A SIMULATION MODEL FOR PREDICTING THE TRANSIENT PERFORMANCE OF A HYBRID PV/T FORCED-CIRCULATION SOLAR WATER-HEATING SYSTEM

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ABSTRACT

A transient simulation model for a hybrid PV/T forced-circulation solar water-heating system is presented, along with algorithms for making quantitative predictions regarding the performance of the system. The model consists of a set of mathematical equations governing the main components in the system; namely, transparent cover, solar cell, absorber plate, operating fluid, storage tank, and controller. The model is developed based on the analysis of the balance of energy, which includes photoelectric conversion, thermal conduction, convection, and radiation. It predicts the dynamic variations of several system performance parameters such as electrical power output, amount of heat gained, and various types of efficiencies of the PV/T system. In this research, the developed model was used to investigate the effects of various physical and operational parameters on the system performance, i.e., water mass flow rate, size of water storage tank and overall thermal conductivity of adhesive used for binding solar cells to the absorber plate. These results are useful for designing the most effective PV/T system to meet the load requirement at any operating site location.

INTRODUCTION

A hybrid photovoltaic/thermal (PV/T) collector is basically constructed by pasting solar cells directly over the absorber plate of the solar collector in conventional forced circulation type solar water heater; thus, it can simultaneously produce the two types of energy: low temperature heat and electricity. Normally, the adhesive used for pasting solar cells is characterized by high thermal conductive and good electric insulating material. The solar energy is partly converted to electricity by solar cells in thermal contact with a solar heat absorber so that the excess heat generated in the solar cells can be served as input for the thermal system. During operation, a heat carrier fluid removes heat from the absorber and solar cells. Those cells, cooled by the heat carrier, operate at a low and stable temperature that gives increased solar cell electrical power output. The collected heat can be utilized in domestic hot water systems.
THE PV/T MODEL FORMULATION

Generally, a PV/T system consists of a PV/T collector, a storage tank, a circulating pump and a differential controller as shown in Fig. 1. A pump is used to circulate the water and controlled by a differential controller which has two temperature sensors; one measures the water temperature of the collector at the inlet and the other measures that at the outlet. The pump is switched on when the water temperature at the outlet is higher than that at the inlet. To simplify the model, it is assumed that the connecting pipes are well insulated so that there is no heat loss through them. Hence the inlet water temperature of the collector would be the same as the outlet water temperature of the storage tank and the inlet water temperature of the tank would be the same as the outlet water temperature of the collector.

![Figure 1. Basic Configuration of PV/T System](image1)

![Figure 2. Cross Section of PV/T Collector with Energy Transfer for Each Component](image2)

A schematic configuration along with associated energy conversion of each component in a PV/T collector is shown in Fig. 2. Thus, the energy balance equations for various components of the collector and those of PV/T system initially developed by Sukamongkol et al. [3] can be rewritten as follows:

For the glass cover, \( Q_{\text{store, }C} = Q_{\text{in, }C} - Q_{\text{rad, }C \rightarrow a} - Q_{\text{conv, }C \rightarrow a} + Q_{\text{rad, }S \rightarrow C} + Q_{\text{conv, }S \rightarrow C} \), (1)

for the solar cell, \( Q_{\text{store, }S} = Q_{\text{in, }S} - Q_{\text{rad, }S \rightarrow C} - Q_{\text{conv, }S \rightarrow C} - Q_{\text{cond, }S \rightarrow P} - Q_{\text{elec}} \), (2)

for the absorber plate, \( Q_{\text{store, }P} = Q_{\text{cond, }S \rightarrow P} - Q_{\text{cond, }P \rightarrow a} - Q_{\text{cond, }P \rightarrow F} \), (3)

for the fluid, \( Q_{\text{cond, }F \rightarrow F} = Q_{\text{cond, }F \rightarrow a} + Q_{\text{th}}, \) and (4)

for the storage tank, \( Q_{\text{store, }ST} = Q_{\text{th}} - Q_{\text{cond, }T \rightarrow a} \), (5)

The average daily PV/T collector efficiency can be determined by the integration of thermal and electrical energy obtained over the daytime period in comparison with total solar energy over the same period, which can be expressed as:

\[
\eta_{PV/T} = \eta_{th} + \eta_{elec} = \left[ \left( \int Q_{th} \, dt + \int Q_{elec} \, dt \right) / \int G \, dt \right].
\] (6)
BASIC CONFIGURATION OF THE SIMULATION MODEL

The simulation model is written using C-language computer programming. It can simulate the transient performance of the system at a time interval of one minute. Its inputs require total solar irradiance, ambient temperature and wind speed while its outputs contain the current and voltage generated by the solar cells, the temperatures of the transparent cover, solar cells, absorber plate, water inside the collector and the storage tank. The output data are analyzed and used to estimate the electrical power output, the amount of heat that can be drawn from the system, and the efficiencies of PV/T system.

For this present work, the simulations have been done for two consecutive days on a hybrid PV/T solar water heating system consisting of a 2-m$^2$ single-glass collector, two 42-Wp amorphous-silicon (a-Si) solar cell modules, and a 200-litre storage tank with a circulating pump. The system is assumed to be operated with no load and under the clear sky condition. The hourly total solar irradiances are obtained from the solar radiation model developed by Exell [1] for Bangkok, Thailand. A sinusoidal form of daily ambient temperature and a constant wind speed of 1m/s are used in the analysis for the sake of simplicity.

![Figure 3. The hourly radiation and temperatures of each component in PV/T system for two consecutive days](image)

RESULTS AND DISCUSSION

Figure 3 shows the meteorological data along with the temperatures of various components in the system. All component temperatures are initially set to be equal to $T_a$. The PV/T collector is initially heated up by solar irradiance, $G$. The solar cell temperature appears the highest as most solar radiation passes through the cover and absorbed by the solar cell. The absorbed energy is partly converted to electricity, $Q_{elec}$, and transferred to the absorber plate as thermal energy. This useful energy then heats up the water in the tube resulting in an increase in $T_{Fo}$. As $T_{Fo}$ is higher than $T_{WT}$, the controller sends the signal to turn on the pump to circulate the water. The component temperatures vary with $G$. Although $G$ is peak at noon, those component temperatures are maximum some times later depending on their heat capacities. Around 4 pm, when there is no energy gained by the collector, $T_{WT}$ becomes equal to or lower than $T_{Fo}$, thus the controller turns off the pump so that the hot water in the tank will not be circulated.
out for energy loss at the collector. The value of $T_{WT}$ slightly decreases due to the small heat loss of the storage tank while other component temperatures decrease drastically and eventually equals to $T_{a}$ in the nighttime. On the next day, as $T_{WT}$ is higher than that of the previous day, the controller turns on the pump around 8:00 and turns off around 15:00. According to no load condition, the maximum $T_{WT}$ is found to be about 47°C and 62°C in the first and second day, respectively.

According to Fig. 4, the values of $\eta_{th}$, $\eta_{elec}$ and $\eta_{PV/T}$ for the first simulation day are plotted as a function of $\dot{m}$ for three different values of $k$, which are 0.4, 0.2 and 0.1 W/mK. The results reveal that, for $k = 0.4$ W/mK, when $\dot{m}$ increases from 0.01 to 0.1 kg/s, $\eta_{th}$ increases from 46% to 54% and $\eta_{elec}$ increases from 7.25% to 7.5%. In comparison, when $k = 0.1$ W/mK and with the same increment of $\dot{m}$, the $\eta_{th}$ increases from 38% to 46% and 7.15% to 7.3%, respectively; both increments are smaller. It is obvious that the increment of $k$ results in more energy transfer from the solar cell to the absorber plate, thus both thermal and electrical efficiencies increase. Moreover, the increment of $\dot{m}$ leads to the turbulent flow in the tube which results in higher heat transfer rate from the absorber plate to the water.

Figure 4. The effect of $\dot{m}$ and $k$ of adhesive on various collector efficiencies

Figure 5 presents the maximum temperature of water in storage tank and the values of $\eta_{PV/T}$ as a function of water mass in the tank (storage capacity) for different values of $\dot{m}$. It has been observed that the increment of storage capacity results in larger amount of water flowing in the system and more energy is required to increase $T_{WT}$. For the same amount of solar energy, the maximum $T_{WT}$ thus decreases with the increase of the storage capacity. Moreover, the higher the temperature difference between the absorber plate and the water, the higher the heat transfer rate. Therefore, it can be concluded that $\eta_{th}$ and $\eta_{elec}$ increase with the increment of $\dot{m}$ and water mass in the system. For example, the maximum $T_{WT}$ decreases from 76°C to 42°C but $\eta_{PV/T}$ increases from 42% to 68% when the water mass increases from 50 kg to 250 kg at the 0.09 kg/s mass flow rate.

Figure 5. The effect of $\dot{m}$ and water mass of the tank on the maximum water storage temperature and PV/T collector efficiency
Table 1: Variations of useful energies gained from PV/T system with water mass flow rate and thermal conductivity of adhesive

<table>
<thead>
<tr>
<th>Mass Flow Rate (kg/s)</th>
<th>Qth (MJ)</th>
<th>Qelec (MJ)</th>
<th>Qtotal (MJ)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>k = 0.1</td>
<td>k = 0.2</td>
<td>k = 0.4</td>
</tr>
<tr>
<td>0.01</td>
<td>9.82</td>
<td>11.32</td>
<td>11.88</td>
</tr>
<tr>
<td>0.03</td>
<td>10.71</td>
<td>12.36</td>
<td>13.01</td>
</tr>
<tr>
<td>0.05</td>
<td>11.05</td>
<td>12.76</td>
<td>13.46</td>
</tr>
<tr>
<td>0.07</td>
<td>11.27</td>
<td>13.02</td>
<td>13.74</td>
</tr>
<tr>
<td>0.09</td>
<td>11.44</td>
<td>13.21</td>
<td>13.95</td>
</tr>
</tbody>
</table>

The thermal, electrical and total useful energy of PV/T system, which are obtained from the model for various values of mass flow rate and conductivity of adhesive, are shown in Table 1. When fixing $\dot{m}$, the predicted total useful energy decreases about 2 MJ or 10% for the decrement of 75% conductivity (from 0.4-0.1 W/mK). When, fixing $k$ at 0.4 W/mK, the variation of $\dot{m}$ from 0.01 to 0.09 kg/s results in the total useful energy growing from 13.73 to 15.87 MJ or 15%. Moreover, the data in Table 1 also shows that $Q_{elec}$ and $Q_{th}$ are varied about 0.1 MJ and 4 MJ when $\dot{m}$ and $k$ are varied from their lowest values (0.01 kg/s and 0.1 W/mK) to highest values (0.09 kg/s and 0.4 W/mK). It implies that both energies are directly proportional to $\dot{m}$ and $k$. However the electrical energy is less dependent on $\dot{m}$ and $k$ than the thermal energy.

CONCLUSION

The developed simulation model for predicting the transient performance of a hybrid PV/T forced circulation solar water heating system has been presented. The model can predict the performance of the system such as $T_{WT}$, $T_{Fo}$, $\eta_{PV/T}$, $\eta_{th}$, $\eta_{elec}$ etc., for various weather conditions ($G$ and $T_a$) and operating conditions ($\dot{m}$, $k$ and water mass). It has been observed that the thermal, electrical and total PV/T efficiencies are directly proportional to $\dot{m}$, $k$ and water mass. Moreover it can be concluded that the electrical energy is less dependent on $\dot{m}$ and $k$ than the thermal energy. It is expected that once the developed simulation model is successfully verified by experimental results, it will be useful not only for predicting the PV/T system daily transient performance, but also for sizing the PV/T system to meet the load requirements at any operating site location.

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APPENDIX

\[ Q_{ave,c} = m_c (dT_c / dt), \quad Q_{ave,s} = (mc)_s (dT_s / dt), \quad Q_{ave,p} = m_e (dT_e / dt), \quad Q_{ave,ST} = m_p c_p (dT_p / dt), \]
\[ Q_{th,s} = A_T c_s (T_c - T_s), \quad Q_{th,p} = A_T c_p (T_e - T_p), \quad Q_{elec} = A_T c_e (T_c - T_e), \]
\[ Q_{cond,c-s} = A_{T_{s-c}} c_s c_e (T_c - T_s), \quad Q_{cond,p-s} = A_{T_{p-s}} c_p c_e (T_e - T_p), \quad Q_{cond} = A_{T_{s-c}} c_s c_e (T_c - T_s), \]
\[ q_r = W(F'(T_c - T_s) - U_{r-c} (T_c - T_s)), \quad F' = (1/U_p) \left\{ \left( \frac{1}{W} \right) \left[ \left( \frac{T_c + (W - D) F}{W} \right) \right] + \left( \frac{\pi D h_{r-c}'}{W} \right) \right\} \]
The detailed explanation of these quantities can be found in Duffie & Beckman [2] and Sukamongkol et al. [4].

**NOMENCLATURE**

\[ A = \text{area (m}^2\text{), } G = \text{solar irradiance (W/m}^2\text{), } c = \text{specific heat (J/Kg·K), } F' = \text{collector efficiency factor, } k = \text{conductivity (W/m·K), } m = \text{mass (Kg), } t = \text{time (s), } h = \text{heat transfer coefficient (W/m}^2\text{·K), } L = \text{length (m), } \dot{m} = \text{mass flow rate (Kg/s), } Q = \text{energy (W), } T = \text{temperature (K), } q = \text{heat per length in the fluid direction (W/m), } \alpha = \text{absorptivity, } \sigma = \text{Stephan-Boltzmann constant, } \tau = \text{transmittance, } \eta = \text{efficiency, } \varepsilon = \text{emissivity. } \]

**Subscripts:** \( a \) = ambient, \( S \) = solar cell, \( C \) = cover, \( \text{elec} \) = electrical, \( \text{in} \) = input, \( i \) = inlet, \( o \) = outlet, \( F \) = fluid, \( P \) = absorber plate, \( r \), \( \text{rad} \) = radiation, \( \text{th} \) = thermal, \( T \) = storage tank, \( \text{WT} \) = water in tank, \( \text{conv} \) = convection, \( \text{cond} \) = conduction.

**REFERENCES**


