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A Simulated Design and Analysis of a Solar Thermal Parabolic Trough Concentrator

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***Abstract*—**In recent years Malaysia has included renewable energy as an alternative fuel to help in diversifying the country's energy reliance on oil, natural gas, coal and hydropower with biomass and solar energy gaining priority. The scope of this paper is to look at the designing procedures and analysis of a solar thermal parabolic trough concentrator by simulation utilizing meteorological data in several parts of Malaysia. Parameters which include the aperture area, the diameter of the receiver and the working fluid may be varied to optimize the design. Aperture area is determined by considering the width and the length of the concentrator whereas the geometric concentration ratio (CR) is obtained by considering the width and diameter of the receiver. Three types of working fluid are investigated. Theoretically, concentration ratios can be very high in the range of 10 to 40 000 depending on the optical elements used and continuous tracking of the sun. However, a thorough analysis is essential as discussed in this paper where optical precision and thermal analysis must be carried out to evaluate the performance of the parabolic trough concentrator as the theoretical CR is not the only factor that should be considered.

***Keywords*—**Parabolic trough concentrator, Concentration ratio, Intercept factor, Efficiency.

I. Introduction

THE improper use of fossil fuels has led to negative imbalance in the natural environment. One cannot deny that the exploitation of fossil fuels has brought about a better future for mankind but if the environment is destroyed in the process, then appropriate ways and new resources must be introduced to balance the situation. Energy is the key ingredient to any economic activity. Adequacy of energy supply is important for the acceleration of economic development. In 1981, Malaysia formulated the fuel diversification policy to reduce the country's overdependence on oil as the major energy source. The policy focuses on four main energy sources; oil, gas, coal and hydro for a reliable and secure supply of energy to the country [1]. Recently, efforts were undertaken by the government to encourage the utilization of renewable resources, such as biomass, biogas, solar and mini-hydro for energy generation [2]. Like oil and gas, renewable energy sources are also abundant in Malaysia, the most important ones being biomass and solar [3],[4]. In view of this, further research and utilization of non-renewable energy technologies towards supplementing the conventional sources of energy should be actively exploited as it would be a waste not to fully utilise the solar energy that we are blessed with.

There are many concentrative solar energy collection technologies that have evolved and developed. They are the dish concentrator, conical concentrators, the V-trough concentrator, the parabolic trough concentrator and others. Advantages of concentrative collection include its higher temperature and performance efficiencies, its low cost design due to the utilization of available components like mirrors and engines, its kind effect to the environmental, its flexibility to integrate with fossil technologies in hybrid systems, and its reliability as a secure and inexhaustible source of energy. The ANU (Australian National University) solar concentrator dish of 400 m^2 completed in 1994 which is currently producing superheated steam at 500˚C at 4.5 MPa is considered as the world's largest dish [5]. The Solar One and Solar Two projects which adopted the dish concentrator technology known as the SunCatcher have been installed and in operation successfully in San Bernardino County and Imperial County, both in the southern part of California with capacity of 500 MW and 300 MW respectively [6]. Other studies on radiation performance including the optical properties of the dish solar concentrator receiver system and its use as a calorimeter, cooker and generating electricity has been successful [7],[8],[9]. Theoretical and experimental work on conical concentrators has also been studied to predict its concentration ratio and power by assessing its characteristics and geometrical parameters [10],[11],[12]. Applications using a conical concentrator as a solar air heater to look at the effect of selective absorbing surface and packing in a two-pass airflow passage have been investigated [13]. As for the V-trough concentrator which consists of an array of east-west oriented trapezoidal channels with two side reflecting walls and a tubular absorber as a receiver at the base, an analytical study has been carried out to derive the concentration factor and the reflector surface area [14].

Parabolic trough concentrating system (PTCS) is a well known and proven renewable energy technology, which converts solar radiation that strikes earth daily to useful thermal energy [15]. A collection of nine solar-thermal electric generating system (SEGS) plants that were built using a parabolic trough approach at Kramer Junction in California have been operating reliably since 1985 with an impressive

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capacity of 354 MW of power and another parabolic trough plant of capacity 64 MW near Boulder City, Nevada are some successes of this technology [16],[17]. However, there are drawbacks as installations of SEGS need to be large in scale, land use is extensive and the system consumes significant amounts of water or other heat transfer fluid. A study of a PTCS using water as the working fluid to generate steam has great potential in wide spread use for rural applications, such as water heating, steam cooking and sterilization with a reasonably high efficiency of 50% [18]. In another study on PTCS with lower concentration ratios of value 2 or 3, has been found to supply thermal energy for industrial processes, at temperatures below or around 90°C [19] and found suitable for obtaining high air temperatures in tropical climates where the proportion of diffuse solar radiation is high [20]. Other works on hydrogen production [21], absorption refrigeration [22], cooling for photovoltaic cells [23] and electricity generation [24] can be feasible in practical applications.

The scope of this paper is to look at the designing procedures of a solar thermal cylindrical parabolic trough concentrator (CPTC). A device known as a concentrator increases the heat flux rather significantly at the absorber of a solar collector. It is possible to achieve a temperature around 100 °C with a flat plate collector, but for power generation or industrial purposes, concentrators play a vital role. In a CPTC, the concentrator describes the optical reflecting subsystem, while the receiver describes the absorbing system which is normally a small absorbing area. Usually for comparison purposes, a concentration ratio (CR) is introduced. It is a factor by which radiation flux on the energy-absorbing surface is increased. Increasing the ratio means increasing the temperature at which energy can be delivered and also increasing the requirements for optical quality precision and its positioning. Concentration ratios can be theoretically very high with the imaging concentrators of precise optical elements and continuous tracking, in the range of 10 to 40 000.

II. Theory

CPTCs can be used to harness solar energy at moderate temperatures. The level of concentration is restricted by the aperture and the receiver tube (d_R is the diameter of the receiver and w is the width of the concentrator) areas known as the geometrical concentration ratio as given in (1) [25]. The ideal CR gives the highest theoretical concentration. Equation (2) is the optical concentration ratio which relates to the acceptance half-angle of the receiver, θ_C and the rim angle of the concentrator, ϕ_R and considered to be more precise than the geometrical CR [26]. The best value is based on the sun's subtending angle of 0.54° which gives the highest CR value of 212. However, the whole design process cannot be based just on this value. For instance, if a CR of 212 is to be achieved, then the diameter of the circular receiver must be around 9.4 mm for a concentrator's width of one metre. Unfortunately, there are other implications of having a receiver with a very small diameter. A whole system analysis is hence necessary, where the optical precision and appropriate thermal analysis must be carried out to evaluate the performance of a CPTC, instead of relying solely on the theoretical generated CR.

$$CR_G = \frac{w - d_R}{\pi d_R} \tag{1}$$

$$CR_O = \frac{\sin\phi_R}{\pi \sin\theta_C} \tag{2}$$

Since the sun is very far away, the radiation ray that reaches a concentrator is parallel to its axis. The parabolic curve would focus all the rays to a focal point, and in three dimensions it becomes a focal line. The receiver is placed concentrically along this focal line as its axis. The parabolic equation (3) shows the x and y displacements of the CPTC with its width, w and depth, d and used to obtain the right curvature of the parabolic trough. Equation (4) is used to calculate the focus point.

$$y = \frac{d}{(0.5w)^2} x^2 \tag{3}$$

$$f = \frac{w^2}{16d} \tag{4}$$

The rim angle of a CPTC is calculated by using (5) with inputs for the focal point, width and depth.

$$\cos\phi_R = \frac{2f}{\sqrt{(0.5w)^2 + (d-f)^2}} - 1 \tag{5}$$

A rim angle of 90° is preferred as it gives an optimum intercept factor and allows the depth to be the focal point. The focal point, where the rim angle is set at 90° can be calculated by using the width value alone, as shown in (6).

$$f = \frac{w}{4} \tag{6}$$

Fig. 1 shows the parabolic curve and the location of the receiver for a width of 20 m, with a focal length that is equal to the depth. The receiver is concentrically placed along the focal line, which is parallel to the trough. The reflecting surface on the parabolic surface should have a good specular reflectance ρ (electroplated silver has a ρ of 0.96).

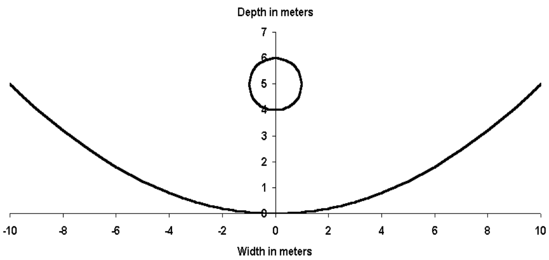

Fig. 1 A parabolic concentrator with good optical reflecting system and absorbing receiver system located concentrically at the focal point

III. Methodology

The simulation procedures were carefully developed and the methodology for the process design is as shown in Fig. 2. After the initial design parameters are finalized, the parabolic equation, focal point and rim angle is obtained. By using a preset value for the CR, the diameter d_R of the receiver is calculated using (1). Next, the full design specifications are processed to define the model. The parameters are the overall heat loss coefficient U_L, convective heat transfer coefficient and heat removal factor. The processed solar insolation data consists of the beam radiation I_b and diffuse radiation I_d. R_b and R_d are the ratio of the total radiation on a tilted surface to that on the horizontal surface for beam and diffuse radiations respectively. Using these values, the absorbed solar radiation S is calculated and used in the energy equation [27]. The energy balance equation will then calculate the rate of energy gained in watts, Q_U whereas the absorbed solar radiation is usually in the units of MJ/m^2. Hence, the necessary conversions are necessary in order to obtain the correct value for Q_U, as this value is then used to calculate the efficiency of the CPTC. The efficiency also takes into consideration the diffuse radiation, while in the evaluation of S, as seen from (7), only the beam component of the radiation is used;

$$S = I_b R_b (\tau\alpha)_b \left(\rho\gamma + \frac{d_R}{w - d_R} \right) \tag{7}$$

where γ is the intercept factor and $(\tau\alpha)_b$ is the transmittance-absorptance product for the beam radiation. An optimization problem arises when the area of the aperture is increased due to the increasing thermal losses and as the area is decreased, optical losses increase. The intercept factor accounts for this problem and is defined as the fraction of the specularly reflected radiation which is intercepted by the receiver. Tracking and dispersion errors usually affects the value of γ. Equation (8) is used to evaluate the transmittance-absorptance product, where τ is the transmittance of the receiver's cover and α is the absorptance of the receiver's absorber. The parameter ρ_d is the reflectance of the cover for diffuse radiation.

$$(\tau\alpha)_b = \frac{\tau\alpha}{1 - (1-\alpha)\rho_d} \tag{8}$$

The value for the intercept factor γ is evaluated using (9) with h obtained based on the maximum radiation. Equation (10) gives the equation that can be used to evaluate h and σ is the standard deviation of the normally distributed radiation that is intercepted by the receiver [28].

$$\gamma = 1 - e^{-h^2\left(\frac{r_D}{w}\right)} \tag{9}$$

$$h = \frac{0.5w}{\sqrt{2}\sigma} \tag{10}$$

The software is written using MATLAB and is designed so that it is really easy to use. A snapshot of the design menu is shown in Fig. 3.

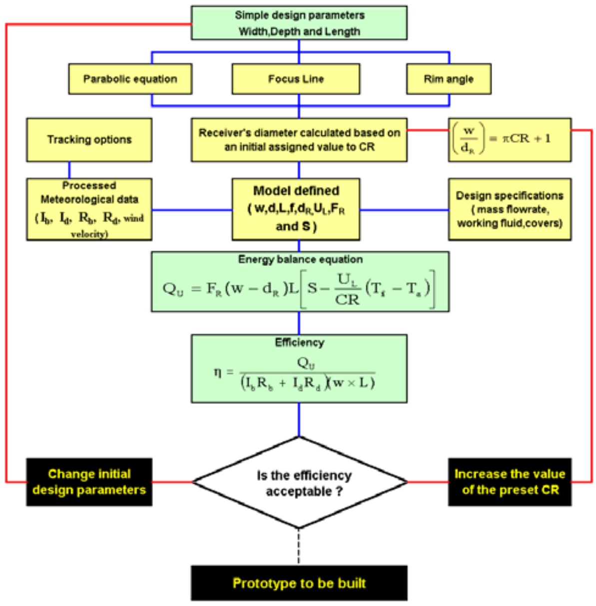

Fig. 2 A flowchart outlining the design process

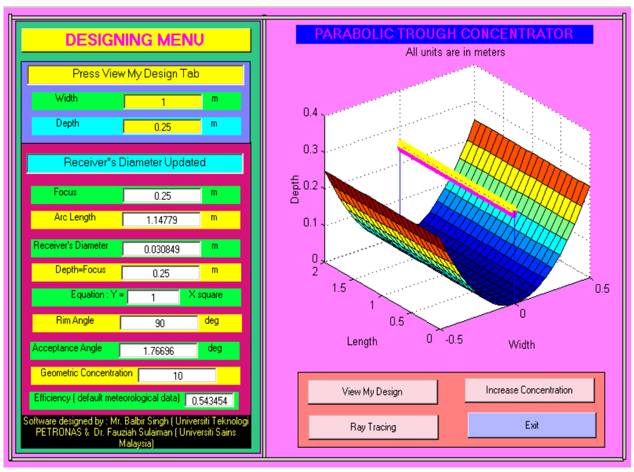

Fig. 3 A snapshot of the design menu and a 3-D model generated by the simulation program in the MATLAB environment

IV. Results

Results were obtained in the process of refining the model, by repeating the steps shown in Fig. 2. In Fig. 4, the concentration ratio was increased till it reached its maximum theoretical value of 212. The simulation was repeated for three different types of working fluid in the receiver, and it shows that the model's efficiency increased until the CR reached the value 10. After that, for all the three types of working fluids, the efficiency decreased by at least 53%, for the CR of above 10 to 212. It is expected that by increasing the CR, the efficiency of the collector too must increase. However, as predicted earlier, designing the CPTC by relying solely on the CR is insufficient.

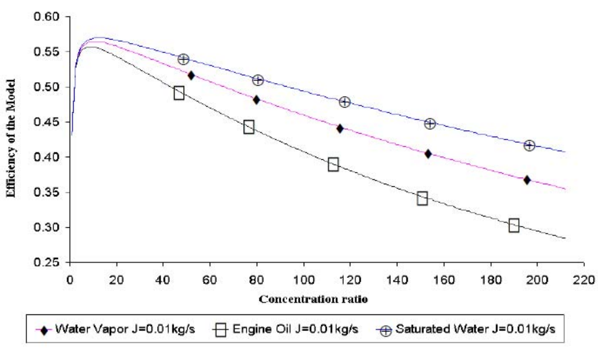

Fig. 4 Graph of the model's efficiency versus the concentration ratio for three different working fluids

It can be seen in Fig. 5 that there is a correlation between the decreasing efficiency and decreasing heat removal factor, as the CR increases. This means that the evaluation of the heat removal factor is very important, as it has a big influence on the efficiency factor. The following equation (11) shows the evaluation of the heat removal factor, F_R where in (12), F' is the collector's efficiency factor.

$$F_R = \frac{JC_{factor}}{\pi d_R L U_L}\left[1 - e^{-\left(\frac{F' \pi d_R U_L L}{JC_{factor}}\right)}\right] \tag{11}$$

$$F' = \left[U_L\left(\frac{1}{U_L} + \frac{d_R}{d_{Ri}} + \frac{d_R \ln\left(\frac{d_R}{d_{Ri}}\right)}{2k}\right)\right]^{-1} \tag{12}$$

The parameter J refers to the mass flowrate of the working fluid in the receiver's tube, while d_{Ri} is the inner diameter of the receiver's tube. The C_{factor} is the specific heat capacity of the working fluid evaluated at the inlet fluid. The method to determine C_{factor} can be found by using other heat factors such as the H_{factor} [29] and R_{factor} [30].

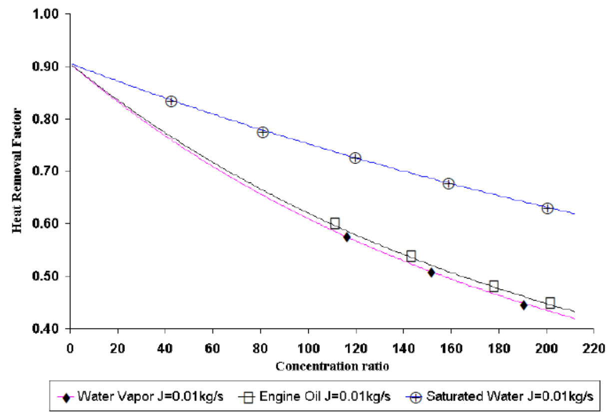

Fig. 5 Graph of heat removal factor versus the concentration ratio for three different working fluids

Even though the efficiency is decreasing with the increasing CR, the rate of energy gained Q_U increases. Referring to (1), if d_R is fixed at a certain value, the width of the model must be increased in order for the CR to increase. If d_R is held at a value of 0.03 m, then to achieve a CR of 212, the width is around 20 meters. If the length of the model is set at twice the width, then the aperture area would be around 800 m^2. As predicted, the heat gained increases. However, the denominator of the efficiency equation increases faster than Q_U as shown in Fig. 6, showing the widening gap as the CR increases. This shows clearly that at high concentration ratios, efficiency of the CPTC drops rather significantly.

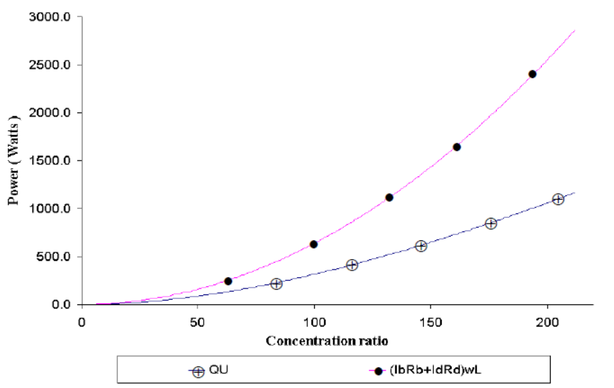

Fig. 6 Graph of rate of energy gained as the concentration ratio increases

Fig. 7 shows the intercept factor γ at a maximum value of unity for the receiver's diameter of 0.03 m and above, which is therefore fixed at that value for the model design. In order to reduce the aperture area by reducing the d_R and to obtain higher CR would cause the intercept factor γ to decrease. If that happens, the amount of the absorbed solar insolation would decrease, causing Q_U to be reduced even further which is undesirable.

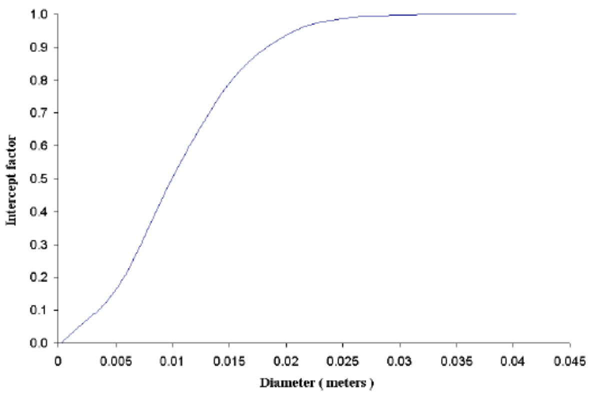

Fig. 7 Graph of intercept factor versus the diameter of the receiver

V. Conclusion

This paper has highlighted the processes that are necessary to evaluate the performance of a CPTC and to use the processed data to design a model by simulation using real meteorological data of locations in Malaysia. By considering the optical factors and thermal analysis, the results clearly showed that there must be an equilibrium achieved between the increasing thermal losses due to the increasing aperture area, with the increasing optical losses due to the decreasing aperture area. The study found that a concentration ratio of 10 and the receiver's diameter of 0.03 m are the optimum parameters for the highest efficiency of the model.

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