PREDICTION METHODOLOGY FOR TRANSIENT THERMAL RESPONSE OF SOLAR PARABOLIC TROUGH COLLECTOR UNDER FLUCTUATING SOLAR RADIATION

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ABSTRACT

Solar parabolic trough collector technology is an effective way to utilize solar thermal energy, which reduces the carbon dioxide emission. Although the weather in Malaysia and other Southeast Asian countries is suited to solar thermal applications for the long daytime that continues all year around. Still, the fluctuation in solar radiation caused by the high humidity must be handled when estimating the thermal performance of the parabolic trough collector application. To perform transient thermal simulation to incorporate the effect from the solar radiation fluctuation, long calculation time and large memory space are required when the existing numerical methods are used. A simple but powerful methodology to predict the time dependent parabolic trough collector tube exit temperature is proposed. In this methodology, the exit working fluid temperature is estimated by superimposing the temperature rise caused by each heat flux pulse that forms the solar radiation. The preliminary results and methodology improvement for more realistic prediction conditions are discussed.

***Keywords*—** Finite element method, solar collector, solar radiation fluctuation, solar parabolic trough technology, transient thermal response

1. INTRODUCTION

Carbon dioxide (CO_2) is the main contributor to the global climate change. 90% of CO_2 emission is resulted from the fossil fuel combustion for power generation and transport sector. Statistics presented by the World Health Organization (WHO) show that direct and indirect effects of climate change lead to the death of 160,000 people per year and the rate is expected to be two times higher by 2020 [1, 2]. Renewable energy is a promising alternative to fossil fuel-based energy, it can reduce the carbon dioxide emission, which leads to the climate change [3]. Solar parabolic trough power plants are one of the most mature and prominent applications of concentrated solar power technology for electricity generation [4]. Solar thermal energy concentrated by the parabolic trough collector is absorbed by thermal fuid inside the collector tube. The collected thermal energy is used to make steam to rotate a turbine for power generation [5, 6].

The parabolic trough collector tube is the key component in solar parabolic trough power generation system [6]. Engineering Equation Solver software was utilized to analyze the thermal performance of parabolic trough collector [7, 8]. Cheng et al. [9] proved that solar radiation models that are both non-uniform and uniform along the collector tube circumference can be used to simulate the whole parabolic trough collector system. Monte Carlo Ray Trace and Finite Volume Method were coupled to analyze the thermal energy transfer process in parabolic trough solar collector under non-uniform heat flux distribution [10]. Lu et al. [11] developed non-uniform model to analyze heat transfer performance of a parabolic trough collector. Wang et al. [12] combined solar ray trace method and finite element method (FEM) to analyze parabolic trough collector thermal performance. All of these previous work handled steady state thermal conditions.

Malaysia is a country with hot and humid weather. The ambient temperature varies from 22 °C to 33 °C [13]. Malaysia is especially suited to solar thermal applications for its longer day time, which continues all year around. The monthly average of daily total solar radiation is shown in Fig. 1. However, measured solar radiation data shows that the solar radiation in Malaysia fluctuates so much that it is rare to see the radiation stays at the same value for more than 10 minutes. The solar radiation in a typical day is displayed in Fig. 2. Since the performances of the solar thermal applications are directly related to yearly solar radiation, the performances must be evaluated based on the yearly solar radiation data. With fluctuating solar radiation, the numerical simulation must incorporate the effect of time response of the solar collector tube. Despite the fact that transient thermal analysis for solar collectors is critical especially in the area where the solar radiation changes frequently, previous work for transient thermal analysis is limited. Zaversky [14] performed transient thermal analysis for parabolic trough receiver, based on one-dimensional fluid flow modeling approach which is according to the Finitie Volume Method. In order to evaluate the thermal performance, further research on the parabolic trough collector tube response for fluctuating solar radiation is needed. Even though various numerical simulation methodologies are available for such transient thermal analysis, it would not be practical to simulate yearly thermal performance because of the long calculation time.

In this work, a methodology to predict the exit working fluid temperature of parabolic trough solar collector tubes with fluctuating solar radiation is developed. The collector tube exit temperature is predicted by superimposing the temperature rise caused by each heat flux pulse that forms the consecutive heat flux pulses in this methodology. Once the temperature rise caused by each heat flux pulse is obtained, the prediction that is governed by simple summation operation takes much less calculation time and less memory size comparing to the existing numerical methods. The validation result of a sample case and further improvement of this methodology are discussed in this paper.

The prediction method will be applied in solar co-generation system showns in Fig. 3. Co-generation means the production of electricity and heat simultaneous from same energy source [15]. In the proposed co-generation system, electricity and chilled water for air-conditioning are provided simultaneously. The solar parabolic trough technology is used to collect solar thermal energy and the low temperature heat released from the steam turbine will be used as the heat source for an adsorption refrigerator. A thermal storage stores the excess thermal energy for later use.

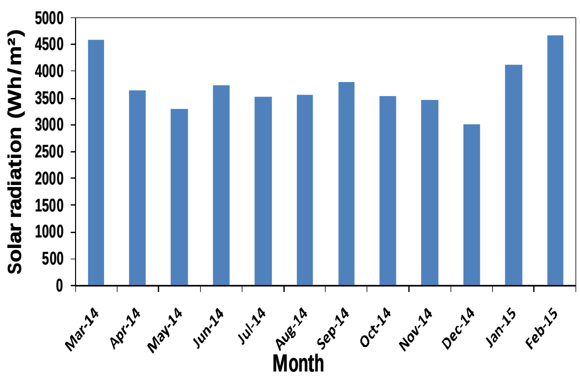

Figure 1. Monthly average of daily total solar radiation at the Malaysia, Kuala Lumpur

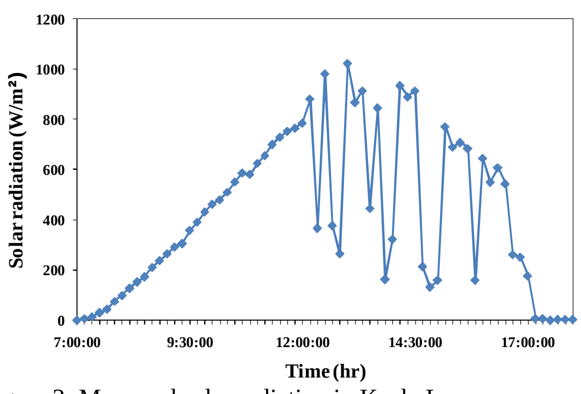

Figure 2. Measured solar radiation in Kuala Lumpur, Malaysia on a typical day

2. SOLAR COLLECTOR TUBE EXIT TEMPERATURE PREDICTION METHODOLOGY

The working fluid temperature rise at a collector tube exit caused by each heat flux pulse is obtained using FEM software. Then, the temperature rise caused by each heat flux pulse is superimposed to obtain the exit temperature caused by the consecutive heat flux pulses. Since the heat loss from the tube outside surface is minimal, the temperature rise caused by a single heat flux pulse is approximately proportional to the heat flux. As a result, the superimposed temperature rise agrees well with the transient FEM analysis result with the corresponding consecutive heat flux pulses.

If the specific heat of the fluid can be considered as a constant, and the heat stored within the tube material can be neglected, the mean temperature at the tube exit at time t, $T_{predicted,t}$, may be calculated as a summation of temperature rise caused by each heat flux pulse as in Eq. 1,

$$T_{predicted,t} = T_{in} + \sum_{i=1}^{n} \Delta T_{i,t} \quad (1)$$

where T_{in} is the inlet fluid temperature of the tube, $\Delta T_{i,t}$ is the exit working fluid temperature rise caused by the ith heat flux pulse at time t, and n is the total number of the heat flux pulses.

A thermal fluid (Therminol VP-1) is flowing inside a copper tube with a constant velocity as illustrated in Fig. 4. The space between the outside of this tube and a glass tube enclosing this copper tube is evacuated to work as an insulation layer [16]. The heat loss caused by convection heat transfer from the outside surface of the copper tube may be neglected because of the vacuum layer. Still, the radiation heat loss from the copper tube outer surface to the surrounding surfaces occurs. An axisymmetrical model for the copper tube and the working fluid inside the tube is created using commercially available FEM software package [17]. Transient conjugate heat transfer analysis is performed to calculate the tube exit temperature for a single heat flux pulse. To predict the tube exit temperature with fluctuating solar radiation, the working fluid temperature rise caused by each heat flux pulse is superimposed using Eq. 1.

A parabolic trough with focal length of 1.71m, aperture width of 5.77m, and concentration ratio of 82 is modeled. The length of the copper tube is 200 m, the inner and outer diameters are 0.065m and 0.07m respectively. The emissivity of the outer surface of the tube is 0.1. The disturbing solar radiation may be approximated as a collection of consecutive 60-second rectangular heat flux pulses. For a demonstration purpose, solar radiation pulses ranged from 10000 to 50000 W/m^2 [12] is created arbitrary (Fig. 5) to apply at the outer surface of the copper tube. Although the incoming solar radiation is not uniform along the circumference of the tube because of the concentrated radiation comes from the parabolic trough mirror, the heat flux is approximated as uniform in the axisymmetrical model. The working fluid inlet temperature of 298K, the

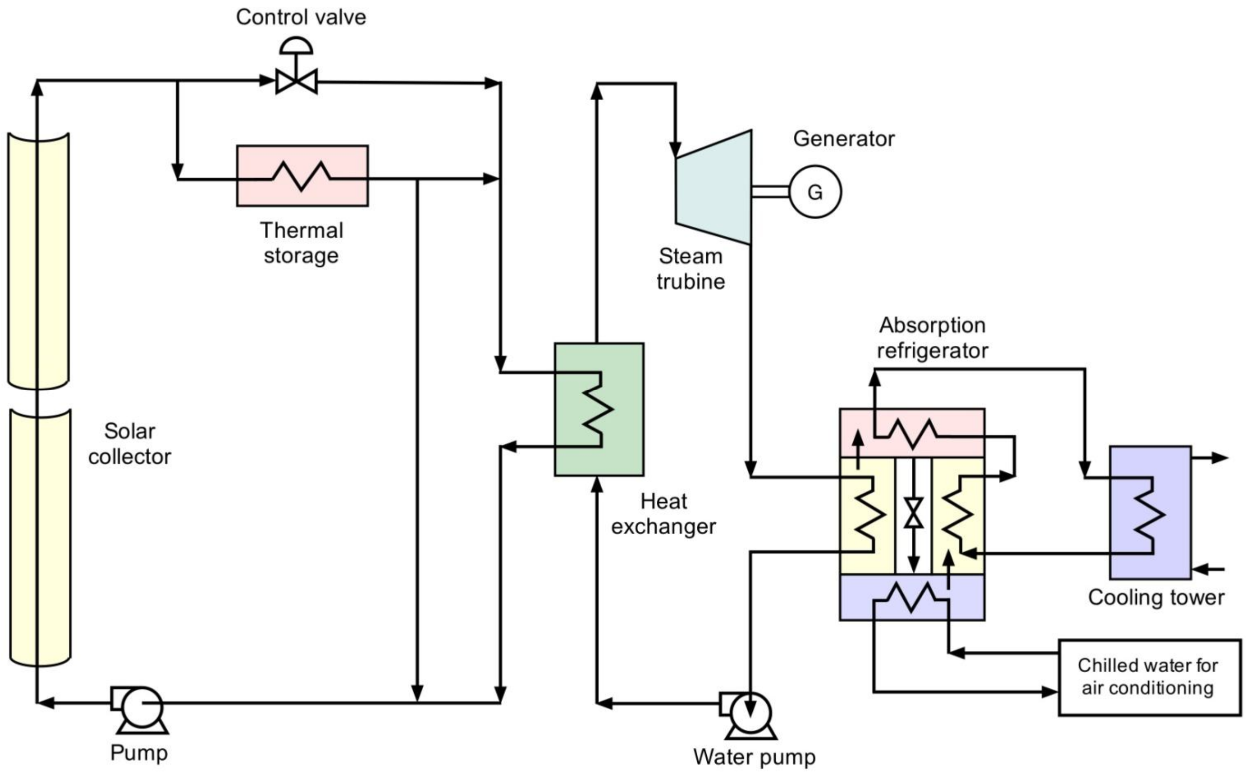

Figure 3. Schematic diagram of solar thermal co-generation system

surrounding temperature of 303K, and fluid velocity of 0.6m/s are assumed. The k-ε turbulence model is used for modelling the working fluid flow.

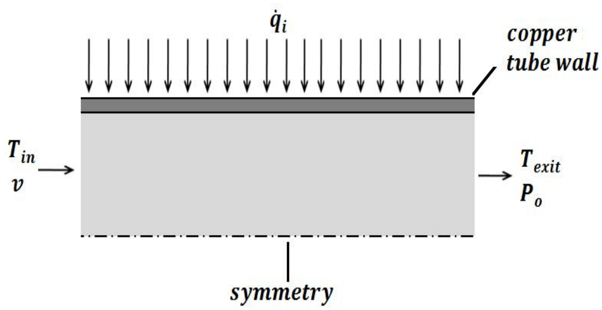

Figure 4. Axisymmetrical model of receiver tube (not to scale)

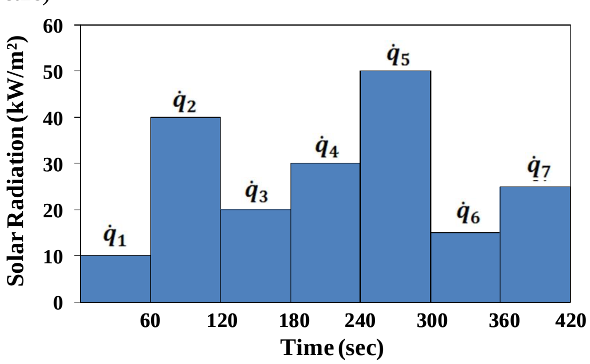

Figure 5. Fluctuating solar radiation heat flux pulses

3. RESULT AND DISCUSSIONS

In a preliminary analysis, it was discovered that it takes about 800 seconds to reach a steady state condition for a constant heat flux condition. The solar radiation fluctuates before the system reaches the thermal steady state condition. The predicted tube exit temperature based on the heat flux in Fig. 5 is shown in Fig. 6. The temperature rise cause by each heat flux and FEM result with the same conditions for validation are shown in the same figure for a comparison. The predicted result shows a good agreement with the FEM result. Still, the predicted temperature tends to be lower than the FEM result. The error is largest at the peak and the temperature difference is 21.2K compared to the FEM result. The FEM analysis for the temperature rise caused by each heat flux pulse starts from the uniform initial temperature. As a result, the tube wall temperature also starts from the uniform initial temperature. In the case of validation FEM analysis, the tube wall temperature is higher than T_{in} when the tube receives heat flux continuously. Extra heat that is used to increase the collector tube temperature is counted which causes the lower temperature in the prediction model. Currently, the proposed methodology is being improved by compensating the extra heat absorbed by the tube wall. Since the temperature rise caused by a single heat flux pulse is function of the magnitude of the heat flux, the temperature rise may be able to predict using an interpolation method such as an artificial neural network.

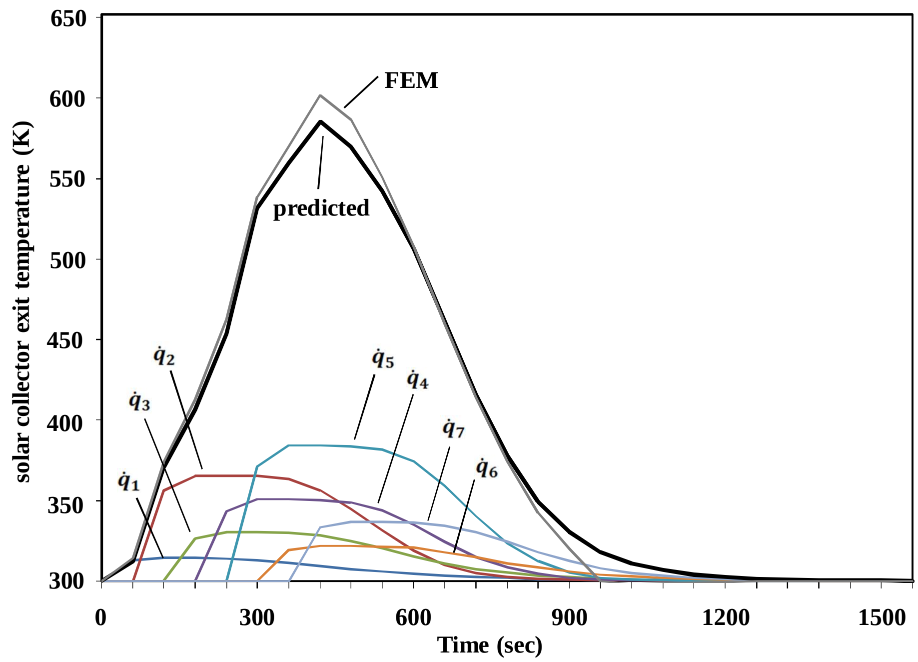

Figure 6. Predicted solar collector tube exit temperature change compared with FEM result, and exit temperature change caused by each heat flux pulse

In the proposed methodology, the exit fluid temperature is predicted by just making a summation of the temperature rise caused by each heat flux pulse once the temperature rise for each heat flux pulse is obtained. The reduction in computational resources both in calculation time and memory size is significant comparing to FEM or other numerical simulation methods. This advantage is especially useful when a parabolic trough solar collector output thermal energy is calculated using yearly solar radiation data.

4. CONCLUSION

Since the solar radiation in Malaysia fluctuates, transient thermal analysis is required to estimate the heat energy obtained by a parabolic trough solar collector. A methodology to predict the time dependent exit temperature of solar collector tubes is proposed. In this methodology, the temperature rise caused by each heat flux pulse is superimposed to predict the temperature rise caused by the consecutive heat flux pulses with different magnitude. The proposed methodology requires much less computational time and memory size compared to the existing numerical simulation methods. Currently, the capabilities of the methodology are being expanded.

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