PROTOTYPE MODELING AND MATHEMATICAL APPROACH FOR THE EVALUATION AND MEASUREMENT OF A PARABOLIC TROUGH REFLECTOR

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ABSTRACT

The increase of demand for energy, stimulated by developing countries and consequent decrease of power sources, is leading to an unsustainable future. These way renewable and clean energies are necessary to be used, particularly solar energy. It can produce heat or be directly converted into electricity, called photovoltaic (PV) energy. To achieve the grid parity the cost of components necessary to build a PV system has to decrease, specially the price of silicon. Focusing the sunlight into smaller cells, the expensive cells are substituted by cheaper elements (Concentrated Photovoltaic (CPV)). Associated to CPV there is the parabolic concentrator mirrors which are one of the vital component of many solar energy systems. The main objectives of this thesis were to study and use the optical testing tools to assist in solar concentrator development and maintenance using experimental and mathematical technique. This technique will use to measure and evaluate an optical performance of solar parabolic trough concentrator for photovoltaic system by comparing it with the ideal profile of the solar parabolic reflector. A prototype model was built to evaluate and measure the solar parabolic trough where two series of experiments is presented with different parabolic contour respectively. Before that, a mathematical formulation related with optical profile is being study to be combined and collaborated with the experimental model. The result of the measurement which is as the surface reflection angle and slope error is presented and analyzed which by then shows that a prototype model to measure a parabolic reflector which is demonstrated and analysed using mathematical modelling and experimental prototype has been achieved together with a method approach to evaluate the solar parabolic trough concentrator.

ABSTRAK

Peningkatan permintaan tenaga oleh Negara-negara membangun telah mengakibatkan kekurangan sumber tenaga, lantas mencenderung ke arah masa depan yang kurang mapan. Oleh itu, sumber tenaga yang bersih serta yang boleh diperbaharui haruslah digunakan, khususnya tenaga solar. Tenaga solar mampu diekstrak habanya mahupun ditukar menjadi tenaga elektrik, atau lebih dikenali sebagai tenaga fotovoltaik(PV). Untuk mencapai “grid parity”, kos komponen yang digunakan untuk membina sesebuah tenaga fotovoltaik(PV) haruslah dikurangkan, terutamanya kos silikon. Dengan menumpukan sinaran matahari kepada sel-sel kecil, sel-sel yang lebih mahal telah digantikan dengan sel-sel yang lebih murah iaitu (Concentrated Photovoltaic (CPV)). CPV ini mempunyai sebuah struktur cermin berbentuk parabola yang merupakan salah sebuah komponen penting dalam mana-mana pembinaan system tenaga solar. Objektif utama tesis ini adalah untuk mengkaji dan menggunakan alat-alat pengukuran optikal untuk menjana pembangunan alat penumpu cahaya solar berbentuk parabola serta penyelenggaraannya menggunakan kaedah-kaedah eksperimentasi dan matematik.Ini bagi menilai prestasi penumpuann alat penumpu tersebut untuk sebuah sistem fotovoltaik dengan membuat perbandingan antara sistem tersebut yang profil nya ideal dan sebuah lagi tidak. Sebuah model prototaip telahpun dibina untuk menilai dan menguji alat parabola penumpu cahaya ini. Selain itu, dua siri eksperimen telah dijalankan menggunakan “parabola penumpu cahaya ini yang mana mempunyai dua kontur yang berbeza. Hasil penilaian eksperimen ini yang mengkhususkan kepada permukaan sudut biasan dan ralat legkungan akan/telah dibentangkan dan dianalisa. Selaras dengan itu, sebuah formulasi matematik berkaitan profil optika akan/telah dikaji dan diselaraskan dengan model eksperimen tersebut terlebih dahulu.

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CHAPTER 1

INTRODUCTION

1.1 Project Background

Photovoltaic (PV) conversion offers the human beings a clean, durable, and applicable way to obtain electricity from solar radiation. In recent years, with the fast growth of demand for electricity, the photovoltaic power generation has played an increasingly important role in the field of renewable energy sources. However, as the cost of conventional solar cell accounts for more than 70% of the total cost of a PV system, the PV technology still does not fully penetrate into the electricity generation market [1]. PV Industry is rising at an astonishing compound annual rate of 65% [2], showing that the interest in this technology is increasing and it is believed that photovoltaic (PV) technologies can really supply the growing energy demand, and even be the basis of grid supply around the world [3] .At present, there is an increasing interest in concentrator photovoltaic (CPV) power generation systems as an alternative to replace or complement the existing power generation systems that consume fossil and nuclear fuels. The idea of concentrating solar energy to generate electricity has ingeniously made use of the concept in concentrator optics especially for designing a specific geometry of reflectors or lenses to focus sunlight onto a small receiving solar cell [4-7].One of the components of CPV is the reflector and one its famous type used as a solar reflector is the parabolic trough solar reflector .As we pursue efforts to lower the capital and installation costs of parabolic trough solar reflector, it is essential to maintain high optical performance. One of the main influences on the overall performance of a parabolic trough power plant is the optical quality of the concentrator field, which is determined by the reflectivity of the mirrors, the absorptivity of the receiver, and in particular the geometric precision of the reflector shape. Deviations from the optimum parabolic shape can lead to optical losses on account of reflected rays that pass the absorber tube. To check, qualify and improve existing collectors it is therefore important to have a tool that measures surface slope errors with adequate precision. Figure 1.1 below shows the illustration to define solar reflector and its components used in the CPV.

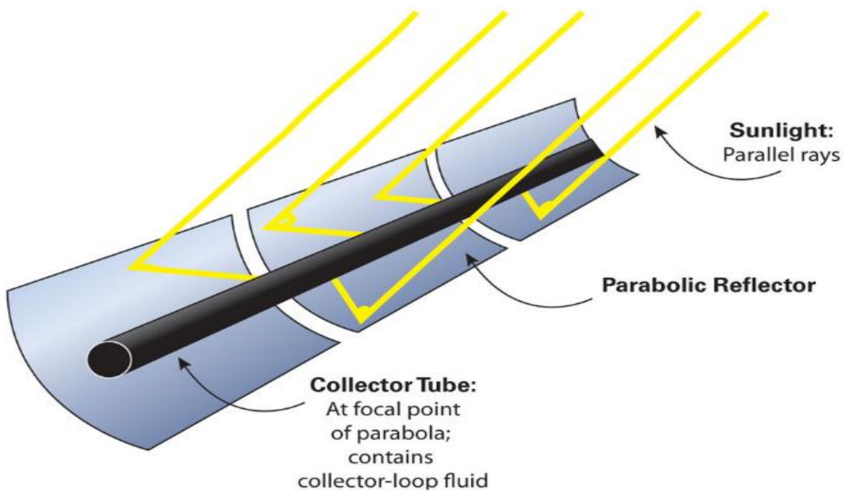


Figure 1.1: Parabolic trough reflector and components

Lenses or mirrors in the concentrator photovoltaic system will replace most of the solar cell material and the price of both is taken into account for determining the optimum configuration. The CPV technologies have being studied for many years to improve their efficiency and reduce the price per watt of energy and the optics of the CPV systems need to be properly designed and together with the lenses and mirrors used also must be well designed and resistant to be able to withstand the climate, in order to the CPV system be functioning at top efficiency along the entire lifetime.

1.2 Problem Statement

There is the trend toward urbanization and migration to cities in many developing countries such as our country, Malaysia itself, which is exerts increased pressure on the power grid and these forces governments to invest in the electric grid to meet growing demand. United Nations predicts world population will rise to more than 8 billion by 2013, which will lead to a global increase in electricity demand. The energy necessary to keep up with the demand cannot come only from fossil fuels, as they are reaching a limit in production, and they are one of the major causes for the rise in CO2 emissions, which is the number 1 believed cause for global warming. So, the solution is to turn to clean and renewable energy sources, capable of supplying large amounts of energy. PV industry needs to become affordable without government subsidies and incentives and be based on readily available, low cost materials. PV industry researchers searching for lower cost PV have investigated many CPV approaches. One of the popular design approaches for CPV is the parabolic solar collectors and so as we pursue efforts to lower the capital and installation costs of parabolic trough solar collectors, it is essential to maintain high optical performance.

The optical performance of parabolic trough collectors is described by the intercept factor, which includes the optical effects of reflector shape such as the slope error of the curve and reflection angle which determine the receiver absorber alignment among others. The mathematical modeling as we know is a very important approach in engineering world, which in the CPV field itself, it provides a means to measure optical performance of concentrating solar power plants in the field. Despite extensive research and developments efforts, most concentrator solar cell designs encounter series-resistance problems at rather low concentration intensities which limit the operating performance. So, in this thesis, a study on the new method approach to evaluate the optical characterization of a concentrating solar parabolic trough using mathematical and experimental modeling is to be developed in order to assist in initial design optical profile of a solar parabolic trough.

1.3 Objectives

The aim of this project is to evaluate solar parabolic trough reflector for concentrated photovoltaic system using numerical modeling and experimental approach. The others are as follows:

i. To construct a functioning prototype model base on mathematical modeling technique to evaluate errors and optical profile of a parabolic reflector.

ii. Propose a measurement technique and procedure in evaluating solar parabolic trough reflector using simple measurement setup and tools.

iii. To analyze the errors and performance of the designed solar reflector using the proposed experimental procedure and mathematical approach.

1.4 Scope of Project

This project implementation generally comprises a study and research through experimental and development evaluation. It needs to be appropriate with the aspects of solar parabolic trough (reflector) in a concentrated photovoltaic. The scope particularly is:

i. Building a functional prototype model to evaluate solar parabolic trough reflector with the size limit of reflector up to 20 cm square.

ii. Conceptualize the mathematical method to evaluate solar parabolic trough model which will provide the result of reflective angle and the surface slope error along the reflector.

iii. Analyzed the parameters value obtained from the experiment by three different condition; ideal (consider zero error), actual and measurement (using protractor).

1.5 Thesis Outline

This thesis is divided into five chapters. First, chapter 1 is on the introduction to the project where problem statement, objectives and scope of project is presented on this chapter. Chapter 2 describes previous work, idea and concept which is related and a motivation for the work performed throughout this project. Chapter 3 describes the methodology used in the design of the experiment where flow of the project, experiment procedure and materials used is included in this chapter. While in chapter 4, it present the experiment results together with its analysis and discussion. Chapter 5 summarizes the main conclusion of the thesis and presents an outlook for future work.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

Literature review is a study about the project and this chapter covers the fundamental concepts of Concentrated Photovoltaic (CPV) and the fundamentals of optics applied to concentration.

It involves all the aspect which can be linked to the project or research which is available in outside world. The research is not mainly focus directly to research which is already performed but also focused on fact research and references of studies. The source and information can be available from internet, library, and also from a person who has high knowledge about the research. This research is important because it resemble the starting point to creating, upgrade and producing a quality research which have trustable result obtained.

From past research that had been done, lot of knowledge can be obtained such as the equipment needs to be used, type of disadvantages can be expected, the basic knowledge need to master to run the experiment and the expected result to be obtained. This will help to reduce the time and cost used for performs of the research.

2.2 Review of photovoltaic energy

A definition of a photovoltaic (PV) system is a system that converts directly solar radiation into electricity [4]. Since it was first found, in 1839 by Edmond Becquerel, and after improvements made in the almost 100 following years, the photovoltaic energy has raised a constantly growing interest all over the world. The possibility to generate electrical energy in practically any place in the world was extremely appealing. With the major drawback of the high cost of solar cells, the almost exclusive use of PV energy was made by space industry to fuel satellites, where no budget constraints were applied. The efficiency of solar cells more than double from 6% in 1954 to 13.5% [8], but still too expensive. Today the top efficiency of silicon cells is around 27.6% 2.2

Ironically, it was in offshore oilrigs and isolated on-shore gas and oil fields, among others, where PV systems were used, replacing the toxic and short-lived batteries [5]. Nowadays, total PV installed capacity is estimated to reach 50.9 GWp, representing a growth of 62.1% comparing to 2010 [8]. The continuously increasing price of oil, the global warming, the Kyoto Protocol, and the recent nuclear disaster that occurred in Fukushima, Japan, turns the attention of the world to renewable energies [4].

2.3 Concentrated photovoltaic (CPV)

A concentrated photovoltaic (CPV) system consists in a technology in which mirrors and lenses are used to concentrate sunlight onto PV cells. This way, the solar cell can be significantly reduced, which is the most expensive component in a PV system. Concentrating the light, the collected sunlight is the same, hence maintaining the power output [11]. The main advantages of CPV are the decrease of PV system costs, as less area of solar cell is necessary, silicon cells can still be used and a higher efficiency. The major disadvantage of CPV systems is the necessity to have a sun tracking system to keep the CPV module focused to the sun throughout the day. This extra cost, compared to conventional PV, is attenuated with the higher power output. CPV systems are usually divided into three categories depending on the concentration level: low (lower than 10

Suns); medium (up to around 150 Suns); high (higher than 200 Suns) [11]. Small concentrations try to ally the advantages of conventional PV models (high acceptance angle) with the advantage of CPV (lower costs related to solar cells, higher efficiency) [6]. Higher levels of concentration drastically reduce the solar cell area (sometimes to a few square millimeters) but usually require high efficiency solar cells (which are expensive),a very high sun tracking precision, and usually require active cooling systems, as the efficiency of solar cells, decrease with increasing temperatures.

Medium concentration was the most popular choice as it combines the best features of both low and high concentration. With the recent entering in conventional PV market by Chinese companies, which build cheaper PV modules, and the advent of thin-film PV cells, the PV modules price dropped significantly. These factors decrease the main advantage that CPV systems had over conventional PV that is the price reduction. This fact will force the CPV market to increase the concentration to much higher values [12]. A CPV system is mainly formed by three different components which are optics, solar cells, and the sun tracking system.

2.3.1 Solar mirror collectors

Solar mirror collectors are a major subsystem of many solar energy systems, particularly for solar thermal generators [13]. Large thermal systems may use many collectors covering large sites as shown in Figure 2.1. Collectors generally consist of concentrating parabolic mirrors, an absorber tube and a supporting structure, which is often equipped with a solar tacking mechanism. They are called parabolic trough collectors (PTCs) [14], see Figure 2.2.

The parabolic shaped mirror (reflector) focuses the sunlight onto a linear tube located at the mirror’s focal line that contains working fluid that absorbs the solar energy and carries it to some thermal plant. The mirror is usually supported by a structure that often contains an active tracking mechanism that keeps the mirror pointed towards the sun.

Figure 2.1: A large solar mirror collector field located at Kramer Junction California, USA [14].

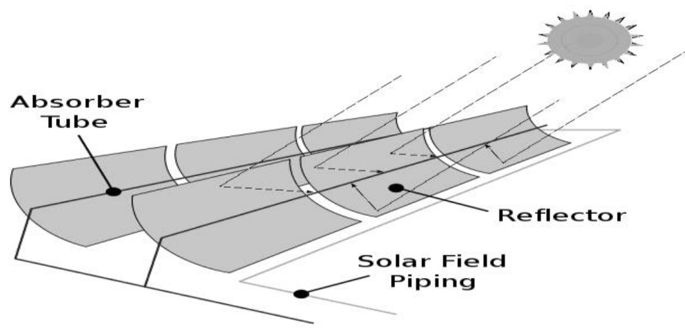
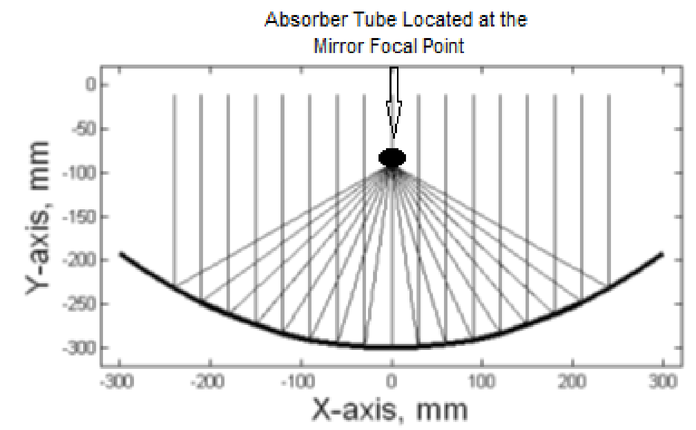
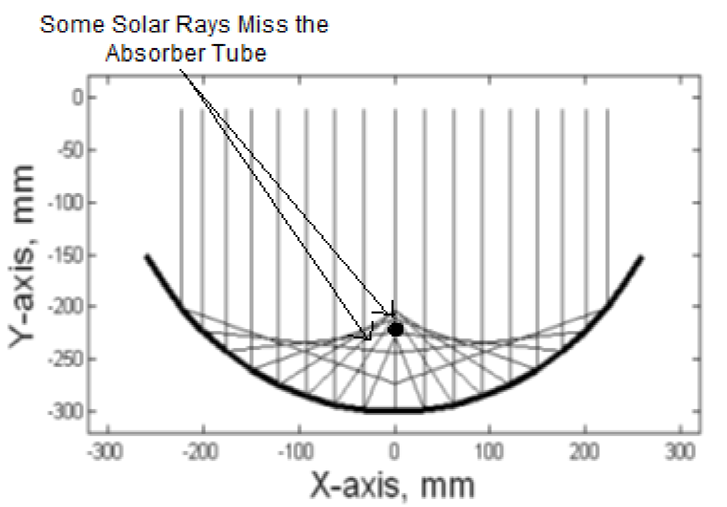


Figure 2.2: Schematic of solar trough collector [15].

The mirror shape must be precise enough to insure that the reflected sunlight is focused on the absorber tube. As shown in Figure 2.3 (a) and Figure 2.3(b)**,** it has been long known that if the shape of the mirror is not a parabola, the light will not precisely focus on a small tube [16]. There are important practical reasons to keep the absorber tube small, such as cost, thermal radiation and convection losses. Mirror precision is important and conventional methods to fabricate precision parabolic mirrors are complex and costly. The reflectivity of the surface materials is an important factor in the optical efficiency. In solar energy applications, back silvered glass plates, anodized aluminum sheets and aluminized plastic films serve as reflectors. They are widely commercially available . Films are usually adhered to a supporting material such as aluminum. However the supporting material must be held with a precision parabolic shape by some supporting structures.



(a) Reflecting Mirror with Ideal Parabolic Cross Section

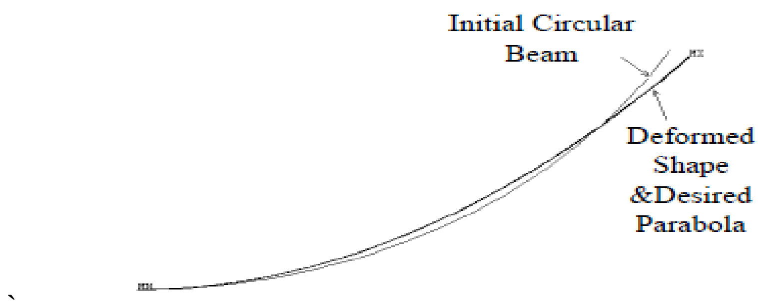


(b) Reflecting Mirror with Non-ideal Cross Section (Circular)

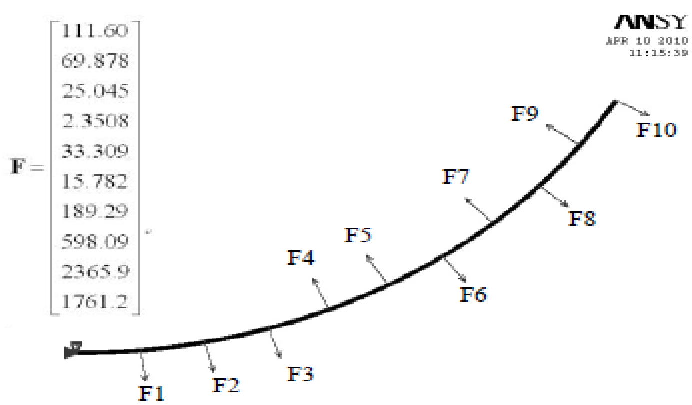
Figure 2.3: Parabolic and Non-parabolic Mirror Cross Section.

Parabolic dies or precision milled mirrors are usually required for these solar concentrators. However, they are often heavy and complex, which makes them unsuitable for rapidly deployable and portable systems. Moreover, their shape cannot be adjusted in real-time to compensate for thermal variations.Many future solar power plants will use very large numbers of parabolic mirror collectors, see Figure 2.1. Hence, methods to design precision parabolic mirrors at relative low cost, such as the one discussed in this paper, are potentially of great commercial importance.

Distributed forces to form parabolas from simple circular shapes also have ever been used**.** Figure 2.5 shows a set of distributed forces that will make an easily made a circular mirror into approximately parabolic shape. Figure 2.4 (a) shows the shape adjustment required to forming a parabola from a rolled circular sheet material. Figure 2.4 (b) shows an example of the required forces when 11 distributed forces are applied. While this approach can achieve the desired result, it requires far more forces than the 11 shown to achieve a smooth parabolic shape, and the implementation of the applied forces in the real system is very complex. A complete discussion of this work is beyond the scope of this paper, and the reader is referred to [16] for further details. Hence a new approach that is simpler to implement is presented in this paper.



(a) Finite Element Analysis



(b) Resulting Applied Forces (in N)

Figure 2.4: Deforming a circular arc to a parabola by distributed forces [16].

2.3.2 Optics

CPV system use reflective and/or refractive materials, mirrors or lenses, to concentrate the light. The most common lenses used are Fresnel lenses, either point-focus or linear focus, depending on the type of focus shape that each one forms. The material chosen to manufacture the lenses is usually PMMA, an acrylic plastic with special characteristics. It is molded relatively easy where it has good weather ability, important to guarantee a large warranty of the module (usually up to 15-20 years).

A factor that decreases the long-term durability of the lenses is the fact that they tend to gain a yellow color, result of the effect of ultraviolet radiation that deteriorates the PMMA [17]. Some tests have been done to produce lenses using glass, but so far, they have not been successful [18].Alternatively to lenses, are mirrors, which instead of refracting the light, it reflect it. Made of aluminum or a special reflective coating, mirrors can have different shapes and have a large longevity as the aluminum does not deteriorate and can even be recycled. The most common shapes are the parabolic mirrors, that concentrate light parallel to their axis in one point, or parabolic troughs that form a focus line.

2.3.3 Fundamentals of Optics Applied to Solar Concentration

The theory of optics is usually associated with the creation of an image from an initial object. Therefore, in imaging optical systems the light emitted by a point in the object, is captured by the optical system and is concentrated onto a specific point in the image, in order to the image be proportional to the object [17]. In CPV systems, it is not necessary to form an image of the Sun in the receiver, as the main goal is to transfer the maximum energy from a source into a receiver.

In non-imaging optical systems, the optical system have to take the light from the light source, instead of an object, and concentrate it in any point at the surface of the receiver, instead of an image. The non-imaging optical theory is called Non-imaging or Anidolic Optics [18].

2.3.4 Reflector Slope Errors

It was first recognized in 1981 by Wood that a great deal of information could be ascertained by analyzing the reflection of the absorber tube in parabolic trough collectors [19]. Just as parallel rays from the sun are reflected off a parabolic trough onto the absorber, so are the lines of sight from an observer reflected onto the absorber tube. Thus an observer aligned with the optical axis of the collector sees the reverse, an enlarged image of the absorber on the reflective surface. Wood's method utilizes the shape of this reflected image to ascertain detailed information about the optical performance of the collector. The German Aerospace Center (DLR) has successfully implemented a quantitative variation of Wood's method to measure slope errors of parabolic troughs from the reflected absorber image [20]. The method uses high-resolution digital photography. A series of photographs is taken of the collector from either the ground or a radio controlled helicopter (second publication). In the original paper, the absorber location and camera position on the ground are measured with a laser distance meter.

Most recently, the camera position in the air is determined using photogrammetric resection based on a series of ground control targets placed around the collector. The authors do not disclose their method for measuring the absorber position for the airborne technique. In all of these techniques, the uncertainty in the reflector slope errors depends on the uncertainty in the absorber location measurement. In each case, the absorber location is measured independently and then used along with images of the reflection of the absorber to find the reflector slope errors.

2.3.5 Solar cells

Conventional solar cells are made of silicon, a semiconductor capable of absorbing light and deliver a portion of that energy, to carriers of electric current, electrons and holes. This phenomenon generates a DC current in a preferential specific direction, working like a silicon diode [7]. A typical solar cell scheme is shown in Figure 2.5. A solar cell is usually formed by several layers, each one with a specific function. The top layer, is an anti-reflective material that decreases the reflection of light, hence increasing the amount of light that reaches the silicon. Usually located right under this layer, is the metal grid that with the bottom contact, form the electrical contacts to where the current carriers will pass.

The silicon is divided to form two layers: one n-type, thinner and negatively doped with phosphorus, and the other p-type, thicker and positively doped with boron [7]. Several types of PV cells exist, depending on the semiconductor used. The most common is the silicon, but even using just silicon, there are different configurations.

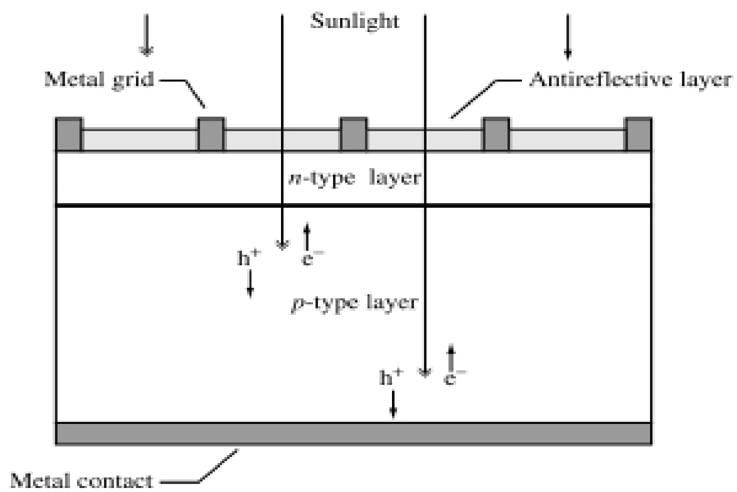


Figure 2.5: Schematic of a PV solar cell. The sunlight creates electron-hole pairs, e^- and h^+ respectively.

2.3.6 Sun Tracking System

The tracking system is a component with a major importance, as with the increase of concentration, lower is the angle that the sunlight can enter in the CPV. To guarantee that the CPV module is always facing the Sun, in order to the sunlight enter the aperture of the module within the acceptance angle, a mechanical system needs to track the position of Sun in the sky, and align the CPV module. Sun tracking systems are usually divided into 1 or 2 axis trackers, depending on the configuration of the optics.

Usually in low concentration levels, only tracking in 1 axis is required, while in medium to high concentration, 2-axis trackers are used. Trackers are an extra cost in CPV systems compared to conventional PV modules, being the price proportional to the tracking precision (usually measured in degrees). The tracking precision necessary is imposed by the acceptance angle, which is the tolerance that the optical system have to a deviation in the angle of sunlight rays [10].

2.4 Previous work on parabolic trough evaluation

One of the methods to evaluate solar parabolic trough performance is by using the finite element modeling and ray tracing by Joshua M. Christian et al [9]. In this paper the finite-element models were used to determine the impact of gravity loads on displacements and rotations of the facet surfaces, resulting in slope error distributions across the reflective surfaces. The geometry of the parabolic trough collector was modeled in SolidWorks, and the effects of gravity on the reflective surfaces are analyzed using SolidWorks Simulation. The optical performance of the deformed shape of the collector (in both positions) is analyzed with additional induced slope errors ranging from zero up to 1° (17.44 mrad). The intercept factor for different solar incident angles found from ray-tracing is then compared to empirical data to demonstrate if the simulations provide consistent answers with experimental data.

Before that, Lüpfert et al. [10] used a ray-tracing code to evaluate the EUROTROUGH parabolic collector intercept factor. Measuring the experimental solar flux distribution resulted in flux maps which could then be used to calculate the experimental intercept factor. Photogrammetry techniques were used to map the parabolic trough and then a ray-tracing code was utilized with these mapped models to evaluate the intercept factor of the system. However if we see from this two paper, it required a big fund for the experiment to be done and this is only suitable for large scale of parabolic trough solar collectors and where in the project presented here, it only requires a simple experimental tools and procedure which able to obtained the same results and parameter as describes in these two paper.

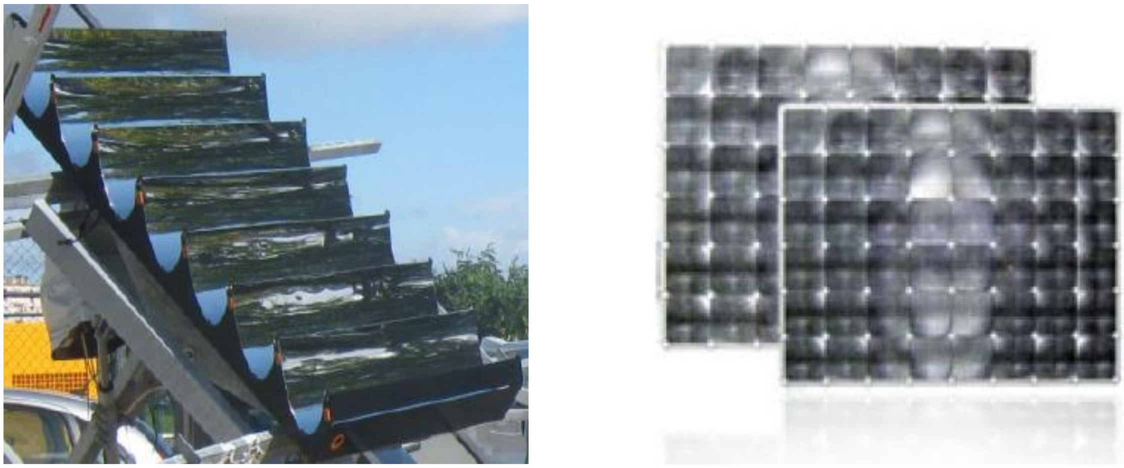
2.5 State of the art of concentrated photovoltaic technologies

Despite increasing market of PV systems, there are just 28 MW of CPV capacity installed, out of more than 33000 MW of PV installed capacity [21]. Low penetration in the market is mainly related to the areas that where the market increased, were developing countries, where CPV systems are not that advantageous as they require more maintenance, comparing to conventional PV modules. Despite these facts, future perspective is of growth for CPV systems. Actually, there are around 689 MW of new CPV capacity under construction, that may increase with potential large scale projects to be constructed India and South Africa [22].

In Figure 2.6, low concentration CPV systems are presented. Both systems, either Double Sun from WS Energia or the one from Zytech, use mirrors to concentrate light into a conventional PV system. Two medium CPV systems are shown in Figure 2.7. The first system, HSUN, from WS Energia, uses parabolic trough mirrors to concentrate light into PV cells located in the back of the next parabolic trough. The second system, from Zytech, uses prismatic lenses to concentrate the sunlight. Figure 2.8 shows two high concentration CPV systems. The first system, from Emcore, uses point-focus Fresnel lenses, while the second concentrator uses parabolic dishes mirrors to concentrate in a single PV cell, while the previous seen systems use smaller modules.

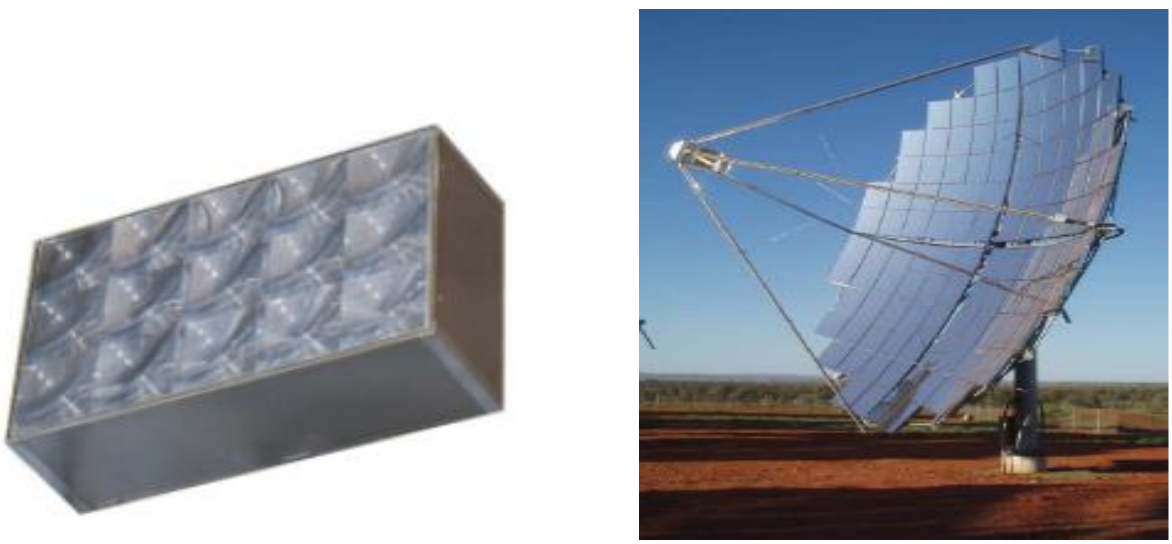
(a) (b)

Figure 2.6: a) Low concentration (2 Suns) DoubleSun, from W.S. Energia b) Low concentration (2.25 Suns) from Zytech



(a) (b)

Figure 2.7: a) Medium concentration (20 Suns) HSUN, from W.S. Energia. b) Medium concentration (120 Suns) from Zytech



(a) (b)

Figure 2.8: (a) High concentration (1090 Suns) G3-1090X, from Emcore. (b) High concentration (500 Suns) from Solar Systems.

CHAPTER 3

METHODOLOGY

This chapter presents the general working flow of the project, which also discuss in detail the mathematical modeling to be implemented and the experimental model developed to evaluate parabolic troughs together with the details of its experimental works. As what we discussed in the previous chapter, parabolic trough is the optical element that most losses can inflict, within reasonable values. The errors in the contour, especially those where parts of the parabola are rectilinear, can make the total incident power drop drastically. To be able to evaluate and measure quantitatively those errors, an experimental model to evaluate parabolic troughs was developed. This evaluation model had to satisfy these three objectives:

1. Measure the optical parameter profile of the parabolic trough by experimental analysis which is to be synchronized and compare with the mathematical modeling

2. Measure the reflection angle along the surface of the parabolic trough.

3. Measure slope (hence position) errors and their direction, along the parabolic trough

3.1 The Evaluation of Parabolic Using Prototype Model

The parabolic evaluation model consists in a mathematical model that is able to measure the errors of slope along a section in a parabolic trough. The laser light scanning the parabola trough will forms a section that has a form of a parabola. To ease the description, in this chapter the line drawn by the laser scanning along the parabolic trough is referred as a parabola. The prototype was built at this period of time later to experimentally apply the model to real parabolic troughs. To begin the model, it was defined that, to evaluate a parabolic trough, it was divided into several parabolas, and then each one of those parabolas was individually studied. Then, it is possible to evaluate a parabolic trough in different sections.

This study is particularly important because of the manufactured structure used to support the parabolic trough. As it has only two supports, located in the ends, the contour of the parabolic trough have different characteristics and defects, depending on the position analyzed. As seen in the prototype, the primary mirror has a more perfect curvature where is supported than in the middle section.

3.2 Reflection Angle of a Parabolic Reflector Surface

For an ideal parabola, all incoming rays parallel to the optical axis (normal rays) will be reflected through the focus point of that parabola. A surface ideal reflection angle, θ_r is defined as the angular difference between the measured surface normal and the ideal surface normal of the design parabolic surface. The transverse reflection angle, θ_r is of much greater significance than the longitudinal reflection angle because parabolic troughs are linear concentrators. The Distance Observer method only measures transverse reflection angle. The transverse reflection angle is defined perpendicular to the length of the collector and the longitudinal reflection angle, θ_r is defined parallel to the length of the collector. The distance observer measurement principle for measurement principle for measuring the reflection angle, θ_r is shown in Figure 3.1 below. For an absorber to be aligned with the focal line of the collector, the reflection angle, θ_r at each point on the collector can be measured by finding the angle between the incoming ray from the laser pointer with ray which is reflected through the focal point of the collector where in this project, opaque glass as a target is assume as a collector.

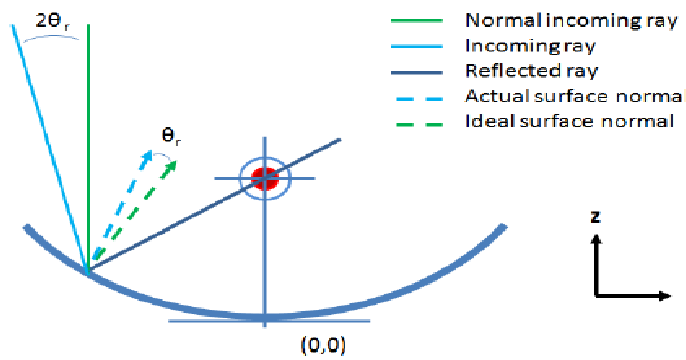


Figure 3.1: Graphical representation of a reflector surface reflection angle

3.3 Slope Error of a Parabolic Reflector Surface

Slope error of a parabolic trough must be modeled as a distribution of reflection angle in order to combine the effects of reflector slope. For a perfect reflector with no surface slope errors, an incoming ray, assumed to be parallel to the optical axis, will be reflected and pass through the focal point of the parabola as shown in Figure 3.2 (labeled as "ideal reflection"). For an incoming ray to pass through the center of an absorber that is not aligned with the focal point, the reflector surface must have non-zero slope error or by means that the incoming ray from the laser pointer is reflected at a point other than the focus point. An absorber misalignment or indicate as focal error in this project can thus be modeled as a perfectly aligned absorber and a set of effective slope errors in the reflector surface.

The effective slope error, ε_{α} at each point across the aperture is determined by finding the surface slope error required for an incoming solar ray to intersect the center of the absorber instead of the focal point. The effective slope error is equal to half of the angle between the absorber tube, the point on the aperture, and the focal point as shown in Figure 4.Further explanation on this matter is represented in section 3.4 of this chapter where it is represented in a mathematical modeling.

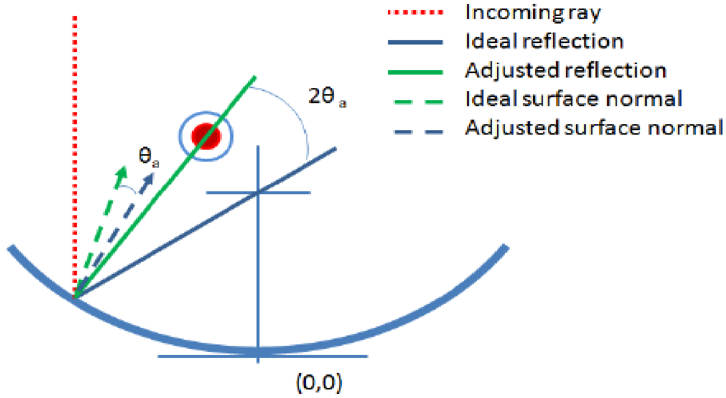


Figure 3.2: Graphical representation of a reflector surface slope error

3.4 Mathematical description of the evaluation model

The principle of the model is that an incident ray of light, parallel to the axis of a parabola, will be reflected to the focus of that parabola. If the parabola has some sort of defect in the surface, the ray will be reflected to a point, other than the focus. Knowing that the refection angle (θ_r) of a ray of light is changed by a surface with an inclination, by the following equation:

$$\theta_{r\prime} = \theta_r + 2 \text{ X } \alpha \,, \tag{3.1}$$

if a reflected ray has a certain angle deviation, $\Delta\theta_{r\prime} = \theta_{r\prime} - \theta_r$,from the theoretical ray that pass through the focus, the error in slope of the point in the parabola where the ray was reflected, is given by

$$\varepsilon_\alpha = \frac{\Delta\theta_{r\prime}}{2} \tag{3.2}$$

To obtain the angular deviation $\Delta\theta_{r\prime}$, it is considered a vertical target, placed in the vertical plan where the focus of the parabola is. Measuring the distance from focus in target to the point where the reflected ray focuses in target, and knowing the point where the ray was reflected, it is possible to calculate the angular deviation.

Considering a ray reflected in a point in a parabola, with coordinates *(x,p(x))*, where x the abscissa measured from the focus, and p(x) is the equation of the parabola. The incidence point in the target has coordinates (0,d), where d is the measured distance from focus to the incidence point. The reflection angle of a ray is given by

$$\theta_r(x,d) = ArcTan\left(\frac{d-p(x)}{-x}\right) \quad (3.3)$$

Substituting equation 3.2 in equation 3.3 and substituting for the incident point and the focus, the slope error of the reflection point of the parabola mirror is given by

$$\varepsilon_\alpha(x) = \frac{ArcTan\left(\frac{d-p(x)}{-x}\right) - ArcTan\left(\frac{p(x)}{x}\right)}{2} \quad (3.4)$$

With the model presented, it is possible to evaluate a surface of a parabola, point-by-point, using equation 3.4, in which the variables are obtained by measuring the distance from the incidence point in the target to the focus and the reflection point in the parabola.

3.5 Setup of the prototype model

The setup of the prototype model to evaluate the parabolic trough is discussed here including the selection of the materials used in detail to build the prototype and also the explanation of the procedure to setup the prototype model before the experiment evaluation is to be done.

3.5.1 Materials

To build the experimental model prototype to evaluate parabolic troughs, it used the main following materials:

1. Laser pointer

As it is only necessary a visible light source that creates a small spot in the mirror, and no lenses or refractive material is used, a common laser pointer is sufficient to this study.

2. Opaque glass

The rectangular piece of opaque glass was used as target. The function of the target is to intercept the light in the focus vertical plan, but has to let some light pass in order to the camera to capture it or visible to the experimenter to observe it, hence the opaque glass. A regular glass can't be used as a target, since it will cause second reflection to the parabola and back to the target. This fact may not be seen with the use of opaque glass.

3. Aluminum tubes

Due to the relative low density and large amount of aluminum tubes available around UTHM, Parit Raja area, it was the preferred material to build the overall structure.

4. Aluminum mirror

The aluminum mirror is used to build a small rectangular piece and form a parabolic solar collector to be placed in front of the target. The aluminum mirror used here, is the same as used in the manufacturing of the parabolic troughs, due to the availability.

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