Journal of Applied Science and Agriculture, 9(11) Special 2014, Pages: 42-48

AENSI Journals

Journal of Applied Science and Agriculture

ISSN 1816-9112

Journal home page: www.aensiweb.com/JASA

Development of Design Parameters for the Concentrator of Parabolic Dish (PD) Based Concentrating Solar Power (CSP) under Malaysia Environment

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ARTICLE INFO

Article history:
Received 25 June 2014
Received in revised form
8 July 2014
Accepted 10 August May 2014
Available online 30 August 2014

Keywords:
Concentrating Solar Power (CSP)
Parabolic Dish (PD)
Renewable Energy (RE)
Power Conversion Unit (PCU)

ABSTRACT

Concentrating Solar Power (CSP) technologies has the ability to harness solar energy for producing the electricity. The development becomes increasingly important for economies in many countries, especially in the regions that is hot, dry and received excellent solar radiation. Meanwhile, among the CSP technologies, Parabolic Dish (PD) system has demonstrated a high thermal efficiency and the implementation of PD concentrator will result in sustainable energy generation with emission free operation. However, PD based CSP technology is still an emerging industry in Malaysia with no operation plant installed so far. It still needs thorough review before developing the PD technologies under the Malaysia tropical environment. Therefore a Matlab simulink is used in this work to design the concentrator for the PD 1kW system under Malaysia environment. This paper elaborates the methodology utilized to develop the concentrator for the PD 1kW system and outlines the parameter that's used for increasing the efficiency of PD based CSP under Malaysia tropical environment. From the simulation result, it is suggested to use 3.7 meters for the concentrator diameter and aluminium as the reflective material for the concentrator. As a conclusion the size and the reflective material for the concentrator are essential. Therefore, it should be taken into account before developing the geometric parameters for PD concentrator under Malaysia environment.

To Cite This Article: Rosnani Affandi, Chin Kim Gan & Mohd Ruddin Ab Ghani, Development of Design Parameters for the Concentrator of Parabolic Dish Based Concentrating Solar Power (CSP) under Malaysia Environment. ***J. Appl. Sci. & Agric.,*** *9(11): 42-48, 2014*

INTRODUCTION

The development of Parabolic Dish (PD) technology began in late of 1970's and has demonstrated the operating success with the highest of solar to electric efficiency (R. Affandi, Ruddin & Gan, 2013; D. Howard & Harley, 2010). PD system is simple and it is more reliable than other CSP technologies with less occupied land. At the same time, the PD offer the highest thermal efficiencies compared to the other Concentrating Solar Power (CSP) technologies (Lovegrove, Burgess, & Pye, 2011). Zhang et al (2012) in his recent paper has mentioned that the highest system efficiency for PD is about 31.25%. However, when compared to the other of solar technologies such as the Photovoltaic (PV) system, CSP technologies such as the Parabolic Trough, Power Tower and the Linear Fresnel; the PD system do not have a wide operational experience (Mendoza, 2012).

The main components for PD are consist of the concentrator, receiver, Stirling engine, and generator (Refer Fig. 1). Generally, the PD concentrators are made from reflecting mirrors with the receiver, the Stirling engine and generator are located at the focal point inside the Power Conversion Unit (PCU). The concentrator is used for focusing the solar radiation into the cavity of the receiver. The receiver transfers the heat from absorbing solar energy to the working gas. Then the Stirling engine converts the heat energy into mechanical power by expanding the working gas in the cylinder. Finally a linear motion from Stirling engine will be converted to rotary motion and turn the generator to produce electricity (Mohamed, Jassim, Mahmood, & Ahmed, 2012).

Meanwhile, the most important part in the PD system is the concentrator; and to be more efficient, the PD concentrator needs to focus the solar energy exactly on the receiver at the focal point (Sembiring, Napitupulu, Albar, & Husein, 2007). Therefore, in order to focus the solar energy and maximize the thermal energy at the focal point; it's important to optimize the geometric design of the concentrator. The shape of the PD concentrator needs to be precise. Moreover, the viability of the PD system are depends on the design and configuration (Reddy & Veershetty, 2013).

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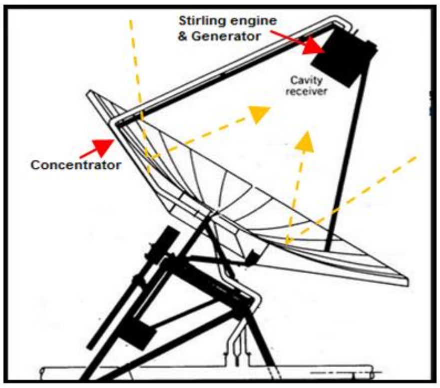

Fig. 1: Parabolic Dish.
(http://www.powerfromthesun.net/Book/chapter09/chapter09.html)

Based on the observations from previous literature, PD systems have not been studied as extensively as other solar system such as PV system or other CSP technologies such as the Parabolic trough and Power Tower. Moreover, information about this technology, especially the PD systems under Malaysia tropical environment is scanty, difficult to obtain and rarely formed in one cohesive report. Therefore, this study is to present and focus on the development of design parameters for the PD concentrator 1kW system as well as outlined the parameter used to increase the efficiency of PD based CSP under Malaysia tropical environment.

1. Methodology:

This study is using a simulation approach and Matlab Simulink is used as the simulation tool. The simulation is done by taking into account the mathematical equations for designing the PD concentrator. The simulation is covering the modeling for PD geometric designs such as the dimensions of the concentrator, the ideal of the focal point distance, the diameter of the focal point diameter, concentration ratio as well as the parameter for increasing the concentrator efficiency for 1kW PD system under Malaysia environment.

1.1 The parameters for design 1kW PD concentrator:

This section identifies some of the parameters that are utilized to develop the concentrator for the 1kW PD system.

1.1.1 Diameter of the PD concentrator:

Before developing the PD system, it is essential to know the size or diameter of the concentrator. This is because the size of the PD concentrator is determined by the Stirling engine. As stated by William B. Stine, he mentioned that the size of PD concentrator is determined by the the Stirling engine or the power output required by the PD system at maximum insolation levels which is nominally at 1,000 W/m (William B. Stine, 1994).

Basically for the PD 25kW system, the diameter of the concentrator is 10 meters. Meanwhile, from the previous studies, William B. Stine and Aker using 10 meters PD diameter for 25kw Stirling engine (Aker, 2012; William B. Stine, 1994). However the other researcher such as Fraser and company of WGA Associates is using 11 meters diameter for PD 25kW system (Fraser, 2008; WGAssociates, 2006). Whilst, the size for PD concentrator that currently being develop for commercial used is from 8 to 15 meter (D. F. Howard, 2010). While, there are many researchers has done their study on the small scale of PD, such as 1.8 meter, 2.5 meter (Peiyao, 2007), 3.0 meter (Sembiring, 2007), 5.5 meter and 7.5 meter (William, 1994).

It is important to sized the PD concentrator to ensure that the concentrator can deliver more thermal energy to the Stirling engine and to ensure that at any irradiance levels; the thermal energy from concentrator will not exceed the PCU can handle (Diver et al, 2001; D. F. Howard, 2010;Aker, 2012). Therefore, manually the diameter of the PD concentrator can be selected by giving a fixed value and can be measured at the aperture from two positions that normal to each other. Besides, the size can be determined by using a freeware program which is Parabola Calculator version 2.0 (http://mscir.tripod.com/parabola/).

1.1.2 Sizing the Aperture Area of Concentrator

The aperture area of the concentrator is the area that receives the solar radiation. The size of aperture area for the concentrator will affect the amounts of thermal energy deliver to the receiver, the optical efficiency and the concentration ratio of the PD system. Increasing in the aperture area of concentrator will increase the amounts of thermal energy deliver to the receiver. Whilst, the smaller aperture of the concentrator would results in smaller geometric factors and will eventually produce higher optical efficiencies (Kadir & Rafeeu, 2010). Therefore, the aperture area of the concentrator can be calculated by using:

$$A_{aperture} = \frac{\pi}{4} D_{con}^2 \tag{1}$$

1.1.3 Focal Length of the PD:

The parabolic mirror concentrator is used for focusing the solar radiation into the receiver, then the radiation will reflect and focused at a focal point. However, to assure that the radiation will always be reflected at the focal point, it will require a continuous adjustment. Therefore, the position of the reflected solar energy will maintain at the focal point as the sun moves through the sky (Kadir & Rafeeu, 2010). The focal length or the distance of the focal point from the concentrator can be calculated by using an equation;

$$\frac{f}{D_{con}} = \frac{1}{4\tan(\phi_{rim}/2)} \tag{2}$$

Meanwhile, Fig. 2 shows the Diameter of the concentrator, focal point and the focal length of the concentrator.

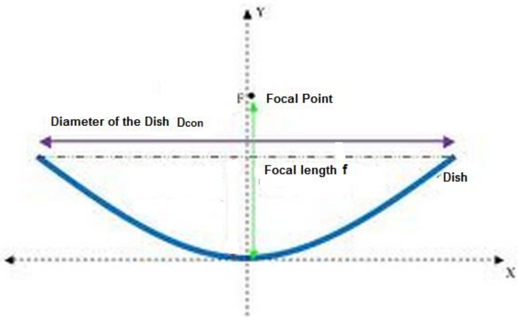

Fig. 2: PD concentrator Schematic diagram.

1.1.4 The Focal Point Diameter:

In a PD concentrator, a circular image centered with diameter d will form when a solar radiations reflected at the focal point of a perfect concentrator (refer Fig. 3). Therefore, the focal point diameter can calculate by using mathematical equations;

$$d = \frac{f \times \theta}{\cos\phi_{rim}(1+\cos\phi_{rim})} \tag{3}$$

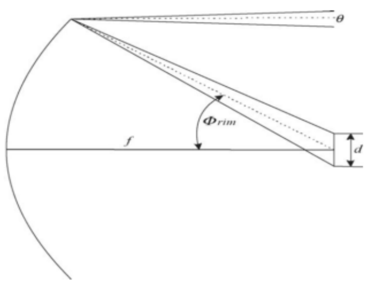

Fig. 3: Circular images centered at the focal point with diameter d (Kadir & Rafeeu, 2010).

1.1.5 Sizing the Aperture Area of Receiver:

The important feature of a receiver is to absorb as maximum as possible the amount of reflected solar energy and transfer it to the working fluid as heat, with a minimum loss. Therefore, the aperture of the receiver must be designed to be large enough to enable a significant fraction of reflected solar energy from the concentrator to be transmitted onto the receiver. By increasing the aperture size, it will increase the amount of solar radiation intercepted by the receiver, but at the same time it will also increase the losses due to convection and radiation out of the receiver aperture (Ngo, 2011). Therefore, the aperture area of the receiver can be calculated by using mathematical equations;

$$A_r = \frac{\pi}{4} d^2 \tag{4}$$

1.1.6 Geometric Concentration Ratio:

The concentration ratio is the ratio of the concentrator aperture area to the aperture area of the receiver and is given as:

$$C = \frac{A_{aperture}}{A_r} \tag{5}$$

Meanwhile, Kalogirou has mentioned in his study that the concentrating collectors such as PD system can only utilise the irradiation if the concentration ratio is greater than 10 (Kalogirou, 2004). Therefore, to assure that the PD system can utilize the irradiation under Malaysia tropical environment, it is essential to sized aperture area of the concentrator and receiver that can produce the concentration ratio value greater than 10. Generally, the concentration ratios can vary from as low as unity to values of the order of 10,000 to the highest is around 46,000 (Fraser, 2008). While, an increased in the concentration ratio means an increasing in the temperatures value at which energy can be delivered. However, most of the existing PD has a very low concentration ratio. Whilst, to have a concentrator with high concentration ratios; the concentrator need to be manufactured precisely (William B. Stine, 1994). Nevertheless, to produce an accurate concentrator, it will increase the cost of the concentrator because generally a direct correlation exists between the accuracy of the concentrator and its cost.

1.1.7 Rim Angle:

In a report "A Compendium of Solar/Dish Stirling Technology", William B. Stine gives the definition for rim angle is an angle that is measured at the focus from the axis to the rim of truncated parabolic (William B. Stine, 1994). While, Fraser defining rim angle as an indicator for the curvature of the parabolic concentrator (Fraser, 2008). Therefore, before sizing the concentrator, rim angle ϕ_{rim} need to be determined. This is because, rim angle will influence the concentration ratio, intercept factor and the losses due to a convection and radiation (D. Howard & Harley, 2010; William B. Stine, 1994). Rather than that, rim angle became the indicator for the curvature of the concentrator. In which, concentrator with larger rim angel will have a stepper slope.

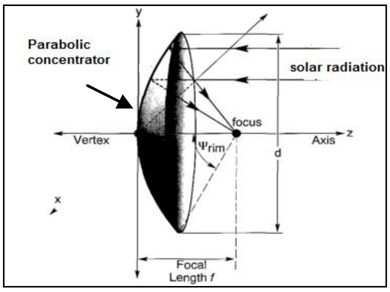

Fig. 4: The Parabolic concentrator surface (William B. Stine, 1994).

Generally, rim angles for Paraboloids in solar applications have rim angles from less than 10 degrees to more than 90 degrees (William B. Stine, 1994). However, many manufacturers have designed the concentrator with a value near to 45 degrees. This is because; theoretical analysis have shows that highest concentration ratio, highest efficiency and highest thermal performance will produce with rim angle value of 45 degree (Fraser, 2008; Lovegrove et al., 2011; Mendoza, 2012).

1.2 Parameters for increasing the PD efficiency under Malaysia tropical environment:

1.2.1 The Efficiency of PD Concentrator:

The primary measure of the concentrator efficiency is how much fraction of solar radiation reaches the opening area of the concentrator and reflected to the receiver. Therefore, the concentrator efficiency can be determined by using an equation:

$$\eta_{conc} = E(\cos\theta_i)\rho\phi \quad (6)$$

From the equation , *E* is the unshaded aperture area fraction and usually the unshaded aperture area fraction for most of the PD design is more than 95% (William B. Stine, 1994). Whereas, K.Reddy in his paper has mentioned that the increasing amount of shadow falling on the concentrator will decrease the conversion of solar energy from the concentrator to the receiver (Reddy & Veershetty, 2013). Meanwhile, the value of incidence angle θ_i for PD system is remaining zero throughout the day (cos 0 making it equal to 1). This is because of the PD system normally using the dual axis tracking system and this will allows the concentrator to collect the solar radiation as maximum as possible.

Whilst, From the equation, reflectance and intercept factor (ρ and ϕ) are two critical terms in determine the concentrator efficiency (Mendoza, 2012; William B. Stine, 1994) . The reflectance for the PD concentrator can be determined as a percentage of incident sunlight that reflected from its surface. However, the weather such as the rainfall and the humidity will affect the reflectivity and the efficiencies of the concentrator. This will indirectly affect the reflecting surface and it will slowly deteriorate when exposed to the weather. Malaysia receives a high value of rainfall and considered as one of the wet climate countries where annual rainfall is

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about 2250 mm/year. Meanwhile Humidity in Malaysia varies from 80% to 90%. Therefore, it is essential to choose the reflective material for the concentrator that is long life and at the same time have a low cost.

Normally the concentrator for PD systems uses reflective surface from material such as silver, aluminium, iron sheet or stainless steel (James Baker & Todd Meyer, 2009; Kruger, Pitz-paal, & Rietbrock, 2003). Table 1 shows the different type or material used for the concentrator has a different reflectivity.

Table 1: Reflectance of the Concentrator.

Material	Reflectivity (%)
Stainless steel	67
Iron sheet	87
Aluminium	92
Silver	96

Meanwhile, intercept factor in the PD system is a fraction of solar radiation that reflected from concentrator and entering the receiver aperture. It becomes the most important factor in matching a concentrator to a receiver. Fraser (2008) mentioned the intercept factor is often between 94 and 99%. However Bakos (2013), in his research has stated that intercept factor is between 90 and 99%. Meanwhile, PD from the type of Wilkinson, Goldberg, and Associates, Inc or (WGA) have a high degree of accuracy with an intercept factor that over 99%. Therefore the value of intercept factor is around 90 % to 99 %.

3. Results:

From the simulation result, to develop a 1kW PD system, it will need 3.7 meters for the diameter of the concentrator, 10.75m^2 for the concentrator aperture area, 2.233 meters for the focal length, 0.00006976 meters for the diameter of focal point and the aperture area of the receiver is equal to 0.01721 m^2 (refer Fig.5).

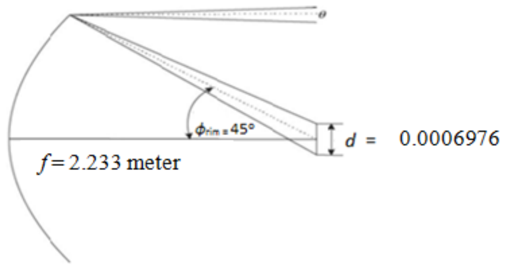

Fig. 5: A dimension of focal length, rim angle and diameter of 1kW PD system.

Meanwhile, fig. 6 shows the relation between the size of the concentrator and the aperture size of the concentrator. It shows that, the increasing size of the concentrator will significantly increase the aperture area of the concentrator that receives the solar radiation. Meanwhile, the behavior of the PD concentrator is determined by the quantity of solar radiation that reaches the opening area of concentrator and reflected the radiation to the receiver at the focal point. Therefore, when the size of the concentrator is increased it will increase the amount of solar radiation that reflected from opening area of concentrator to the receiver.

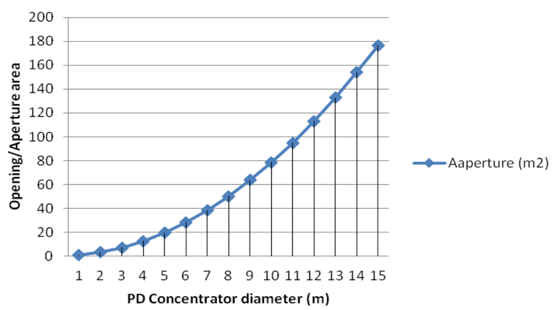

Fig. 6: Relation between geometric factors with aperture of the concentrator.

Fig. 7 shows the variation of concentration ratio as a function of the rim angle for 1 kW PD system with 3.7 meters of concentrator diameter. The result clearly shows that rim angle influence the concentration ratio value. From the figure, the lowest value for the concentration ratio is 56.23 at rim angle 1 degree. Meanwhile, the concentration ratio value starting to increase from rim angle 1 degree until rim angle 44 degrees and reach the highest concentration ratio value 43248.12 at rim angle 45 degrees. The values of concentration ratio start to decrease at rim angle 46 degrees with concentration ratio value 46191.79. Therefore, the PD should be able to utilize the irradiation because the minimal value of the concentration ratio is greater than 10. In which the minimal value of the concentration ratio is 56.23 at rim angle 1 degree. Meanwhile, the simulation result proves the theoretical analysis; in which the highest concentration ratio is achieved with a 45 degree rim angle.

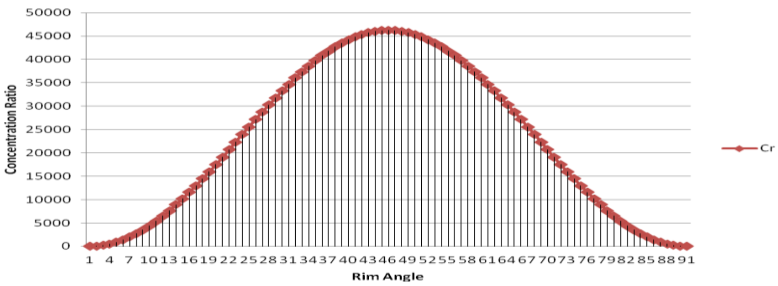

Fig. 7: The variation of concentration ratio.

Meanwhile, a 1 kW PD system with 3.7 meter concentrator can achieve the highest value of concentrator efficiency, which is 0.95 if using silver as the concentrator material. Whilst, it will have the lowest value of the concentrator efficiency if using stainless steel as the mirror reflector. However, among the reflective material, aluminum or silver has been used for centuries. Aluminum or silver has high reflectivity surface and always been the most common candidates to make an efficient mirrors concentrator. Therefore, to increase the efficiency of the concentrator under Malaysia environment, the material must be efficient, long life and low cost. Due to the relatively high price of silver compared to the aluminium, iron and stainless steel. To be more efficient, economically feasible and suitable for Malaysia environment; it is suggested to use aluminium as the reflective material for the concentrator. This is because aluminium is material that produce the second highest of concentrator efficiency after silver, which is 0.91 (ref Fig.8).

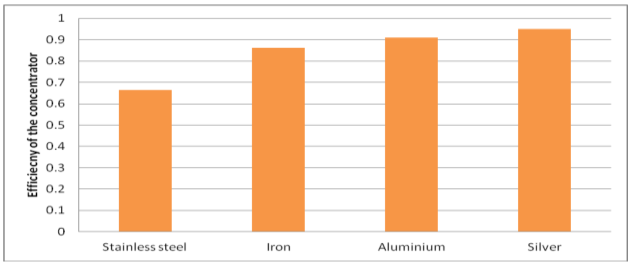

Fig. 8: Concentrator efficiency for four different concentrators reflecting material.

5. Conclusion:

This study shows a simple exercise in designing the PD concentrator for the PD 1kW system. Therefore, it is suggested to use 3.7 meters for the concentrator diameter and aluminium as the reflective material for the concentrator. The medium used as the reflector for the concentrator will influence the concentrator efficiency. Therefore, to have a PD concentrator that is efficient and low cost, aluminium is the interesting material to use as solar reflector material.

ACKNOWLEDGMENT

The authors would like to gratefully acknowledge the funding support provided by the Ministry of Education Malaysia under the research grant No: FRGS/2/2013/TK02/FKE/01/F00167.

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