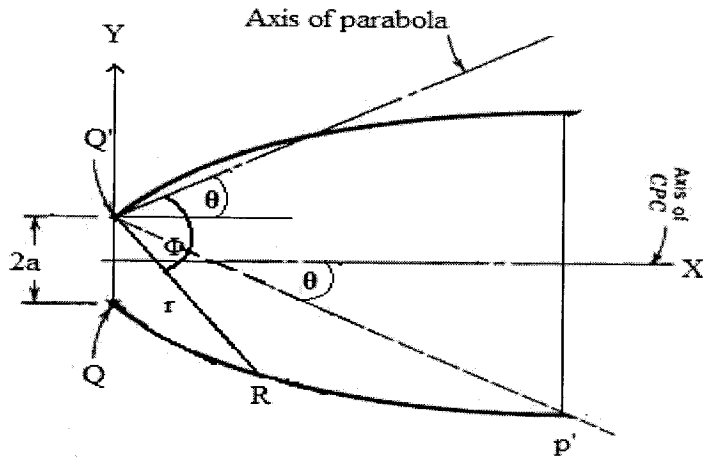


Figure 2.19 Design of the CPC (courtesy R.Winston, 1989)

Compound parabolic concentrators (CPCs) are designed using the polar co-ordinates system that was proposed by Winston. From Figure 2.16 and Figure 2.19 it can be shown that

the focal length f of the CPC is

$$f = a(1 + \sin \theta) \quad (2.20)$$

The Equation of the CPC is

$$r = \frac{2f}{(1 - \cos \Phi)} = \frac{f}{(\sin^2 \frac{1}{2} \Phi)} \quad (2.21)$$

The Cartesian x - y co-ordinates can be found using

$$x = \frac{2f \sin(\Phi - \theta)}{1 - \cos \Phi} - a \quad (2.22)$$

$$y = \frac{2f \cos(\Phi - \theta)}{1 - \cos \Phi} \quad (2.23)$$

Equations (2.22) and (2.23) are used to generate the x and y coordinates which are then plotted on the graph paper into the design a Compound Parabolic Concentrator.

2.3.6 Truncation of the compound parabolic concentrator

In order to reduce on the quantity of material used in making the CPC, it is often truncated but with only a small loss in concentration [23]. If the upper part of the concentrator is removed by cutting through the dashed horizontal line at the height h as shown in Figure 2.20 (a), the geometrical concentration ratio C_g decreases. On the other hand, a fraction of the radiation reaching the entrance aperture with angle of incidence greater than the acceptance half-angle θ_c will reach the absorber directly as indicated by the dashed line for the truncated CPC in the angular acceptance function of Figure 2.20(b).

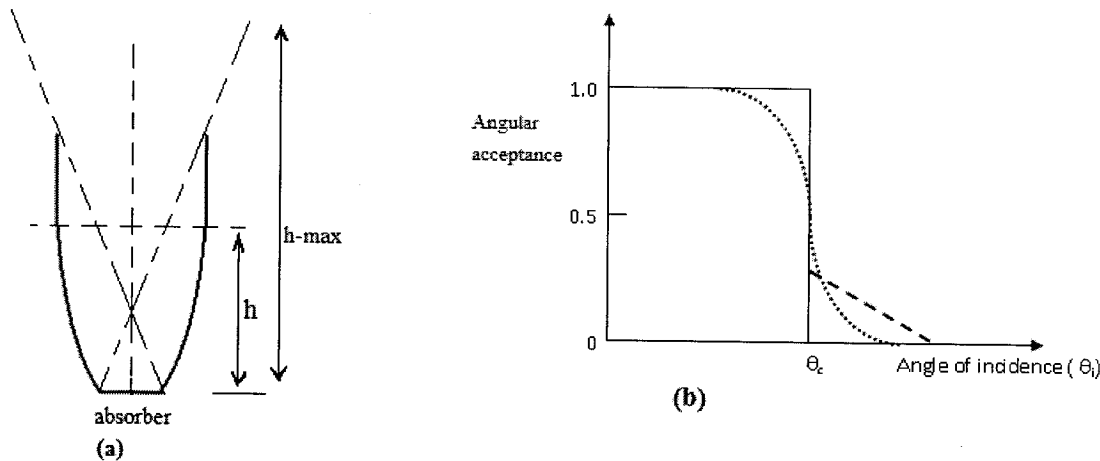


Figure 2.20 (a) The truncated compound parabolic concentrator (b) and the acceptance function of a full CPC shown by solid line (———), a truncated CPC represented by dashed line (- - - - -) and an ideal CPC with optical losses represented by dotted line (.....)

Light with an incidence angle within the acceptance angle ($\theta_i < \theta_c$) will be reflected through the receiver opening as shown in Figure 2.21(a), whereas light with an incidence angle greater than the acceptance angle ($\theta_i > \theta_c$) will not be reflected to the receiver opening. Instead it will bounce back and forth between the reflector sides and finally re-emerge through the aperture as shown in Figure 2.21(b)

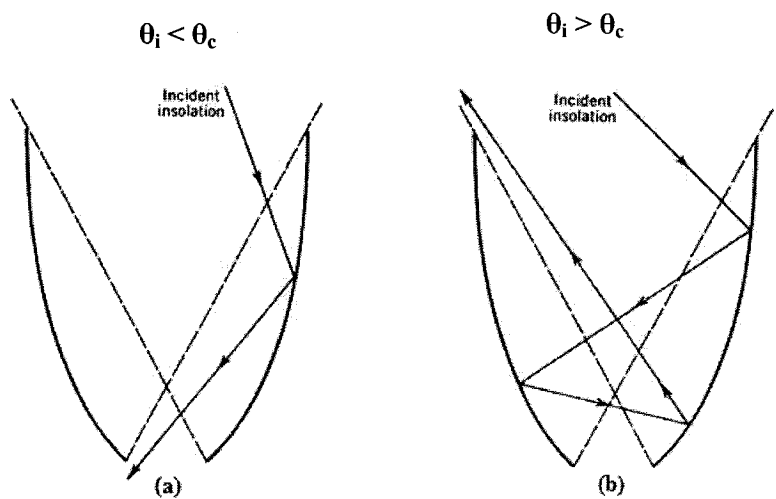


Figure 2.21 Light reflections from the CPC. (a) Incidence angle less than acceptance angle (b) Incidence angle greater than acceptance angle. (Courtesy: www.powerfromthesun.net).

2.3.7 Reflector materials for use in solar concentrators

Brogren [23, 24] points out that in many solar-energy applications, both solar thermal and photovoltaic, it is cost-effective to use reflectors to increase the irradiance on the receiver and thereby the heat or the electricity output. Selecting a reflector material which is both suitable as well as economical is a critical task when designing a solar concentrator. Photovoltaic cells have more than 20 years of life, and so the reflector surface too should retain its optical properties for that duration. Reflectors for solar

energy application should fulfill a number of requirements, which include the following:

- They should reflect as much as possible of the useful incident solar radiation onto the solar thermal absorbers or the photovoltaic cells.
- The reflector material and its support structure should be cheap compared to the solar cells or the thermal absorbers onto which the reflector concentrates radiation.
- The high reflectance should be maintained during the entire lifetime of the solar collector or photovoltaic module, which is often longer than 20 years.
- If cleaning is required, the surface should be easy to clean with cheap detergents, and without damaging its optical properties.
- The construction should be mechanically strong to resist hard winds, snow loads and vibrations.
- The reflector should preferably be light weight and easy to mount.
- The reflector material should be environmentally benign.
- The visual appearance should be aesthetically pleasing.

In our experiment we used semi-diffuse structured aluminium which seemed to meet a number of the stated requirements.

CHAPTER THREE

METHODOLOGY

3.0 Introduction

The use of solar concentrators creates the potential for producing inexpensive solar electricity because they can be used to raise the amount of incident radiation over a relatively small area of the absorber. In Section 3.1 we determine the spectral performance of the locally- purchased semi-diffuse aluminium structures and in Section 3.2 we discuss the construction of the compound parabolic concentrator (CPC). In Section 3.3 we show the experimental set up. In Section 3.4 we discuss how the current and voltage were measured under concentration and in Section 3.5 we show how the angle of tilt for the CPC was measured.

3.1 Spectral Reflectance of Structured Aluminium

Selecting a reflector material which is both suitable as well as economical is a critical task while designing a solar concentrator. An ideal reflector material for solar electricity production should have a relatively high reflectance in the visible and ultra-violet regions of the solar spectrum and should be able to maintain this relative high reflectance for the entire lifespan of the solar module. Silver and aluminium have good optical properties for this application in low concentrating systems but silver is more expensive compared to aluminium which suffers from rapid environmental degradation. However, aluminium has proven to be the most widely used solar-reflector material because it is inexpensive. It is also the most abundant metal in the earth's crust and has good mechanical properties and show some prolonged stability when treated [23]. Aluminium is also malleable, a property that

makes it possible for it to be used in CPCs as it is able to follow the shape of the CPC frame closely. Because of these factors we opted to use aluminium.

The Reflectance is the fraction of the total radiant flux incident upon a surface that is reflected. It varies according to the wavelength distribution of the incident radiation. The effective total solar irradiance of the material G_s can be calculated as an integral of the product of $G_\lambda(\lambda)$ and $R(\lambda)$ [24] as shown in Equation (3.1), where $R(\lambda)$ is the wavelength-dependent spectral property of a material, such as transmittance, reflectance and absorptance. $G(\lambda)$ represents the solar spectral irradiance.

$$G_s = \int_0^\infty R(\lambda)G_\lambda d\lambda \quad (3.1)$$

The mean value R_s of the property $R(\lambda)$, which is effective over the total solar spectrum, is given by

$$R_s = \frac{\int_0^\infty R(\lambda)G(\lambda)d\lambda}{\int_0^\infty G(\lambda)d\lambda} \quad (3.2)$$

Since the spectral property and the spectral irradiance are usually known as discrete values, the integration is performed as a summation so that Equation (3.2) becomes

$$R_s = \frac{\sum_{305nm}^{2450nm} R(\lambda)G(\lambda)\Delta\lambda}{\sum_{305nm}^{2450nm} G(\lambda)\Delta\lambda} \quad (3.3)$$

Highly specular materials have very high reflectance and are good in imaging optics for high concentration. However, semi-diffuse reflectors are preferred in non-imaging optics for flux scattering across the solar cell module(s). The inclusion of grooves on the reflector provides even more scattering of the flux [2, 15, 19]. Previous research [2, 15] has shown that the use of rolling grooves oriented parallel (horizontal grooves) to the plane of the solar cell module can improve the fill factor, as they scatter the solar flux evenly across the solar cell module. It is the even scattering that causes uniform

distribution of current within the solar cell module [2]. Therefore, in this research we study further which other groove orientations are likely to provide uniform illumination the solar cell module and improve the fill factor. We have also included the horizontal grooves in this research as a control. Secondly, we are using a locally available semi-diffuse aluminium structure which is different material from what has been used in previous research and therefore constitutes a new innovation. Our aim is to determine which of the four orientations on the reflector is able to provide the most uniform illumination and the best fill factor improvement when the reflector is used. Figure 3.1 shows the four orientations of the grooves used on the reflector. The optical properties of this aluminium reflector material were obtained using the Perkin Elmer Spectrophotometer Lambda 19 setup in the Solid State Physics Laboratory at the University of Zambia (UNZA). The total integrated reflectance (TIR) was calculated from Equation (3.3) and the results for the four orientations are compared in Section 4.1. The total integrated reflectance (TIR) gives the overall reflectance of the material in visible and ultra-violet regions of the solar spectrum and shows the preferential scattering of the radiation flux within the integrating sphere. Higher reflectance implies the material is likely to be specular while low reflectance may mean the material is diffuse.

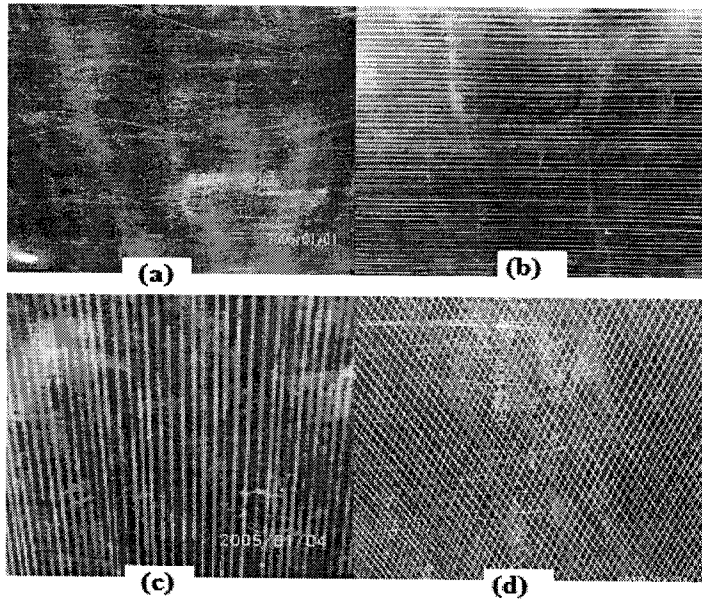


Figure 3.1 The four different orientations of the grooves on the semi-diffuse structured aluminium: (a) plain sheet (NG), (b) horizontal grooves (HG), (c) vertical grooves (VG) and (d) criss-cross grooves (CG).

3.2 Design and Construction of the Compound Parabolic Concentrator

Semi-diffuse aluminium structure was used as the reflector material, but with four different orientations of the grooves inscribed on it. That is to say we evaluated the performance of aluminium material as reflector when different grooves are inserted on it as shown in Figure 3.1. The grooves were made using a carpenter's chisel and a wooden straight edge for lining. The groove sizes ranged from 2mm to 3mm while the thickness of the aluminium sheet used was 0.4mm. The first orientation was just plain (without grooves) (NG); this was taken as the reference material when measuring the total integrated reflectance (TIR). The second sheet had horizontal grooves (HG), while the third orientation involved vertical grooves (VG). The fourth had a criss-cross groove orientation (CG).

We designed the compound parabolic concentrator (CPC) using the standard polar co-ordinate system proposed by Winston [25, 26]. The CPC was made using 20mm

thick plywood as a frame, contact adhesive, 50mm x 4mm screws and wing nuts. The value of the half width of the exit aperture a was determined after fixing the size of the solar module string to be used, after which the acceptance half angle θ of the CPC was decided while Φ varied from 5° to 105° in our case. The Cartesian $x-y$ co-ordinates were obtained using Equations (2.22) and (2.23) which are also repeated here as Equations (3.4) and (3.5) respectively.

$$x = \frac{2f \sin(\Phi - \theta)}{1 - \cos \Phi} - a \quad (3.4)$$

$$y = \frac{2f \cos(\Phi - \theta)}{1 - \cos \Phi} \quad (3.5)$$

where $f = a(1 + \sin \theta)$ is the focal length of the CPC and Φ is the angle subtended by the axis of the parabola and the absorber normal as shown in Figure 3.2.

The calculated values of a and θ (in this case $a=5\text{cm}$ and $\theta=15^\circ$) were then used in Equations (3.4) and (3.5) to generate the x and y co-ordinates of the CPC. These co-ordinates were then plotted on the graph paper to design the CPC. In order to reduce on the amount of material used in making the CPC, the collector was truncated at a height of 52cm with a geometric concentration ratio $C_g=3.6$. A symmetrical CPC is as shown in Figure 3.3(a). Figure 3.3(b) shows the actual Compound Parabolic Concentrator. The dimensions of the CPC were: 130cm length, 48cm width and an entrance aperture of 36cm ($D=36\text{cm}$). The current-voltage (I-V) measurements were obtained for this concentrator and the results are presented in chapter 4 Section 4.4.

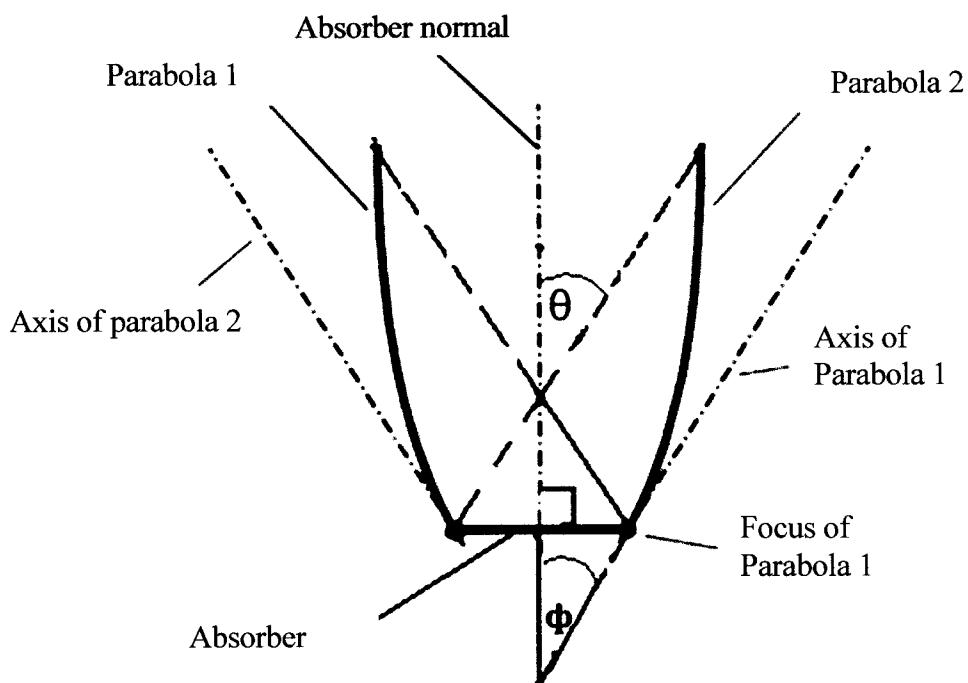


Figure 3.2 The angles θ and Φ used in the designing of the CPC.

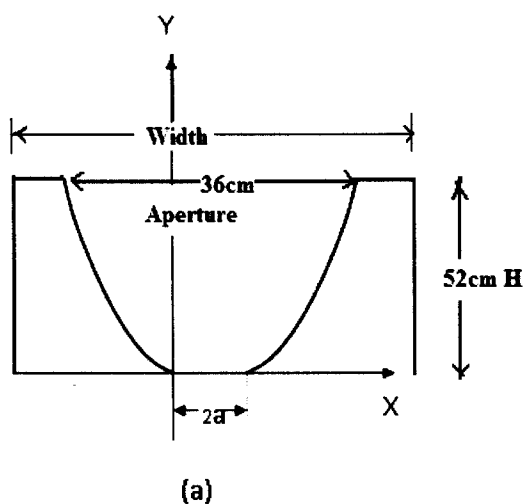


Figure 3.3 the CPC design from polar co-ordinates into the Cartesian x-y co-ordinates system (a) and the actual compound parabolic concentrator constructed (b).

3.3 Experimental Setup

The experiment was mounted at a place free from obstruction from trees and buildings. This was the roof top of the Department of Physics at the University of Zambia with the entrance aperture of the CPC facing the sun. The four orientations were fixed to the frame one after the other using Z68 contact adhesive while following the shape of the concentrator closely. The Z68 contact adhesive enables the reflector materials to be replaced on the CPC easily since it does not make permanent contact between the materials being stuck together. Figure 3.4 shows the experimental set up. The setup consisted of the CPC, an inclinometer, the I-V tracker and connecting cables. The current-voltage (I-V) tracker consists of a power supply, an I-V plotter, the data-logger and the +ve and the -ve terminals to which the solar-cell terminals are connected. The I-V tracker measures the instantaneous voltage and current of a solar-cell module. It can store up to 60 measurements with 100 data points of current and voltage for each measurement. We show its physical features in Section 3.4. The inclinometer measures the angle of tilt for the CPC. We give a detailed description of how the angle of tilt was measured in Section 3.5. Figures 3.5, 3.6, 3.7 and 3.8 show the experimental set up for the four orientations of the grooves on the reflector. The black cloth material shown in Figure 3.4 was used to cover one side of the CPC in order to absorb the light falling on this side of the CPC. This was necessary to determine the performance of the reflector on the other side of the CPC.

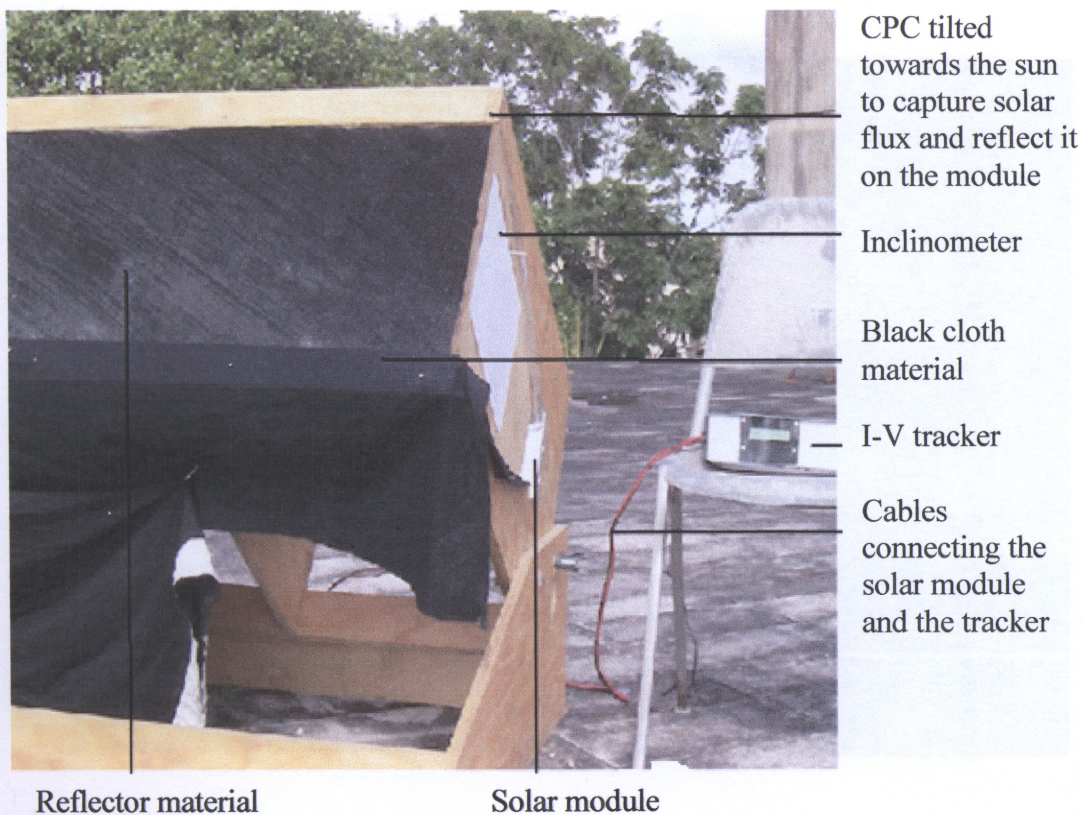


Figure 3.4 The experimental set up of the CPC and the I-V tracker

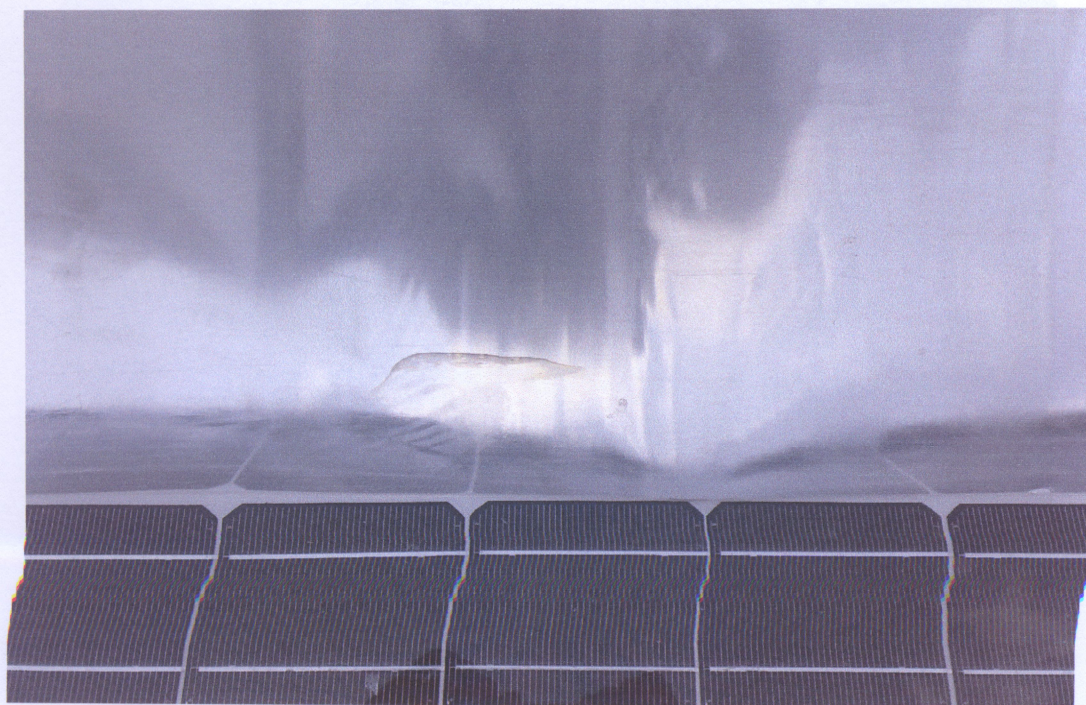


Figure 3.5 No groove (NG) orientation and the solar module

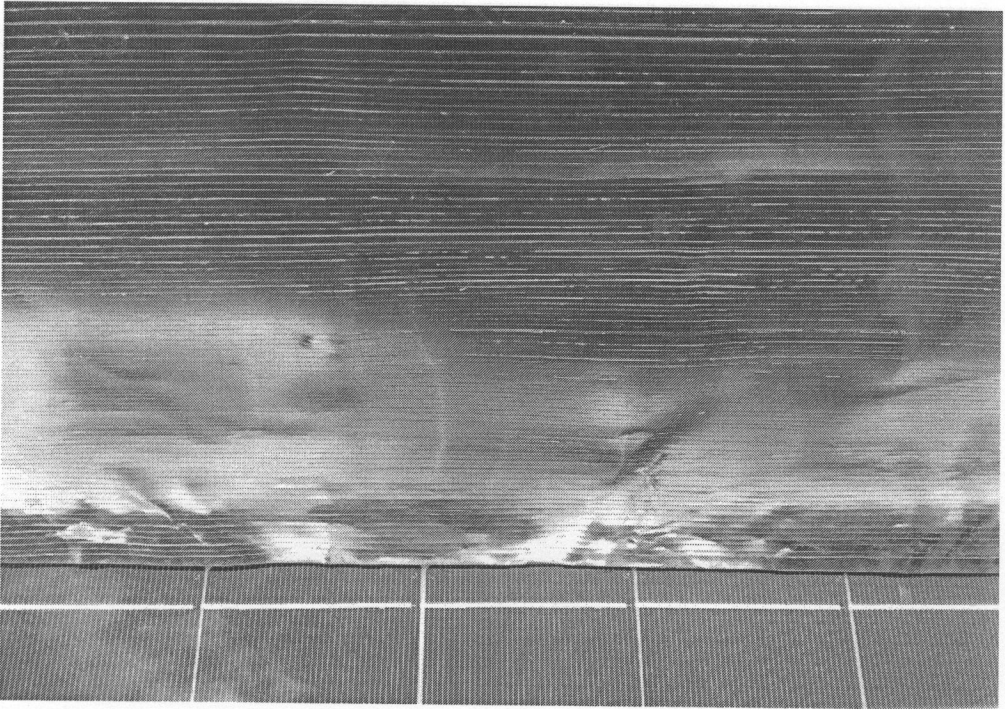


Figure 3.6 Horizontal groove (HG) orientations and the solar module

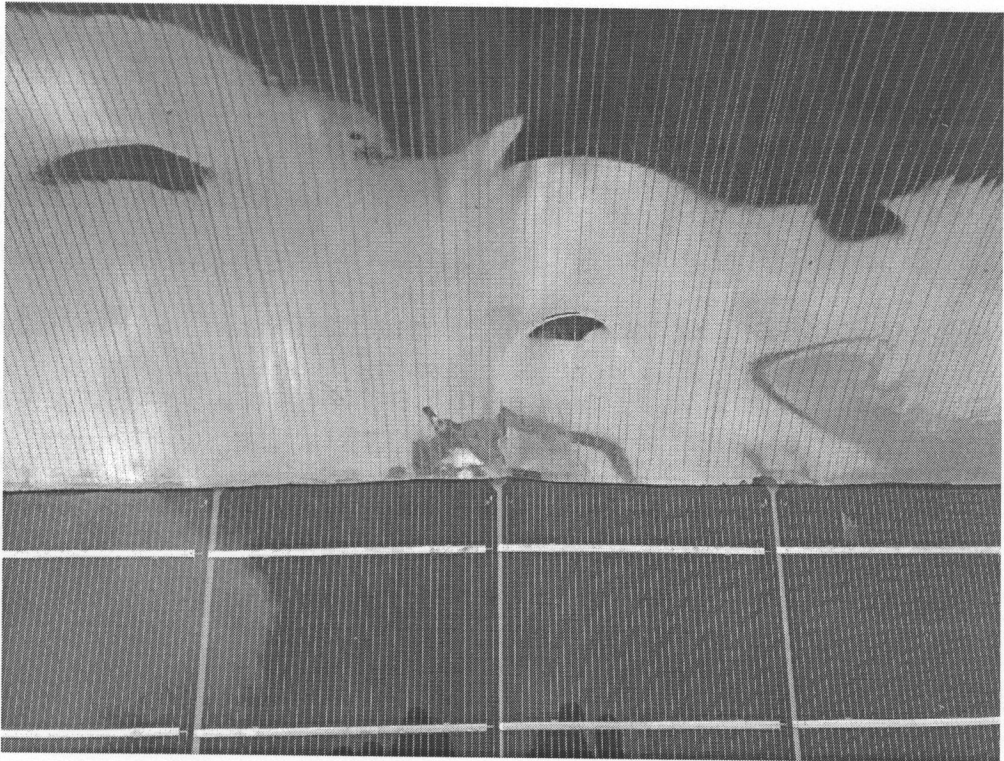


Figure 3.7 Vertical groove (VG) orientations and the solar module

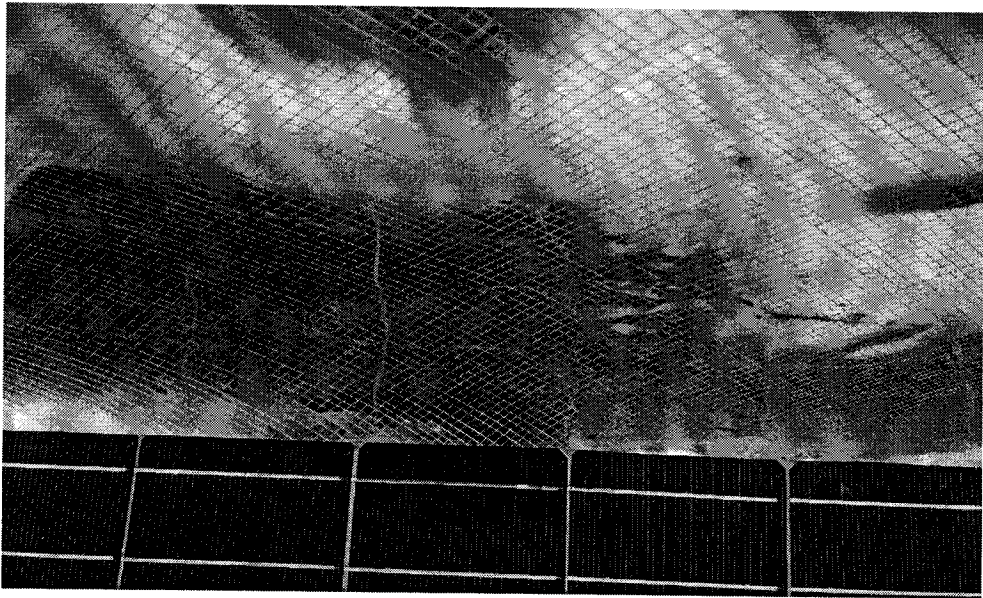
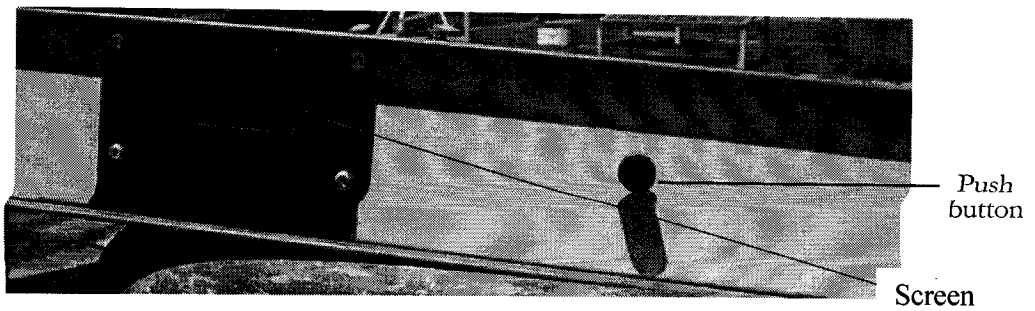


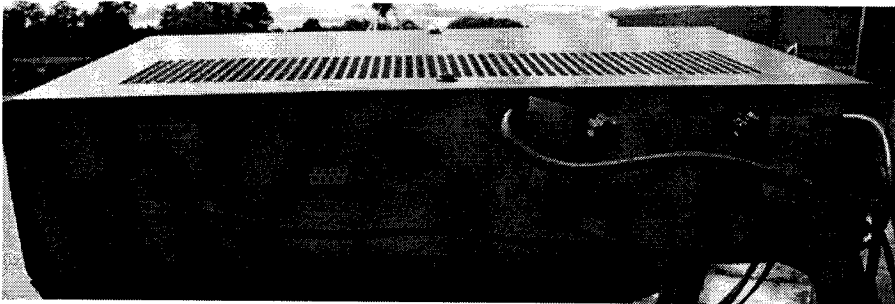
Figure 3.8 Criss-cross orientations (CG) and the solar module

3.4 The Current-Voltage (I-V) Tracker Instrument

The current and voltage generated by the solar module under concentration was measured using the current-voltage (I-V) tracker instrument shown in Figure 3.9. The circuit diagram for measuring current and voltage is inbuilt in the tracker. However, we have shown how the I-V tracker was connected to the solar cell module in Figure 3.4. The tracker consists mainly of a power supply and the +ve and the -ve terminals to which the solar cell terminals are connected, an I-V plotter and data-logger components. The instrument is powered by 9V dc. The measurements are downloaded onto the computer through the HyperTerminal software. The measurements downloaded on the computer were stored in a text file which was then analysed using Microsoft Office Excel.



(a)



(b)

Figure 3.9 The front (a) back panels (b) of the I-V tracker

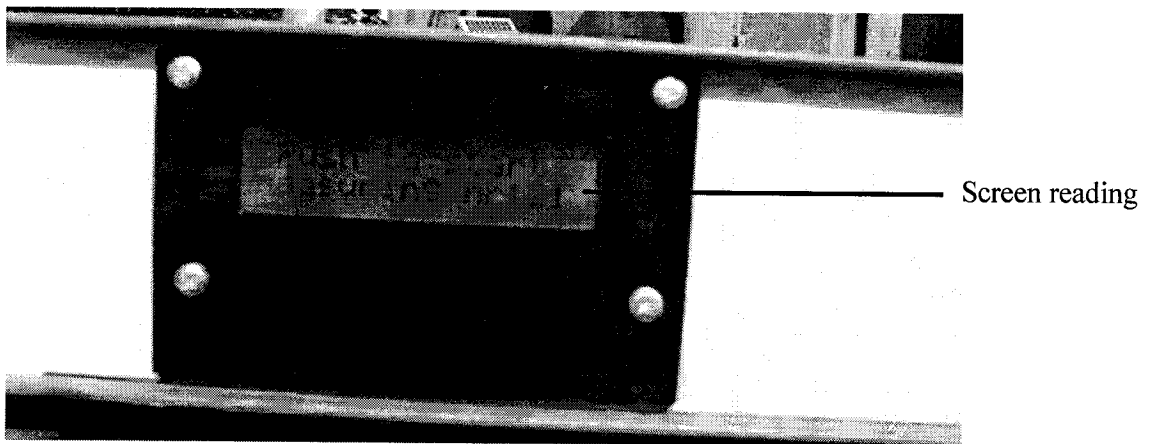


Figure 3.10 The I-V tracker screen indicating that the instrument is ready for use.

The short-circuit current I_{sc} , the open-circuit voltage V_{oc} , the maximum power P_m , the maximum current I_m , and the maximum voltage V_m were obtained for each I-V curve. The fill factor (FF) was evaluated using Equation (3.6).

$$FF = \frac{I_m V_m}{I_{sc} V_{oc}} = \frac{P_m}{I_{sc} V_{oc}} \quad (3.6)$$

The I-V curves were obtained at four angles of incidence and the results are given in Sections 4.1 and 4.2.

3.5 Measurement of Angles

An inclinometer was used to measure the angles through which the CPC was tilted as shown in Figure 3.11. The concentrator was tilted toward the sun, which then cast the shadow of the pin on the inclinometer indicating the angle of tilt. Figure 3.11 shows the experimental setup of the angle measuring arrangement. From simple symmetry relations, the angle of tilt is equal to the angle of incidence measured between the normal and the ray vector from the sun.

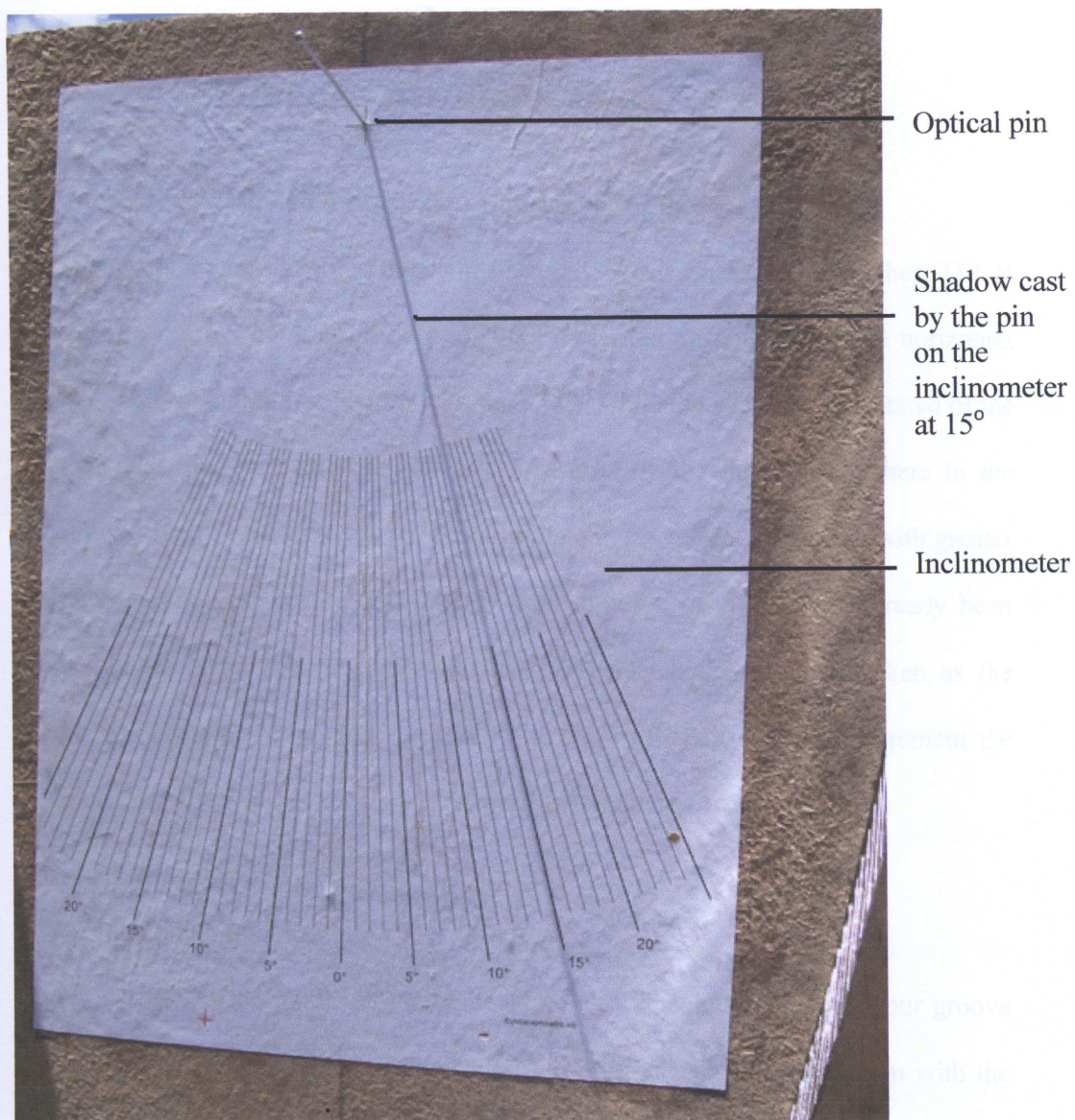


Figure 3.11 How angles were measured using the inclinometer.

CHAPTER FOUR

EXPERIMENTAL RESULTS AND ANALYSIS

4.1 Measurement of Total Integrated Reflectance (TIR)

The results obtained show that the plain sheet (NG = reference) had the highest TIR of 89%, followed by the criss-cross groove (CG) orientation with 88%. The horizontal groove (HG) orientation was third with 85% TIR, while the vertically orientated of the grooves had the least value of 82%, as measured by the integrating sphere in the laboratory. It can be inferred from these results that the reflector material with greater TIR has the highest heating and highest concentration of flux as has already been discussed in the theory. We reiterate that the plain sheet (NG) was taken as the reference during the TIR measurement while during the fill factor measurement the solar cell module without concentration was the reference.

4.2 Total Reflectance Curves

Figure 4.1 shows the nature of the percentage reflectance curves for the four groove orientation. The curves show the typical spectral reflectance for aluminium with the absorption peak near 800nm. The curves validate that the plain sheet had the highest total reflectance, followed by the criss-cross groove orientation. The horizontal grooves had a higher reflectance than the vertical grooves.

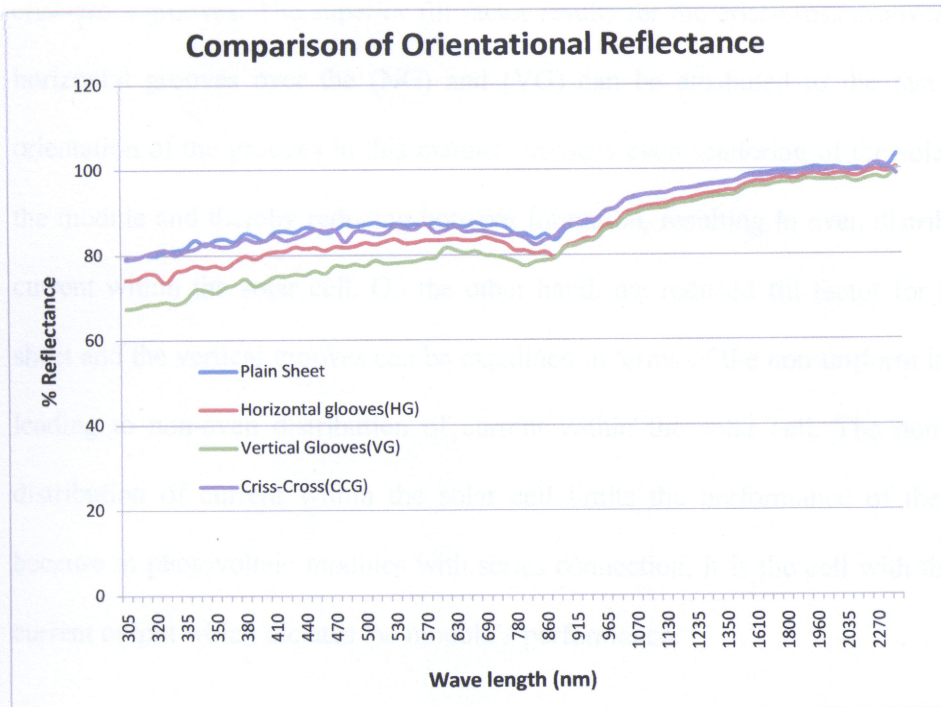


Figure 4.1 Comparison of the orientational reflectance for the four different grooves.

4.3 Fill factor Comparison at 0° (Normal)

Figure 4.2 give a summary of results for the fill factor evaluated at 0° (normal) for the four different groove orientations of the aluminium reflector and the reference (without concetration). It is seen that the criss-cross grooves (CG) gave the highest fill factor followed by the horizontal groove (HG) and then the vertical grooves (VG). The plain sheet (NG) had the smallest fill factor. The results also show that the drop in the fill factors from the reference for the criss-cross groove orientations and the horizontal groove was about 3%, while that for the vertical groove (VG) orientation and the plain sheet (NG) was 8% and 12% respectively. Close examination of the results further shows that the difference in fill factor between the criss-cross groove (CG) and the horizontal groove (HG) orientations is just 0.1%. Therefore, considering the cost involved in making the criss-cross grooves, it is better to use the horizontal groove orientation which, though not so costly, has a fill factor as good as that for the

criss-cross grooves. The superior fill factor results for the criss-cross grooves and the horizontal grooves over the (NG) and (VG) can be attributed to the fact that the orientation of the grooves in this manner provides even scattering of the solar flux to the module and thereby reducing hot-spot formation, resulting in even distribution of current within the solar cell. On the other hand, the reduced fill factor for the plain sheet and the vertical grooves can be explained in terms of the non-uniform irradiance leading to non-even distribution of current within the solar cell. The non-uniform distribution of current within the solar cell limits the performance of the module because in photovoltaic modules with series connection, it is the cell with the lowest current output which dictates the module's performance.

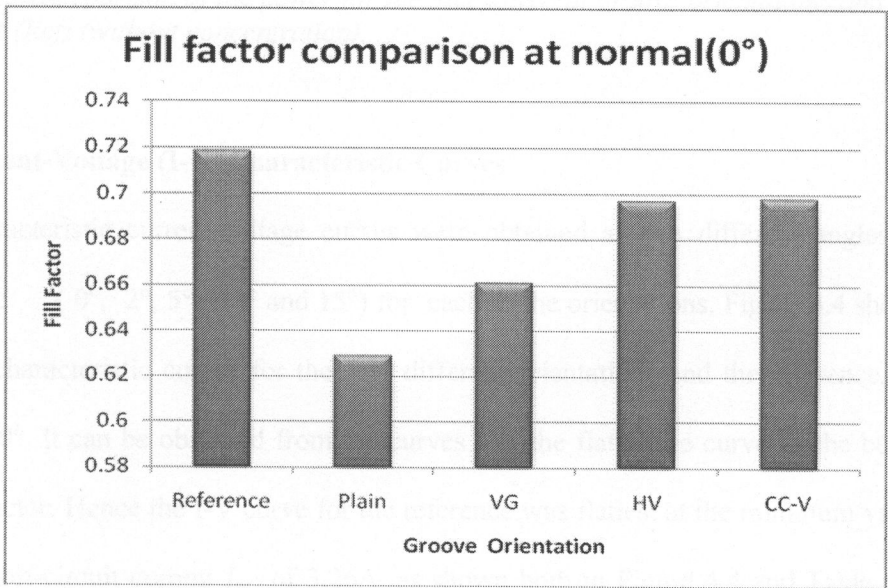


Figure 4.2 Bar chart giving a comparison of fill-factor for the four different groove orientations compare to the reference.

4.4 Power Comparison at 0° (Normal)

Figure 4.3 shows the comparison of power output among the four kinds of reflectors at 0°. The VG and NG orientations gave the highest power output, but these are a result

of high currents which cause hot spots and an overall reduction in the performance of the module.

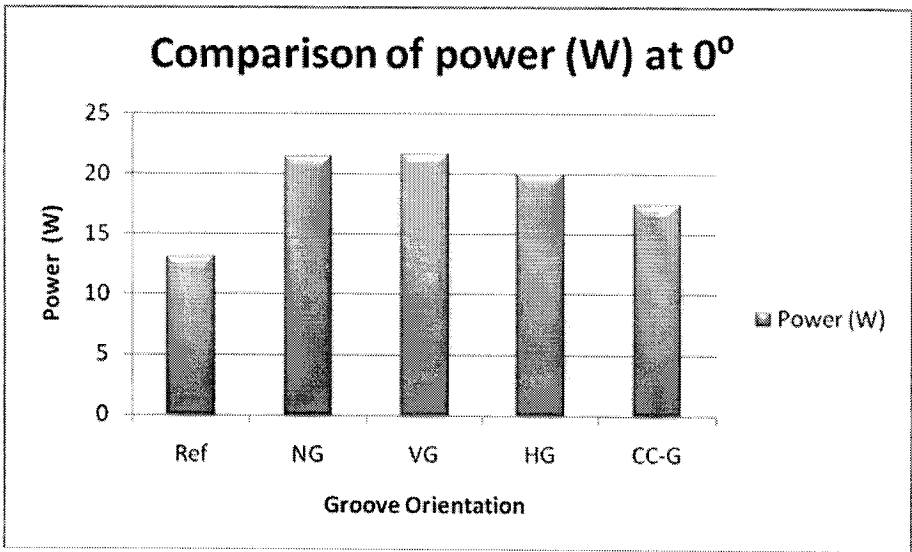


Figure 4.3 Comparison of the power for the four different groove orientations and the reference (Ref) (without concentration).

4.5 Current-Voltage (I-V) Characteristic Curves

The characteristic current-voltage curves were obtained at five different angles of incidence (0°, 2°, 5° , 10° and 15°) for each of the orientations. Figure 4.4 shows the I-V characteristic curves for the four different orientations and the reference, all taken at 0°. It can be observed from the curves that the flatter the curve is, the better the fill factor. Hence the I-V curve for the reference was flattest at the minimum value of the short-circuit current I_{sc} of 3.26A, as shown both in Figure 4.4 and Table 4.1, followed by the criss-cross groove orientation and then the horizontal groove orientation. The plain sheet had the least flat curve with the highest short-circuit current while the vertical groove orientation had a better fill factor than that of the plain sheet. The results in Table 4.1 also reveal that the short-circuit current I_{sc}

increased for each of the four different groove orientations of the structured aluminium reflector material.

Table 4.1 Summary of results for the 4 different orientations and the reference taken at (0°)

Orientation	V _m (V)	I _m (A)	P _m (W)	V _{oc} (V)	I _{sc} (A)	V _{oc} *I _{sc} (W)	FF
Reference	4.42	2.97	13.12	5.61	3.26	18.28	0.718
Plain (NG)	3.85	5.57	21.48	5.39	6.34	34.15	0.629
Vertical Grooves (VG)	4.05	5.35	21.66	5.58	5.87	32.75	0.661
Horizontal Grooves (HG)	4.20	4.75	19.98	5.51	5.21	28.68	0.697
Criss-Cross Grooves (CG)	4.12	4.24	17.46	5.52	4.53	25.03	0.698

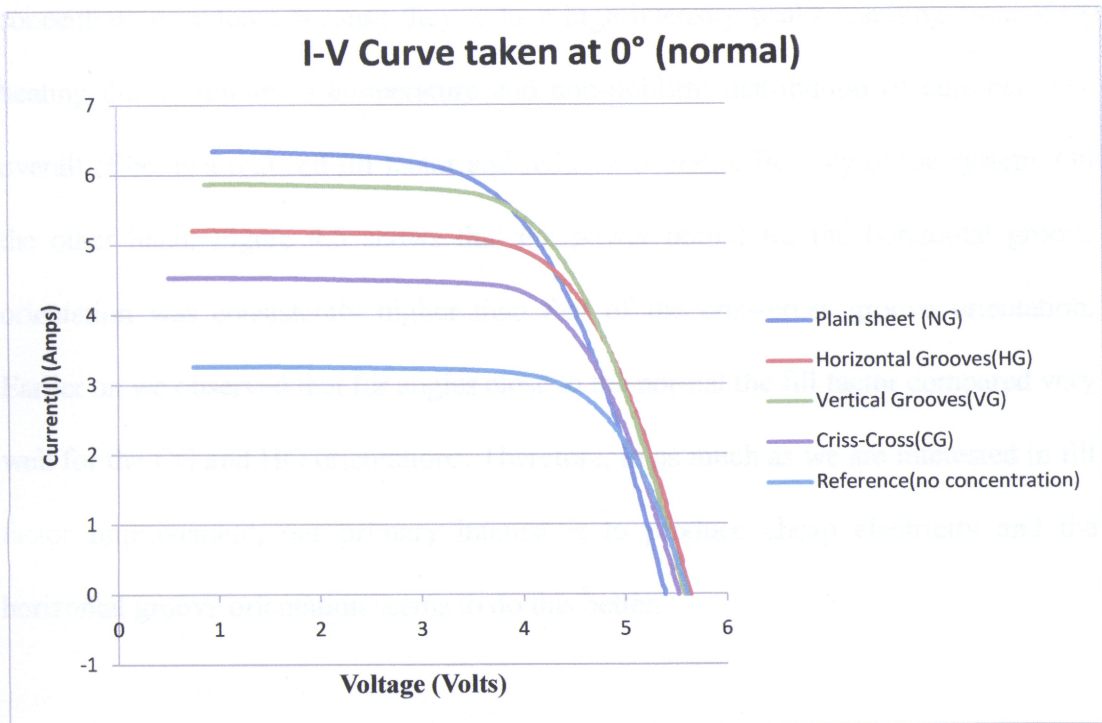
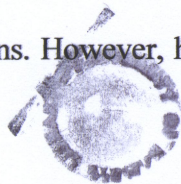


Figure 4.4 I-V characteristic curves for the four different orientations and the reference all taken at 0° (normal).

Figure 4.5 shows the variation of the fill factor (FF) as a function of the angle of tilt from the normal incidence of the CPC within the acceptance angle of 15°. We observe from the figure that for angles close to the normal (0° to 5°) the fill factors for the CG and the HG orientations compare very well and remain higher than those of the VG and NG for reasons advanced in Section 4.3. Figure 4.6 shows the variation of power output for the four groove orientations as a function of the angle of tilt from the normal of the CPC. It can be observed that the power outputs for the plain sheet and the vertical groove orientations compared very well, being almost the same. This was higher than that for the criss-cross groove orientation and the horizontal groove orientation. The higher power output exhibited by these two orientations could be attributed to their specular nature which also resulted in higher short-circuit currents for the two orientations. However, high short-circuit currents are not desirable in low



concentrating systems because they induce high-intensity peaks resulting from local heating due to non-even temperature and non-uniform distribution of currents. The overall effect is a reduced fill factor and reduced overall efficiency of the system. On the other hand, Figure 4.5 shows that the power output for the horizontal groove orientation was consistently higher than that of the criss-cross groove orientation. Earlier on we observed that for angles close to the normal the fill factor compared very well for the CG and HG orientations. Therefore, in as much as we are interested in fill factor improvement, our primary interest is to produce cheap electricity and the horizontal groove orientation seems to do this better.

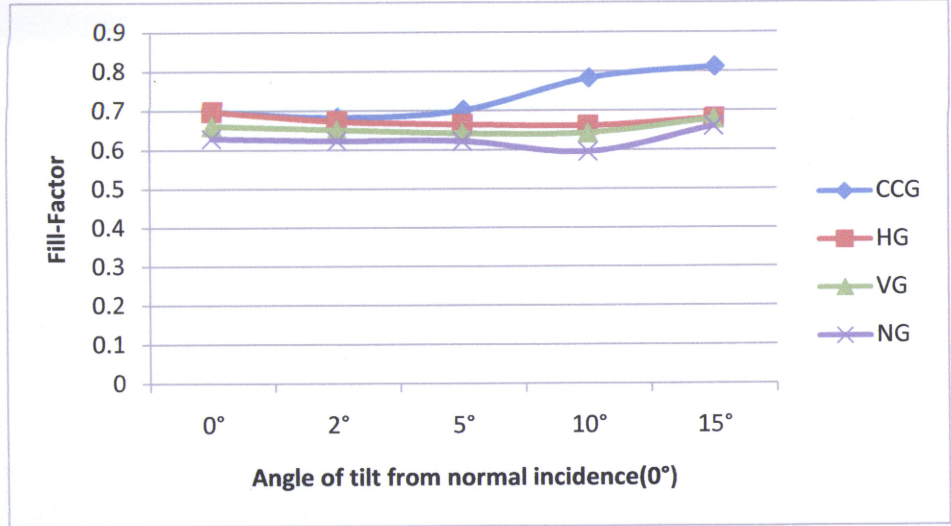


Figure 4.5 Fill factor versus angle of tilt of CPC from the normal incidence (0°) for the four groove orientations.

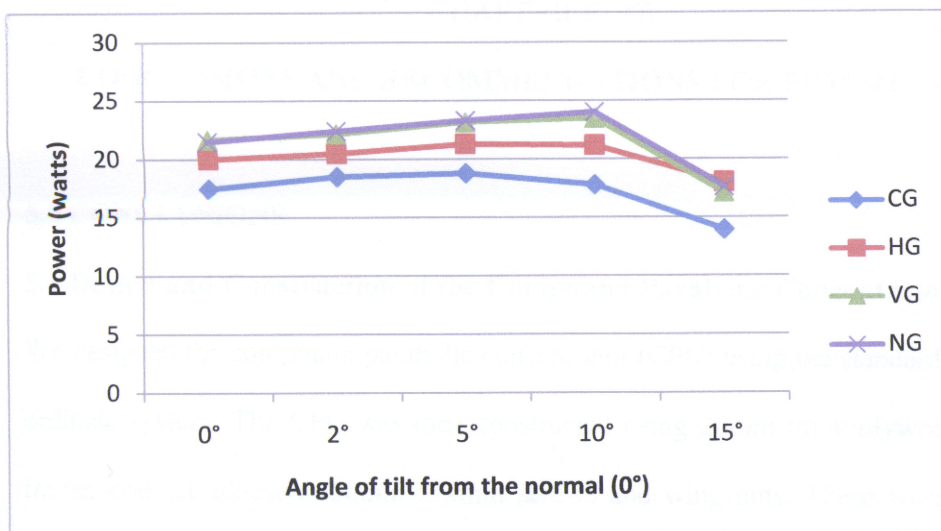


Figure 4.6 Power versus angle of tilt of CPC from the normal incidence (0°) for the four groove orientations on structured Aluminium.

CHAPTER FIVE

CONCLUSIONS AND RECOMMENDATIONS FOR FUTURE WORK

5.0 CONCLUSIONS

5.1 Design and Construction of the Compound Parabolic Concentrator

We designed the compound parabolic concentrator (CPC) using the standard polar coordinate system. The CPC was then constructed using 20mm thick plywood for the frame, contact adhesive, 50mm x 4mm screws and wing nuts. These were all local materials and this confirms the achievement of the first two objectives.

5.2 Evaluation of Performance of the Concentrator System

5.2.1 Surface reflectance of structured aluminium

The surface reflectance of the locally-purchased semi-diffuse aluminium structures was analysed using the integrating sphere mounted in the Solid State Physics Laboratory at the University of Zambia. The plain sheet gave the highest total reflectance of 89% followed by the criss-cross groove (CG) orientation with 88%. The horizontal groove (HG) orientation was the third best with 85% while the vertical groove orientation gave the least value of 82%. The above results suggest that the plain sheet without grooves which had the highest TIR should also give a better fill factor. However, out-door results from the CPC showed a different trend for this orientation. The CPC results showed that the criss-cross groove orientation and the horizontal groove orientations are the ones that gave the best flux scattering at larger angles. Thus, these two groove orientations (CG and HG) gave a better fill factor.

5.2.2 Fill factor improvement

The performance of the CPC constructed from local materials has been analysed and the results show that this can be used as a booster reflector in concentrator photovoltaic systems. The results also show that the criss-cross groove and the horizontal groove orientations are the best orientations for fill factor improvement since they suffered only a 3% drop in fill factor from the reference. The two orientations were able to scatter the solar flux evenly across the solar cell module. It is the even scattering that causes uniform distribution of current within the solar cell, thus reducing the hot spot formation. However, between the two orientations we would recommend the horizontal groove because it is easy to make the horizontal grooves and it gives a fill factor which equals that of the criss-cross grooves. The horizontal groove gave a power increase of 52% which compares favourably with 33% for the criss-cross groove orientation. We further point out that our results uphold Dr. Hatwaambo's finding that rolling grooves oriented parallel (HG) to the plane of the solar cell module can improve the fill factor. This is because horizontal grooves provide a larger angular spread of the flux on the module, which results in a uniform illumination. The major difference in this research work is the type of aluminium material used. Dr. Hatwaambo used rolled aluminium, anodized aluminium and miro. We pointed out earlier that the reduction in cost of solar electricity is achieved by reducing the module area through the use of low-cost reflectors. Therefore, in this research, we are using locally available semi-diffuse aluminium which is different from what has been used in previous research. Secondly, we have introduced another orientation of the grooves. This is the criss-cross (CG) orientation, which has not been evaluated before. This therefore constitutes a new innovation.

5.2.3 Increase in current and power

The analyzed data for current and voltage taken at normal inclination reveal that the short-circuit current I_{sc} increased by a factor of 1.4 to 2.0 for the four different groove orientation. While the power increase was 33% for the CG orientation, and 52% for the HG orientations. The VG orientation and the plain sheet had 65% and 64% increases in power respectively. These results suggest that the horizontal groove orientations would be best in improving both the fill factor and the power of the module since its fill factor compares very well with that of the criss-cross groove orientation but has a higher power increase than the HG. Hence, though the NG and VG orientations showed a high power increase, they are not the best orientations for the operations of the module because they had a higher drop in the fill factor. This implies that the two orientations (NG and VG) cannot give a constant high power for a long time due to formation of hot spots induced by the non-even illumination of the solar flux. The overall result is degradation in the performance of the module. Therefore the HG orientation was found to be the best.

5.3 Recommendations for Future Research

We have shown in our research that the semi-diffuse aluminium structures purchased locally can be used as booster reflector on the CPC and with the right orientations of groove scribed on them they are capable of improving the uniformity of the illumination on the solar cell modules. Though we have used groove sizes ranging from 2mm to 3mm in all the orientations, we recommend that further work be done on different groove sizes and also on the effect of different depths of the grooves on the semi-diffuse aluminium structure. This is especially important for the horizontal groove orientation as it promises to offer a better fill factor and an increased power for

the module. We further recommend that study on the degradation of the structured aluminium used be carried out so as to ascertain its life span as a reflector material.

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