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Design and modeling of solar parabolic trough power plant with MATLAB

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Abstract. With the fact that Malaysia is one of the fast- growing countries, demand of energy increment is rapid. Malaysia is able to obtain ample amount of annual solar radiation due to its location at equator. If this is utilized proficiently and effectively, then, it can suffice the domestic needs as well as the industrial needs in terms of energy consumption. This article proposes a parabolic Trough Power Plant which is designed with 1.2 kW net electric output. Consequently, the results of theoretical calculations are detailed in the article, while, ensuring the analysing of design proposed through the MATLAB software. The results showed that by making use of aperture having an area of approximately 80 m2, maximum useful heat gain of 20701W at 13:00 pm was attained in March. The maximum net power is 11.84 kWh/day in February.

1 Introduction

The solar thermal power generation is closely similar to traditional ways of producing power based on fossil fuel combustion, which is also relying on the heat engines for conversion of energy to electricity. The implementation and experimentation begun in US, when the oil crisis occurred during 1970s and the first commercial plants were implanted at California in the late 1980s [1]. Due to compelling effect of global warming and volatile gas prices, both interest and investment are accelerated in solar thermal power technology, quickly. From the last two decades, investment is the biggest reason which lacked for the solar thermal power technology. If the investment were sufficient, this source of electrical power production will be the biggest source of electricity in economical way. It shows that there is a strong chance that this technology is one of the main stream of producing electricity, along with hydro, wind, and solar photovoltaic technologies; which is a key renewable energy for the future [2].

Solar energy is inexhaustible, locally available and renewable source of energy. It allows a local energy independence due to its clear and clean energy source. As the sun's power of reach earth at the annual rate of approximately 1000 W/ m^2 [3], it still varies its availability with the location and time of year. In order to capture the solar energy, it requires equipment with demands a high initial capital cost.

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Nevertheless, certain cases were reported where a lifetime of the solar equipment is mostly to state that these systems are able to prove a cost competitive market, when it is compared with the conventional energy technologies [4]. The solar thermal power technologies are distinguished to concentrate solar radiation by systems, such as, (1) parabolic trough, (2) solar tower, and (3) solar dish. The direct radiation from the sun is concentrated with the use of reflectors and the concentrated energy is then transformed into steam, which can be used to drive conventional electricity generators [5]. Therefore, this study explores the conceptual design and performance analysis of solar thermal power plant using Direct Steam Generation (DSG) criteria in a parabolic trough solar field by using MATLAB software. The location of the study is in Universiti Teknologi PETRONAS, Perak Malaysia. This study also proposes case study which assumes the total output of solar thermal power plant at 1.2 kW.

2 Mathematical modeling

A basic Rankine cycle with a variety of reference values and inputs are incorporated in the design shown in Figure 1. Firstly, there is a different state points which are determined through a theoretical concept by analysing the heat transfer that occurs in each component of the cycle. Consequently, these state points are then used to obtain steam flow rate, condenser water flow rate and other related values.

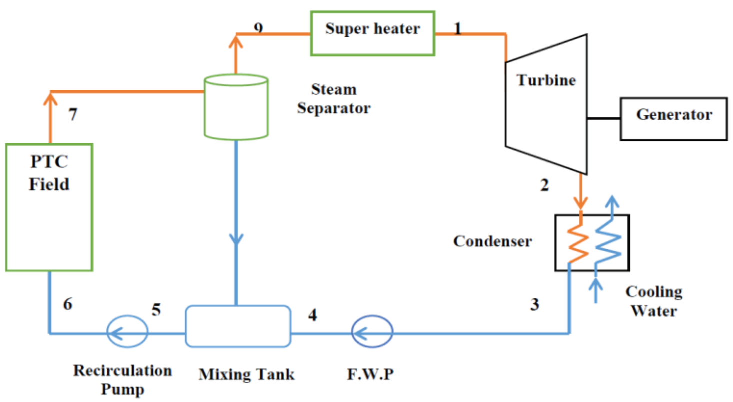

Fig. 1. Simplified process flow diagram a PTC based solar thermal power plant.

This system present mathematical modeling, where the energy analysis of the PTC is referred to the equations presented in Refs [6, 7, 8]. In presentation, the modeling of solar system is displayed first. Next, the performance assessment equations to represent the entire system are presented, respectively. For the calculations, assumptions are made. One of the assumptions is that the system is at a steady state. Other than that, the pressure change is negligible except in the turbines and pumps. The equation to define useful energy rate from the collector are:

$$Q_{gain} = \dot{m}_{CL} \ (h_7 - h_6) = \eta . I . A_p \quad (1); \quad \eta = \eta_o - U_L . \left(\frac{\Delta T}{I}\right) \quad (2); \quad \Delta T = T_m - T_a \ (3)$$

Where: m_{CL} is the mass flow rate of steam passing through Collector (kg/s), I is direct normal incidence radiation (W/m^2, A_P is aperture area of the collector (m^2), $T_m = (T_6 + T_7)/2$, denotes mean temperature (˚C), Ta is ambient temperature (˚C), and U_L is loss co-efficient based on aperture area (W/m^2.K). If the work input Feed Water Pump (*F.W.P*) and Recirculation Water Pump (*RC.W.P*) as well as heat losses through piping are neglected then:

$$Q_{gain} = \dot{m}_{CL} \ (h_7 - h_6) = .(h_1 - h_3) \quad (4)$$

From Eqs. (1) and (4):

$$\dot{m}_{CL}\,(h_1 - h_3\,) = \eta\,.I.A_p \qquad (5)$$

It may be noted that the PTC inlet mass flow rate (m_{cl}) will generally remain fixed during the operation and as a result the PTC outlet dryness fraction as well as mean temperature difference ($\Delta\,T$) will vary at part load. The value of $\Delta\,T$ can be calculated by neglecting the pump work and assuming design point outlet dryness fraction of the PTC field (x_7). The value of PTC field inlet temperature (T_6) can be calculated from inlet pressure (P_6) and inlet enthalpy (h_6) which could be obtained from:

$$h_6 = (1 - x_7).\,h_8 + \,x_7.\,h_3 \qquad (6)$$

It may be noted that h_i and T_i denote the enthalpy and temperature at *i*-th state point, respectively. η_o is optical efficiency which is defined as:

$$\eta_o = \;\rho_c\,\gamma\,\tau\,\alpha\,K_\gamma \qquad (7)$$

where ρ_c, γ , τ , α and $K_\gamma$are the reflectance of the mirror, intercept factor, transmittance of the glass cover, absorbance of the receiver, and incidence angle modifier, respectively and their values are given in Table 1. The aperture area is defined as:

$$A_p = (w - D_{co}\,)L \qquad (8)$$

Where *L*, *w*, and D_{co} are collector (module) length, collector width, and receiver cover outer diameter, respectively. The solar collector heat loss coefficient between ambient and receiver is defined as:

$$U_L \;=\; \left[\frac{A_r}{(h_{c,ca}+h_{r,ca})A_C} + \frac{1}{h_{r,cr}}\right]^{-1} \qquad (9)$$

The radiation heat coefficient between ambient and the cover is defined as:

$$h_{r,ca} = \;\varepsilon_{Cv}\,\sigma\,(T_c + \,T_a)\big(T_c{}^2 \;+T_a{}^2\big) \qquad (10)$$

Where ε_{Cv} is the emittance of the cover and σ is Stefane-Boltzmann constant. The radiation heat coefficient between the receiver and the cover is defined as:

$$h_{r,cr} \;=\frac{\sigma\,(T_c+\,T_{r,av})(T_c{}^2+T_a{}^2)}{\frac{1}{\varepsilon_r}+\frac{A_r}{A_c}\left(\frac{1}{\varepsilon_{cv}}-1\right)} \qquad (11)$$

Where ε_r is the emittance of the receiver and the subscript *av* is refers to average. The convection heat loss coefficient between the cover and ambient is defined as:

$$h_{c,ca} \;=\; \left(\frac{Nu\;k_{air}}{D_{c.o}}\right) \qquad (12)$$

Where Nu is the Nusselt number and k_{air} is the thermal conductivity of the air. The subscript r refers to the receiver. The temperature of the cover can be calculated using this equation:

$$T_c \;=\; \frac{h_{r,cr}\;T_{r,a}+\left(h_{c,ca}+h_{r,ca}\right)\,T_O\,\frac{A_C}{A_r}}{h_{r,cr}+\left(h_{c,ca}+h_{r,ca}\right)\,\frac{A_C}{A_r}} \qquad (13)$$

The amount of the solar radiation that shines upon the collector, considered as heat into the system, is defined as:

$$Q_{solar} \;\;=\;\; m_{cl}.\,(h_7 - h_6) + m.\,(h_1 - h_9) \qquad (14)$$

The performance equations of the overall system are presented next. The power produced by the steam turbine is defined as [8, 9]:

$$W_{st} \;=\; \dot{m}\;(h_1 - h_2) \qquad (15)$$

Where h is the enthalpy and the subscript *st* indicates steam. The net power of the steam Rankine cycle is defined as:

$$W_{cyc} = \;\eta_g\;W_{st} - \;(W_{F.W.P} + \;W_{Rc.P.W}) \qquad (16)$$

$W_{F.W.P}$ is power for feed water pump and $W_{Rc.P.W}$ is power for Recirculation pump water are defined as:

$$W_{F.W.P} = \dot{m}\,(h_4 - h_3) = \dot{m}\,\vartheta\,(P_4 - P_3) \quad (17)$$

$$W_{Rc.P.W} = \dot{m}\,(h_6 - h_5) = \dot{m}\,\vartheta\,(P_6 - P_5) \quad (18)$$

The net electrical efficiency for the steam Rankine cycle system is defined as:

$$\eta_{el} = \frac{W_{cyc}}{Q_{solar}} \quad (19)$$

The considered PTC specifications and characteristics are shown in Table 1.

Table 1. Characteristics of PTC used for simulation

Parameters	Value
Length of the receiver (L)	6.4 m
Width of the collector (W_a)	2.6 m
Focal length (F)	0.87 m
Receiver external diameter (Dao)	40 mm
Receiver internal diameter (Dai)	38 mm
Concentration ratio (C)	20
Rim angle (°)	72.5

3 Result and discussion

The collection of data was measured at every 5 minutes direct normal irradiation (DNI) by a device located in the solar side zone of Universiti Teknologi PETRONAS. A typical day of the month is selected to represent the month as per [5] criterion of recommended average day of the month. It accumulates total solar radiation starting at sunrise hour and ending at sunset hour. The input parameters of PTC field, turbine and condenser used for the simulation are given in Table 1. Simulation of the plant, based on selected typical day of each month average hourly DNI, has been done to see the daily variations of collector efficiency and heat gain. For these calculations, the typical day monthly average hourly DNI and ambient temperature data are taken from EKO Pyranometer located in the solar side zone of UTP. Hourly solar insolation of a direct normal irradiance on a specific day each month throughout the year is depicted in Figure 2.

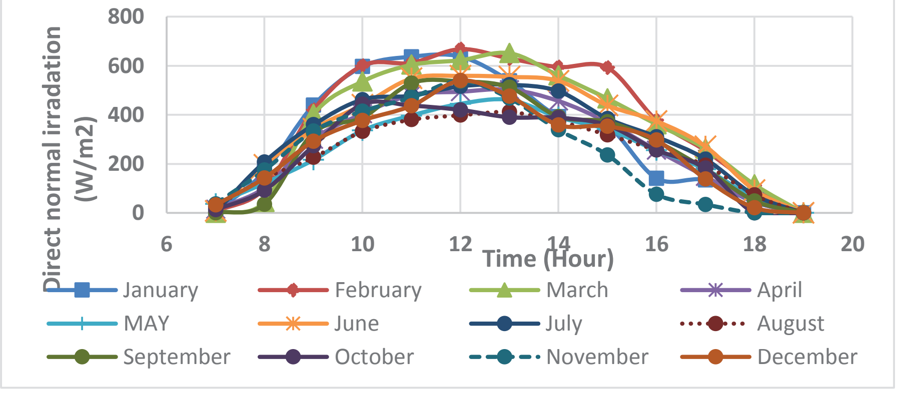

Fig. 2. Monthly average hourly direct normal irradiance in Universiti Teknologi PETRONAS during the year.

It was observed that the hourly maximum direct normal beam insolation on the collector was recorded around 668 W/m^2 in the month of February at noon. However, there are more fluctuations occurring in the direct normal beam for all months because of cloud covers in Malaysia. Figure. 3 shows the variation of useful heat gain by the PTCs against the hourly time on a specific day of every month. It is evidently shown in the figure that the highest useful hourly heat transferred by PTCs considerably fluctuates during the year.

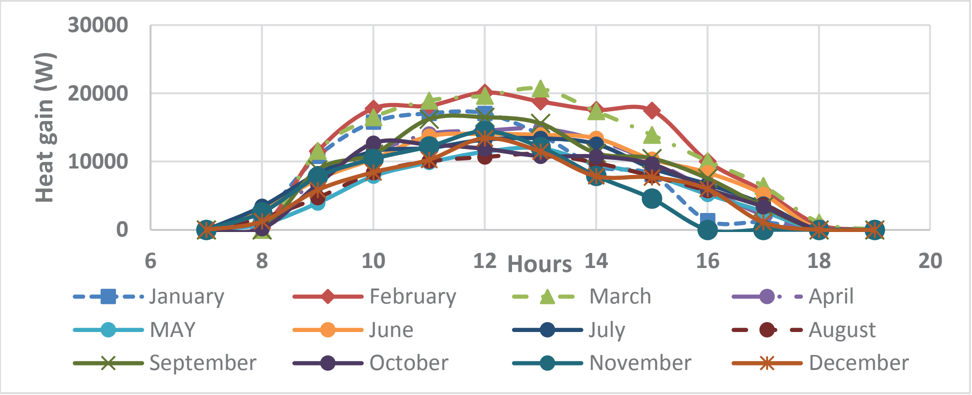

Fig. 3. Hourly collectors useful heat gain during the year.

It can touch maximum 20701.7 W at 13:00 pm in the month of March due to high direct normal irradiance (DNI) approximately 650 W/m^2 and approximately 11137.2 W (minimum) in the month of August on plane. This is a considerable fluctuation in useful heat gain occurs due to cloudy weather and rainfall (mainly between August and November) as a contrast to the driest season (generally between December to April), where insolation is attained by PTCs in Ipoh. As a result, higher values of useful heat gain were obtained throughout the low rainfall season as compared to various high rainfall seasons and it has high values on the plane according to the earlier expectation of system.

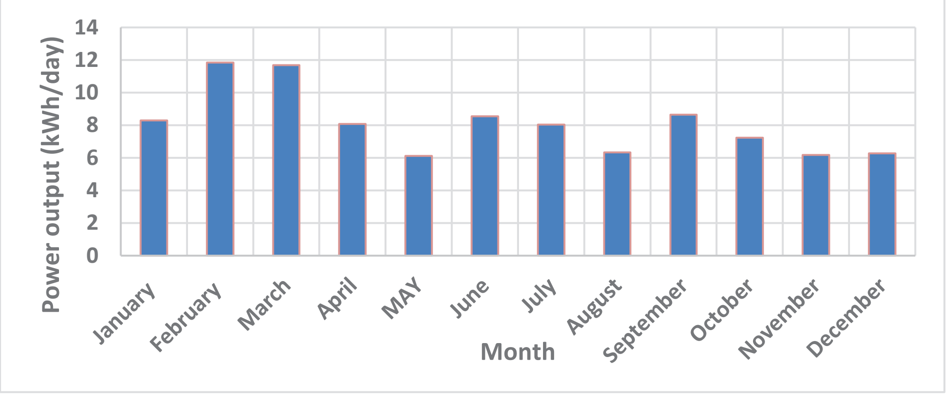

Fig 4. The daily power output for the Universiti Teknologi PETRONAS location in the year.

An analysis of the daily power output, DNI and the efficiency for the Universiti Teknologi PETRONAS location was carried out. Figure. 4 shows the annual gross electrical power output at various chosen days of every month during the year. It was clearly observed that the gross output of the plant was maximum at higher solar radiation. Furthermore, it was observed from results that the maximum net power is 11.84 kWh/day in February. The lowest of electrical power output is 6.11 kWh/day in May.

The fluctuations of solar radiation affect the collected thermal energy directly as well as the efficiency. Figure 5 shows the average efficiency of parabolic trough power plant. It was observed the average efficiency is 8.85 %, during low rain season in March. The lowest of efficiency of 6.23% was obtained in high rain season in November.

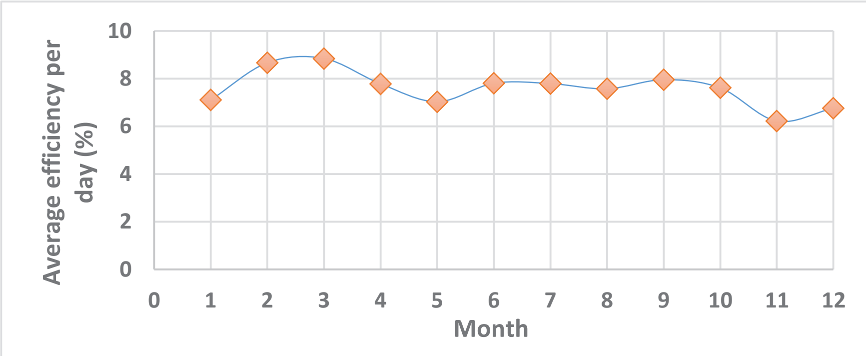

Fig. 5. The daily efficiency for the Universiti Teknologi PETRONAS location in the year.

4 Conclusion

This article presents a parabolic based thermal collector solar thermal power plant simulated mathematically for conceptual design calculations. The model was converted into a computer program within MATLAB environment to predict the required hydrothermal parameters of the system. The control ideology of plant consists the joint effect of the solar field under ambient conditions as well as mentioned solar radiation to account for the constant generation of power from turbine-generator unit in the hours of sunshine. As can be seen from the plotted results, the maximum useful heat gain 20701W was attained on a plane in March. The maximum net power is 11.84 kWh/day in February. These outcomes can be utilized to plan the operation and create a proper control strategy of power plant.

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