DESIGNING A SOLAR THERMAL CYLINDRICAL PARABOLIC TROUGH CONCENTRATOR BY SIMULATION

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ABSTRACT

The focus on renewable energy in Malaysia gained momentum with the active involvement of the government and the private sector. This move can potentially help in diversifying the country's energy options besides relying on oil, natural gas, coal and hydropower. The scope of this paper is to look at the designing procedures of a solar thermal cylindrical parabolic trough concentrator (CPTC) by simulation. The designing effort starts off with the selection of certain parameters such as the aperture area and the diameter of the receiver to obtain the geometric concentration. 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. A thorough analysis is necessary, where the optical precision and proper thermal analysis must be carried out to evaluate the performance of a CPTC. The results will clearly show that there must be an equilibrium achieved between the increasing thermal losses with the increasing aperture area, and the increasing optical losses with the decreasing aperture area for the optimization of the long-term performance of the CPTC.

INTRODUCTION

Improper use of fossil fuels has led to negative imbalance in the natural environment. The impact on the environment is fast surpassing the positive development brought about by the discovery of fossil fuels. 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 proper ways and new resources must be introduced to strike a balance. Malaysia is keen on promoting the use of renewable energy which can help in diversifying the country's energy options besides relying on oil, natural gas, coal and hydropower. The National Energy Policy, introduced in 1979 aims to have an efficient, secure and environmentally sustainable supply of energy, which is moving parallel with the global efforts. The development plans for using both non-renewable and renewable energy resources were taken to be the main aim and the utilization objective outlined the need to use energy efficiently (Yap, 2002). The journey to embark on non-renewable energy technologies should be geared towards supplementing the conventional sources of energy. Since solar energy is readily available in Malaysia, it would be beneficial to fully exploit it.

The scope of this paper is to look at the design procedures of a solar thermal CPTC. 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. Usually for comparison purposes, concentration ratio (CR) is introduced. Increasing ratios means increasing temperatures at which energy can be delivered and also increasing requirements for precision in optical quality and positioning of optical systems. 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.

THEORY

A solar thermal CPTC can be used to harness solar energy at rather high temperatures depending on the working fluid used. The level of concentration is restricted by the design parameters and is given as Eq.(1). Eq.(2) relates the CR to the acceptance half-angle and the best value is based on the sun's subtend angle of 0.54° with the highest CR at 212. Although the values look promising, the whole design process cannot be based only on these values.

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

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

There is a distinguish reason on the selection of a parabolic concentrator. Since the sun is very far away, the radiation rays that reach a concentrator is parallel to its axis. The parabolic curve would focus all the rays to a focal point, and a trough normally extends the shape in three dimensions to turn the focal point into a focal line. The receiver is placed concentrically along this focal line, as its axis. Eq.(3) shows the important relationship between the width and depth, and Eq.(4) is used to calculate the focal point as shown below;

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

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

The following Eq.(5) is used to calculate the rim angle, based on 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 Eq.(6).

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

The reflecting surface on the parabolic surface should have a very good specular reflectance, ρ where electroplated silver records a value of 0.96. Thermal analyses on the overall heat loss coefficient, convective heat transfer coefficient, collector efficiency factor and heat removal factor are performed. Finally, by the aid of meteorological data, the efficiency of the collector is determined.

METHODOLOGY

The simulation procedures were carefully developed with the design specifications that can be changed and simulated using the same meteorological data (Singh & Sulaiman, 2000). The final model, together with the design specifications can then be constructed mathematically. Using a preset value for the CR, the diameter d_R of the receiver is calculated by using Eq.(1). The full design specifications are next 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 total radiation on a tilted surface to the horizontal surface for beam and diffuse radiations respectively. Using these values, the absorbed solar radiation S parameter is calculated and used in the energy equation. It is important in order to obtain the correct value for Q_U, the heat gained as it is later used to calculate the efficiency. The efficiency also takes into consideration the diffuse radiation, while in the evaluation of S, as seen from Eq.(7), only the beam component of the radiation is used.

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

Another efficiency ratio that can be used which totally ignores the diffuse radiation is given in Eq.(8) below;

$$\eta = \frac{Q_U}{(I_b R_b)(W \times L)} \qquad (8)$$

In Eq.(7), γ is the intercept factor and $(\tau\alpha)_b$ is the transmittance-absorptance product for the beam radiation. An optimisation 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. The equations used to evaluate these two parameters are given in Eq.(9) and Eq.(10). In Eq.(9), τ is the transmittance of the receiver's cover and α is the absorptance of the receiver's absorber. ρ_d is the reflectance of the cover for diffuse radiation.

$$(\tau\alpha)_b = \frac{\tau\alpha}{1 - (1 - \alpha)\rho_d} \qquad (9)$$

Eq.(10) provides the value for the intercept factor γ and h obtained is based on the maximum radiation. Eq.(11) can be used to evaluate h with σ being the standard deviation of the normally distributed radiation that is intercepted by the receiver (Magal, 1990).

$$\gamma = 1 - e^{-h^2 \left(\frac{r_D}{w} \right)} \qquad (10)$$

$$h = \frac{0.5w}{\sqrt{2}\sigma} \qquad (11)$$

The software was written by using MATLAB was designed in such a way that it is user-friendly. A snapshot of the design menu is shown in Fig. 1. The following two equations show the design parameters that are used to evaluate the heat removal factor, where in equation (13), the symbol F' is the collector's efficiency factor.

$$F_R = \frac{JC_{factor}}{\pi d_R L U_L}\left[1 - e^{-\left(\frac{F' \pi d_R U_L L}{JC_{factor}}\right)}\right] \qquad (12)$$

$$F' = \left[U_L\left(\frac{1}{U_L} + \frac{d_R}{d_{Ri}} + \frac{d_R \ln\left(\frac{d_R}{d_{Ri}}\right)}{2k}\right)\right]^{-1} \qquad (13)$$

The parameter J refers to the mass flowrate of the working fluid flowing in the receiver's tube, while d_{Ri} is the inner diameter of the receiver's tube. The C_{factor} is specific heat capacity of the working fluid evaluated at the inlet fluid temperature and is found by the authors. The method to find C_{factor} can be found by evaluating heat factors such as the H_{factor} (Singh & Sulaiman, 2001) and R_{factor} (Singh & Sulaiman, 2002).

RESULTS

The results obtained in the process of refining the model by repeating the steps had provided some interesting findings. In Fig. 2, the concentration ratio was increased until it reached its maximum theoretical value of 212 for three different types of working fluid. The model's efficiency increased until the concentration ratio reached 10 for all three working fluids flowing in the receiver and then gradually decreased by at least 53 percent. The expectation is that by increasing the concentration ratio, the efficiency of the collector too will increase. However, this proves that designing the CPTC by relying solely on the CR is not sufficient.

By observing the results shown in Fig. 3, it can be seen 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 great influence on the efficiency of the CPTC.

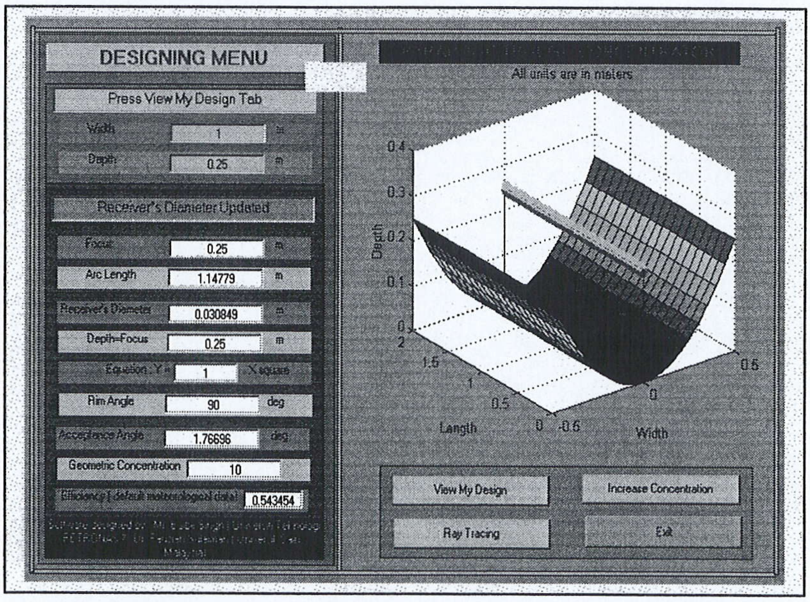

Fig. 1. A snapshot of the software written in the MATLAB environment.

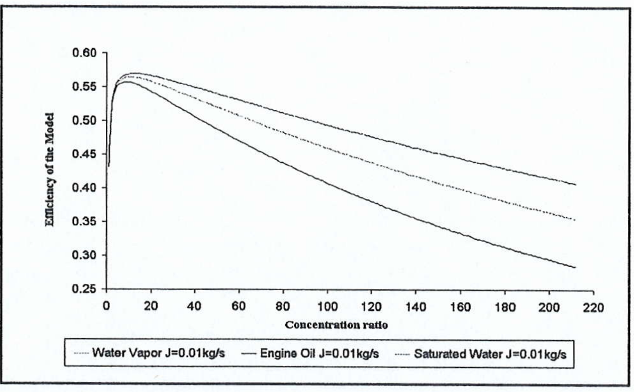

Fig. 2. Graph of CPTC's model efficiency versus the concentration ratio for three different working fluids.

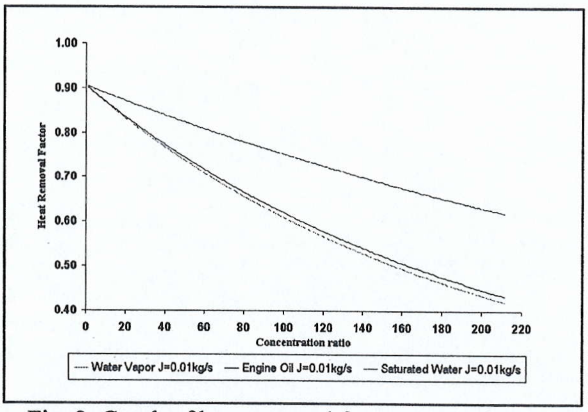

Fig. 3 Graph of heat removal factor versus the concentration ratio for three different working fluids.

Even though the efficiency is decreasing with the increasing CR, the rate of energy gained Q_U actually increases. Looking at Eq.(1), if d_R is fixed at a certain value, the width w must be increased in order for the CR to increase. If d_R is held at a value of 0.03m, then to achieve a CR of 212, the width must definitely be around 20 meters and the length if it is set to be twice of the width, would be around 40 meters. This makes the aperture area to be around 800 m^2. Obviously, the heat gained must increase, but unfortunately, the denominator of the efficiency equation increases more than Q_U. This is shown in Fig. 4, where the gap widens as the CR increases.

The diameter was held at 0.03 m so that the intercept factor γ has a maximum value of unity as seen in Fig. 5. Therefore, in order to reduce the aperture area by reducing the d_R for higher CR would cause the intercept factor γ to decrease. If this happens, the amount of the absorbed solar insolation would decrease, causing Q_U to be reduced further.

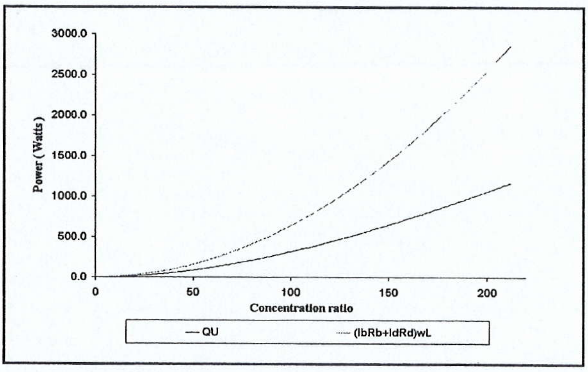

Fig. 4. Graph of rate of energy gained versus the concentration ratio for efficiency.

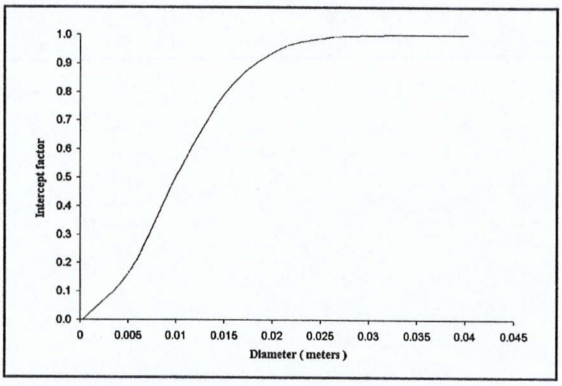

Fig. 5. Graph of intercept factor versus the diameter of the receiver

CONCLUSION

This paper has highlighted the processes that are necessary to evaluate the performance of a solar thermal CPTC and to use the processed data to design a simulated model by using the same meteorological data. The results indicated that there must be an equilibrium achieved between the increasing thermal losses with the increasing aperture area, and the increasing optical losses with the decreasing aperture area. Hence, it would be important to optimise the long-term performance of the CPTC.

The utilization of renewable energy in Malaysia should be increased, as there is a global concern that the upcoming and developing nations could be faced with yet another energy crisis. As recently reported, major oil-producing countries such as the United States and OPEC have managed to block the United Nations target to hasten a global shift towards renewable energy sources (Ball, 2002). With the opposition of the Kyoto treaty on global warming, it is expected that more damage and pollution of the environment will continue. As fossil fuels begin to exhaust, the prices of these commodities will be increasing by many folds. Fortunately, Malaysia is working positively towards using renewable energy as seen by its approval of four renewable energy producers' licenses by the Malaysian Energy Commission recently (Yeap, 2002).

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