Mathematical Modelling and Simulation of the Performance of PV/T Air Solar Collector

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Abstract. The world demand of energy is increasing continuously, and solar energy is one of the renewable energies that can be utilized to fulfil the demand. Over the years, there are many researches that have been carried out on hybrid air solar collector. Hybrid-PV system or PV/T system is an integration of photovoltaic (PV) cells and solar thermal components. It is proven in many researches that combined PV and thermal system gives higher efficiency than individually working system. Therefore, this paper discusses the development of mathematical model of a photovoltaic/thermal (PV/T) solar collector. The effects of various parameters on the performance of the solar collector are also discussed. Since there is a drop of efficiency of the photovoltaic cells as the operating temperature increases, this study proposes a design of PV/T solar collector with an air-cooling system with a set of fins attached to improve its overall performance. A mathematical model representing the system by using one dimensional energy balance equations is developed. A simulation has been carried out by using MATLAB to determine the effect of parameters such as solar radiation and temperature on the performance of the solar collector. It is found out that when the temperature of the collector is reduced by removing heat through working fluid, its performance can be improved. Therefore, when air mass flow rate increases, the electrical and thermal efficiencies of the collector increase. Meanwhile, the collector efficiency also increases with the increase in solar radiation.

1. Introduction

Solar energy is one of the important renewable energy recognized in environmentally-friendly electricity production. It is an energy resource freely available on earth, and a system of solar energy can fulfill the global energy demand. Usually, solar energy is utilized after it is converted into certain energy forms for various applications, including electrical and thermal energy.

Separately, in thermal system, the collector absorbs the heat from the sun transfer the heat to a working fluid. Meanwhile, in photovoltaic system, the photovoltaic cells in the collector convert the solar radiation into electrical energy. However, these two types of system are combined and called hybrid photovoltaic/thermal (PV/T) system. Photovoltaic/thermal (PV/T) solar collector is a system of heat exchanger that is capable to harness not only electrical energy but also thermal energy from solar radiation absorbed with no noise, pollution or moving parts. PV/T is used to describe a solar thermal
collector with PV cells as part of it which can produce electrical and thermal energy at the same time [1].

To improve efficiency of a PV module as well as to reduce its thermal degradation rate, a proven effective way is to reduce stored heat to cool it down during its operation [2]. In the previous study, it has been shown that a PV/T module gives out electrical efficiency which is nearly the same to a PV module, but if a forced fluid (air or water) is passed through a channel underneath the PV/T module, the efficiency can be improved [3]. The efficiency of the collector system depends on various factors. As in the paper by Mojumder et al. [4], the thermal and electrical performance of the PV/T system was studied in various conditions for the designs proposed by developing an analytical model through experiment. It is found out that maximum heat gain is obtained at highest heat convection which can be obtained at highest air mass flow rate. On the other hand, at higher solar radiation value, the heat gain is relatively higher.

The next section emphasised on the energy balance equations which represented a system of PV/T solar collector used in this study. Then, the energy balance equations are used to calculate the energy efficiencies. A simulation is carried out in MATLAB to demonstrate the effects of chosen parameters on the performance of the collector system.

2. Energy Balance Equations

By referring the work by Abu Bakar et al. [5], Jarimi et al. [6] and Othman et al. [8], the energy balance equations for every nodes of temperature are expressed as follows:

i) For the solar cells’ nodes on the PV module;

\[
\frac{1}{\tau_g} \alpha_p (1-PF) G + \frac{2}{\tau_g} \alpha_{pv} (PF)(1-\eta_{pv}) G = h_{cpf} (T_p - T_f) + h_{rpm} \frac{A}{A_{ab}} (T_p - T_{bp}) + h_{rps} (T_p - T_s) \\
+ h_{cpp} (T_p - T_w)
\]

(1)

ii) For the air temperature nodes;

\[
\frac{m C_f}{W} \frac{dT_f}{dx} = h_{cpf} (T_p - T_f) + h_{chpf} \frac{A_{ab}}{A_{c}} \eta_p (T_{bp} - T_f),
\]

(2)

where fin effectiveness, \( \eta_p = 1 - \frac{A_{fin}}{A_{ab}} (1 - \eta_{fin}) \); fin efficiency, \( \eta_{fin} = \frac{\tanh(m_{fin} h_{fin})}{m_{fin}} \);

and \( m = \left( \frac{2 h_{chpf}}{k_{fin} w_{fin}} \right)^{1/2} \).

iii) For the nodes of the surface of back plate with fins;

\[
\frac{U_{bp} (T_{bp} - T_s)}{A_{ab}} + h_{chpf} \frac{A}{A_{ab}} \eta_p (T_{bp} - T_f) + h_{rps} \frac{A_{ab}}{A_{c}} (T_{bp} - T_p) = 0.
\]

(3)

The heat transfer terms involved in the equations above are defined as follows:

1: The rate of the solar energy absorbed by the absorber plate of the PV module per unit area.
2: The rate of the solar energy received by solar cells of the PV module after transmission and the rate of electrical energy available per unit area.
3: The rate of heat transfer to the air flow per unit area.
3. Energy Analysis
The thermal parameters and efficiency of a PV/T air collector are obtained from the energy balance equation for each component of a PV/T air collector in Section 2 as follows, however to have a brief note, the governing equations proof on PV/T air collector thermal analysis is excluded.

From Eq. (1) and Eq. (3), the expression for temperature of absorber plate and backplate can be written as Eq. (4) and Eq. (5) respectively:

\[
T_p = \frac{H_{17} - T_f H_{15}}{H_{16}}, \tag{4}
\]

\[
T_{bp} = \frac{T_p H_{12} - T_f h_{qpf} - H_{11}}{h_{qpb}}, \tag{5}
\]

where \(H_{11}, H_{12}, H_{15}, H_{17}\) are obtained through the algebraic manipulation process. The variables \(T_p\) and \(T_{bp}\) can be eliminated from Eq. (2) by substituting Eq. (1) and Eq. (3) into it. The following linear first order differential equation with boundary condition is obtained.

\[
\frac{dT_f}{dx} = A_0 - A_1 T_f \quad \text{where} \quad T_f \bigg|_{x=0} = T_{in} = T_a, \tag{6}
\]

Solving the first order linear differential equation in Eq. (6) gives the solution as expressed in Eq. (7) below:

\[
T_f(x) = \frac{A_0}{A_1} + T_a e^{-A x} - \frac{A_0}{A_1} e^{-A x}. \tag{7}
\]

Average temperature of the PV is calculated by using numerical integration rule to obtain Eq. (8).

\[
\overline{T_{pv}} = \overline{T_p} = \frac{1}{L_c} \int_0^L T_p dx. \tag{8}
\]

3.1 Thermal and Electrical Efficiencies
The thermal efficiency, \(\eta_{th}\) is calculated by simplifying the equations by Abu Bakar et al. [5]:

\[
\eta_{th} = \frac{m_f C_f (T_0 - T_f)}{A_c G}. \tag{9}
\]

When the temperature increases, the open circuit voltage, \(V_{oc}\) and fill factor, \(FF\) decreases, but the short circuit current, \(I_{sc}\) increases slightly. As a result, the crystalline silicon cells efficiency decreases. The electrical efficiency, \(\eta_{ele}\) of the collector is written as a function of temperature based on Abu Bakar et al. [5] and Michael et al. [7] is as follows:

\[
\eta_{ele} = \eta_{ref} \left(1 - \beta_{ref} (\overline{T_{pv}} - T_{ref})\right). \tag{10}
\]
The total overall thermal equivalent efficiency, $\eta_{\text{total}}$ of a PV/T solar collector can be expressed as the total of both thermal and electrical efficiencies:

$$\eta_{\text{total}} = \eta_{\text{th}} + \eta_{\text{ele}}.$$  

(11)

4. Simulation

The simulation of the solar collector is performed by using MATLAB. The flowchart in Figure 1 shows the proposed algorithm for the simulation. The program starts with the temperature of air and thermophysics properties of the fluids calculated using the set-up parameters (table 1) and guessed temperatures of absorber plate, $T_p$ and temperature of back plate, $T_{bp}$. Then, the calculated values of the temperature of air, $T_f$ will be used to compute the new value of $T_p$ and $T_{bp}$. The differences between the guessed temperature and the temperature that has been computed is calculated. The process stops if the difference is less than 0.01°C. Then the new computed temperature values will replace the old ones. Table 1 shows the values of parameters used in the simulation.

The results obtained from the simulation performed in MATLAB are shown in the figures below (figure 2 - 4). Figure 2 shows the relationship between a range of mass flow rate on the performance of
the solar collector in terms of thermal, electrical, and total efficiencies. When mass flow rate increases, the electrical and thermal efficiency of the collector increase, until they reach plateau.

In figure 3, as expected it is shown that the temperature rises in PV temperature decreases when mass flow rate increases. Figure 4 shows the changes on the temperature rise by different solar radiation values at different air flow rate (0.04 m/s and 0.1 m/s). It is presented that higher mass flow rate help to reduce PV temperature in high solar radiation which is expected to happen during noon. The result obtained showed that the overall photovoltaic efficiency can be improved with higher air mass flow rate.

Table 1. Values of coefficients and ambient conditions used in the simulations

| Parameter                  | Value | Parameter                  | Value |
|----------------------------|-------|----------------------------|-------|
| Collector Width            | W     | 0.54                       |       |
| Collector Length           | Lc    | 0.69                       |       |
| Collector Depth            | Dc    | 0.02                       |       |
| Absorptivity of PV         | \(\alpha_{pv}\) | 0.938                     |       |
| Absorptivity of absorber plate | \(\alpha_p\) | 0.951                     |       |
| Electrical conductivity    | \(\sigma\) | 5.67 \times 10^{-8}      |       |
| Fin Thermal conductivity  | \(k_{fin}\) | 204                      |       |
| Width of fin               | \(w_{fin}\) | 0.001                     |       |
| Height of fin              | \(h_{fin}\) | 0.01905                   |       |
| Wind speed                 | \(v\) | 2.0                        |       |
| Temperature                | \(T_a\) | 303                        |       |
| Irradiance                 | \(G\) | 800                        |       |
| Ref. solar cell temperature| \(T_{ref}\) | 298                      |       |
| PV panel power temp. coeff.| \(\beta_{ref}\) | 0.00544                   |       |
| Ref. electrical efficiency | \(\eta_{ref}\) | 0.14                     |       |

Figure 2. The simulated values for the performance of the PV/T solar collector against various mass flow rate (\(G=800\) W/m², \(T_a=303\) K)

Figure 3. The simulated values for the temperature rise against various mass flow rate rate (\(G=800\) W/m², \(T_a=303\) K)

Figure 4. The simulated values for the temperature rise for various solar irradiance (\(T_a=303\) K)
5. Conclusion
In this paper, a mathematical modeling of a proposed simple design of a PV/T air solar collector has been discussed. One-dimensional energy balance equations have been developed which implied the heat transfer that occur in the PV/T system. It is found out that when the temperature of the collector is reduced by removing heat through working fluid, its performance can be improved. Therefore, when air mass flow rate increases, the electrical and thermal efficiencies of the collector increase. Meanwhile, the collector efficiency also increases with the increase in solar radiation.

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Nomenclature

| Symbol | Units | Description |
|--------|-------|-------------|
| $A_{ab}$ | total exposed surface area (m$^2$) | Greek Letters |
| $A_c$ | solar collector surface area (m$^2$) | $\alpha$ | absorptivity |
| $C_f$ | specific heat capacity of fluid (J/(kg K)) | $\eta$ | efficiency |
| $h$ | heat transfer coefficient | $\tau$ | transmittivity |
| $m$ | air mass flow rate (kg/s) | $k$ | conductivity |
| $T$ | temperature (K) | $\rho$ | absorber plate |
| $U$ | overall heat loss coefficient (W/(m K)) | $a$ | ambient |
| $Voc$ | open circuit voltage | $bp$ | back plate |
| $FF$ | fill factor | $c$ | convection |
| $PF$ | packing factor | $s$ | sky |

Subscripts

- $p$: ambient
- $pv$: PV
- $r$: radiative
- $w$: wind
- $o$: output