Theoretical model of solar thermoelectric generator for heat and power generation

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Abstract. Solar energy can be harnessed to produce thermal and electrical energy. With regard to this, Solar Photovoltaic (PV) is a well-known solar technology that is used to convert from solar energy to electrical energy. Nevertheless, Solar PV efficiency drops as the solar PV panel temperature increases. Another way to generate electricity from the solar energy is to use Solar Thermoelectric Generator (STEG). STEG is a hybrid technology between solar thermal collector and Thermoelectric Generator (TEG). A main advantage of STEG is it can produce thermal and electrical energy simultaneously. In this study, a theoretical model was developed to predict the STEG output and performance. An STEG model which consists of an Evacuated Tube Heat Pipe Solar Collector (ETHPSC), four water cooling jackets and four TEGs, was set up in this study. In order to determine whether the theoretical model is accurate enough for the prediction, a comparison was carried out between the theoretical and experimental data. Based on the result, the comparison provides a good correlation between the former and the latter and the highest error obtained is less than 20%.

Nomenclature

$A_{gi}$ external surface area of inner glass tube [=$\pi D_{gi} L_e$, m$^2$]
$A_{go}$ surface area of outer glass tube [=$\pi D_{go} L_e$, m$^2$]
$A_{SC}$ horizontal area of ETHPSC exposed to solar radiation [=$D_{go} L_e$, m$^2$]
$A_{ei}$ heat pipe evaporator tube internal surface area [=$\pi D_{ei} L_e$, m$^2$]
$A_{ci}$ heat pipe condenser pipe internal surface area [=$\pi D_{ci} L_e$, m$^2$]
$D_d$ diameter of hole in aluminum block to fit heat pipe [=0.024 m]
$D_{ci}$ internal diameter of heat pipe condenser pipe [=0.022 m]
$D_{co}$ external diameter of heat pipe condenser pipe [=0.024 m]
$D_{ei}$ internal diameter of heat pipe evaporator pipe [=0.006 m]
$D_{eo}$ external diameter of heat pipe evaporator pipe [=0.008 m]
$D_{go}$ external diameter of outer glass tube [=0.058 m]
$D_{gi}$ external diameter of inner glass tube [=0.048 m]
f$_{ref}$ multiple reflection factor between inner and outer glass tubes
$h_c$ condensation heat transfer coefficient in heat pipe [=1774 W/m$^2$K]
h$_e$ evaporation heat transfer coefficient in heat pipe [=1854 W/m$^2$K]
1. Introduction

Solar energy is one type of renewable sources which is widely available throughout the world. It is abundant, clean, and always replenished [1][2][3]. Solar energy can be harnessed to produce electrical and thermal energy. There are two main solar technologies which are associated with electrical and thermal energy generation: solar photovoltaic (PV) and solar thermal [4][5][6]. Although solar PV is used to convert electricity from solar energy, its efficiency drops when the panel temperature increases [7][8][9][10][11]. Another technology that can be used to generate electricity from solar energy is Solar Thermoelectric Generator (STEG).

STEG is a combination of solar thermal and Thermoelectric Generator (TEG). TEG is the direct conversion of temperature difference across it to electricity, by the Seebeck Effect. Several studies on TEG are carried out by various authors in [12][13][14][15]. [16] presented an experimental and theoretical research of STEG model. The model consists of an evacuated tube heat pipe solar collector (ETHPSC), a TEG and a water cooling jacket. They achieved 55% thermal efficiency and 1% electrical efficiency with 600 W/m² solar irradiance. Also, by comparing both experimental and theoretical data of electrical outputs, they obtained a maximum deviation of 10%. Lv et al. [17] designed a STEG model with a flat-plate micro-channel heat pipe inside a solar evacuated tube. This type of heat pipe provides an advantage of having direct thermal contact with TEG since it is flat-shaped. They obtained the electrical and thermal efficiencies of 2.8% and 58% respectively at 1000 W/m² solar irradiance. Also, a theoretical model was developed in this study. By comparing theoretical and experimental electrical output data, a maximum deviation of 5% was obtained. A similar STEG model consisting of micro-channel heat pipe was developed by [18]. The study was carried out theoretically and experimentally. By comparing theoretical and experimental data of TEG hot-side and cold-side temperatures, a maximum deviation of 5% was attained. [19] carried out a theoretical and experimental research on
STEIG. In this study, the STEG consists of one TEG and four heat pipes. By comparing water temperature of theoretical and experimental data for each heat input rate, a maximum deviation of 8% was obtained. Most studies as mentioned previously only compared either temperature or electrical output data. Therefore, in this study, a theoretical model was developed to predict the STEG output and performance; not only on electrical but also on thermal output.

2. Mathematical Model
A theoretical model was developed to predict the STEG heat and power generation. Heat transfer in the STEG model is shown in Figure 1. The whole thermal resistance network of the model is illustrated in Figure 2. The following assumptions are made prior to the development of the theoretical model:
   a) Thermal contact resistances between an aluminium block and four TEGs are neglected
   b) All thermal properties are assumed to be constant and independent of temperature
   c) All temperatures at their respective sections are assumed to be uniform
   d) Heat from the heat pipe condenser to the aluminium block, and from the aluminium block to each of the four TEGs are assumed to be spread equally. No heat loss to surrounding
   e) Aluminium block, TEGs and water cooling jackets are assumed to be perfectly insulated
   f) Water flowrate inside water cooling jacket is assumed to be equal and constant
   g) The effect of tilt angle on STEG heat and power output is negligible.

By applying an energy balance equation on the STEG, total power input is equal to power output:

\[ \Sigma Q_{in} = \Sigma Q_{out} \]  \hspace{1cm} (1)

According to the thermal resistance network in Figure 2, the power input (\(\Sigma Q_{in}\)) and output (\(\Sigma Q_{out}\)) are:

\[ Q_{fin} = Q_{sky} + P_L + Q_w \]  \hspace{1cm} (2)

Radiation heat loss from the outer glass tube of ETHPSC to the sky is defined by:

\[ Q_{sky} = h_{sky} A_g (T_{glass} - T_{sky}) \]  \hspace{1cm} (3)

Where
\( h_{\text{sky}} = \sigma \varepsilon_0 (T_{\text{glass}}^2 + T_{\text{sky}}^2)(T_{\text{glass}} + T_{\text{sky}}) \)  \hspace{1cm} (4) \\

\( T_{\text{sky}} = T_{\text{amb}} - 6^\circ \text{C} \)  \hspace{1cm} (5) \\

Thus, equation (3) can be rewritten as:

\( Q_{\text{sky}} = \sigma \varepsilon_0 A_{\text{go}} (T_{\text{glass}}^4 + T_{\text{sky}}^4) \)  \hspace{1cm} (6) \\

Heat absorbed by the ETPSC aluminium fin is given by:

\( Q_{\text{fin}} = \eta_{\text{opt}} H A_{\text{SC}} - U_t A_{\text{go}} (T_{\text{fin}} - T_{\text{amb}}) \)  \hspace{1cm} (7) \\

where

\( U_t = h_{\text{sky}} \)  \hspace{1cm} (8) \\

\( \eta_{\text{opt}} = \tau_0 \alpha T_{\text{ref}} \)  \hspace{1cm} (9) \\

\( f_{\text{ref}} = \left[ 1 - \rho_i \rho_o (A_{\text{gi}}/A_{\text{go}}) \right]^{-1} \)  \hspace{1cm} (10) \\

Heat transfer along ETPSC heat pipe is defined as follows:

\( Q_{\text{hp}} = (T_{\text{fin}} - T_{\text{block}})(R_{\text{hp}})^{-1} \)  \hspace{1cm} (11) \\

Where

\( R_{\text{hp}} = R_e + R_c + R_{\text{ewall}} + R_{\text{cwall}} \)  \hspace{1cm} (12) \\

\( R_e = (h_e A_{\text{ei}})^{-1} \)  \hspace{1cm} (13) \\

\( R_c = (h_c A_{\text{ci}})^{-1} \)  \hspace{1cm} (14) \\

\( R_{\text{ewall}} = \frac{\ln(D_{\text{eo}}/D_{\text{ei}})}{2\pi \kappa_{\text{hp}} L_e} \)  \hspace{1cm} (15) \\

\( R_{\text{cwall}} = \frac{\ln(D_{\text{co}}/D_{\text{ci}})}{2\pi \kappa_{\text{hp}} L_c} \)  \hspace{1cm} (16) \\

At the temperature node \( T_{\text{fin}} \) in Figure 2, \( Q_{\text{fin}} \) is equal to the sum of \( Q_{\text{sky}} \) and \( Q_{\text{hp}} \):

\( Q_{\text{fin}} = Q_{\text{sky}} + Q_{\text{hp}} \)  \hspace{1cm} (17) \\

Substituting equation (6) and equation (11) into equation (17), \( T_{\text{fin}} \) can be calculated as follows:

\[
T_{\text{fin}} = \frac{\eta_{\text{opt}} H A_{\text{SC}} + \sigma \varepsilon_0 A_{\text{go}} (T_{\text{glass}}^4 - T_{\text{sky}}^4) + T_{\text{block}}(R_e + R_c + R_{\text{ewall}} + R_{\text{cwall}})^{-1} + h_{\text{sky}} A_{\text{go}} T_{\text{amb}}}{\left[ (R_e + R_c + R_{\text{ewall}} + R_{\text{cwall}})^{-1} + h_{\text{sky}} A_{\text{go}} \right]} \]  \hspace{1cm} (18)

From Figure 2, \( Q_{\text{al}} \) is equal to \( Q_{\text{hp}} \):
\[ Q_{al} = Q_{hp} \]  
(19)

\[ Q_{al} = (R_{al})^{-1}(T_{block} - T_h) \]  
(20)

Thus,

\[ T_h = T_{block} - Q_{al}R_{al} \]  
(21)

Where thermal resistance of the aluminium block (R_{al}) is defined as follows:

\[ R_{al} = (W_{al} - D_{al})[\kappa_{al}L_{al}(4W_{al} + \pi D_{al})]^{-1} \]  
(22)

The total heat transfer rates at both hot and cold sides for four TEGs are defined as:

\[ Q_h = 4[\alpha_{TEG}I_L T_h - 0.5I_L^2 R_{TEG-int} + \kappa_{TEG}(T_h - T_c)] \]  
(23)

\[ Q_c = 4[\alpha_{TEG}I_L T_c + 0.5I_L^2 R_{TEG-int} + \kappa_{TEG}(T_h - T_c)] \]  
(24)

Total power produced by four TEGs is given by:

\[ P = Q_h - Q_c \]  
(25)

Substituting equation (23) and equation (24) into equation (25), total power output by four TEGs is as follows:

\[ P = 4[\alpha_{TEG}(T_h - T_c)I_L - I_L^2 R_{TEG-int}] \]  
(26)

Since \( P = 4V_L I_L \), the voltage across one TEG is given by:

\[ V_L = \alpha_{TEG}(T_h - T_c) - I_L R_{TEG-int} \]  
(27)

Since \( V_L = I_L R_L \), therefore the current flows in the circuit is defined as:

\[ I_L = \frac{\alpha_{TEG}(T_h - T_c)}{(R_{TEG-int} + R_L)^{-1}} \]  
(28)

By assuming no heat loss to surrounding, total heat transfer at TEG cold-side is equal to total heat gain by water inside four water cooling jackets:

\[ Q_c = Q_w \]  
(29)

The flow chart for the theoretical model is illustrated in Figure 3 below.
3. Methodology

An STEG model consists of an Evacuated Tube Heat Pipe Solar Collector (ETHPSC), four water cooling jackets and four TEGs, as shown in Figure 4 to 5. Four TEGs with each is located between each side of aluminium block and water cooling jacket. Water flowed into each individual water cooling jackets with the maximum water flowrate of 33 ml/s and flowed out into the drain. Power output is the highest when water flowrate is at maximum [20][21]. The STEG tilt angle is set to 10° since STEG receives the most DNI solar irradiance. One set of TEG electrical characterisation which consists of voltage, current and power was measure for each individual TEGs. In order to obtain electrical characterisation data for each individual TEG, TEG 1 was connected directly to a DC electronic load. This step was repeated for TEG 2, TEG 3 and TEG 4.

Figure 4. Schematic drawing of the STEG model.

Figure 5. Physical STEG Model at Site.
4. Results and Discussion
Figure 6 shows the experimental values of open circuit voltage, DNI solar irradiance, maximum power output and heat gain by water. $P_{\text{max}}$ produced by each TEG is different to each other. This is because water flowrate inside each water cooling jacket is not uniform due to its different location in STEG. Water cooling jacket no 4 is located on top of the aluminium block, while water cooling jacket no 2 is located at the bottom of the aluminium block. This led to nonuniformity of water flowrate inside each water cooling jacket. Also, it was observed that $V_{\text{oc}}$ depended on $H$. As $H$ increased, $V_{\text{oc}}$ also increased and vice versa. This is because when $H$ increased, heat gain by STEG also increased, causing the temperatures in the STEG including $T_h$ to increase. Thus, electricity output in term of $V_{\text{oc}}$ also increased.

![Figure 6. Open circuit Voltage, DNI Solar Irradiance, Maximum Power Output and Water Heat Gain.](image)

A comparison was made between the experimental and theoretical data, as shown in Table 1. The assumed geometric and other parameters are shown in the Nomenclature. Both experimental and theoretical data are in a good agreement, with deviations of less than 20%.

| Parameter          | Experiment | Theory | $|\delta|$ |
|--------------------|------------|--------|---------|
| $H$ (W/m²)         | 825        | -      | -       |
| $\dot{m}_w$ (g/s)  | 33         | -      | -       |
| $T_{\text{amb}}$ (°C) | 35.1      | -      | -       |
| $T_{\text{win}}$ (°C) | 29.8      | -      | -       |
| $T_{\text{wout}}$ (°C) | 29.9     | -      | -       |
| $T_{\text{block}}$ (°C) | 51.9     | -      | -       |
| $T_c$ (°C)         | 33.9       | 30.1   | 11%     |
| $T_h$ (°C)         | 51.1       | 47.4   | 7%      |
| $\Delta T_{\text{TEG}}$ (°C) | 17.2     | 17.3   | 1%      |
| $Q_w$ (W)          | 41.5       | 44.1   | 6%      |
| $V_L$ (mV)         | 214        | 209    | 2%      |
5. Conclusion
A theoretical model was developed in order to predict the STEG output in terms of heat and power. The STEG comprised of one ETHPSC, four TEGs and water cooling jackets. The experiment was run with a tilt angle of 10° and water flowrate inside each water cooling jacket of 33 ml/s. The experimental data is then compared with the theoretical data. Both data indicated a good agreement with the deviations of less than 20% considering all the uncertainty analyses for each parameter measurement. As for electrical and thermal efficiencies, both showed deviations of 0% and 4% respectively.

6. References
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| I_L (A) | 0.073 | 0.077 | 5% |
|--------|-------|-------|----|
| P (mW) | 63    | 65    | 3% |
| η_e    | 0.08% | 0.08% | 0% |
| η_th   | 54%   | 56%   | 4% |
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