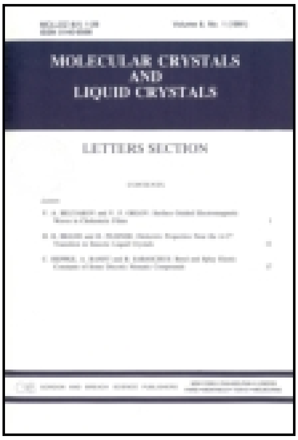

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Modeling and Design Consideration of a Simple Hybrid Solar Energy Conversion System

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Modeling of a simple hybrid photovoltaic-thermoelectric system has been presented to find optimum condition for higher conversion efficiency of solar energy. In this modeling, not only reflectance but also thermal radiation loss at the front side of the photovoltaic cell was taken into account. The efficiency of the thermoelectric generator was never higher than that of the photovoltaic cell. The influence of the material properties of the hybrid system on the overall efficiency was investigated. For practical use it should bear in mind that the heat sink should maintain low temperature on the cold side of the thermoelectric generator.

Keywords Heat sink; hybrid system; photovoltaic; thermoelectric; temperature coefficient of efficiency; solar energy conversion

Introduction

As concerns about rising price of fossil fuel, greenhouse effect, and energy security, renewable energy is getting important and its capacity is also growing fast. Among many renewable energy types such as solar energy, wind energy, geothermal energy, bioenergy, ocean energy, and hydrogen and fuel cells, solar energy is one of the most fast growing energy source in world as it is environment friendly and inexhaustible. In addition, as the cost of the photovoltaic (PV) cell came down, the solar energy is getting into the mainstream of the renewable energy. However, one of reasons of limited efficiency of the PV cell is that the PV cell could not utilize the whole spectrum of the solar energy. About 40% of solar energy would not be absorbed by the PV cell [1]. Thus, in order to convert the solar energy which was not absorbed by the PV cell, the thermoelectric (TE) generator has been utilized [2–4]. Vorobiev et al. suggested two stacked PV-TE hybrid system designs [2]. In one design, the PV cell is directly mounted on the TE generator. The hybrid system is under the concentrator. In the other one, the PV cell is placed on the concentrator, and only the TE generator is below the concentrator. van Sark also reported an economical hybrid system design without any concentrators. The PV cell is in directly contact with the TE generator [3]. However, both researches did not consider any reflectance and thermal radiation loss at the front side of the PV cell.

In this study, a hybrid PV-TE system to convert wide spectrum of solar energy into electricity was modelled to find optimum condition to get higher conversion efficiency. The

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structure of the hybrid system is an economic one without any concentrators. Reflectance at the front of the PV cell and thermal radiation at the PV cell were taken into account in this model to be more practical. The contribution of the PV cell and the TE generator to the overall efficiency was calculated based on theoretical conversion efficiencies. Effect of radiation loss and reflectance on the overall efficiency was investigated. The effect of material properties of the PV cell and TE generator on the efficiency was explored to find the optimum design of the hybrid system.

System Design and Modeling

A schematic diagram of the simple hybrid system is shown in Fig. 1. The front side of the PV cell is exposed to the solar radiation, and to the other side of the PV cell the hot side of the TE generator is attached. Heat sink then adheres to the cold side of the TE generator. The electrode from the PV cell is connected in series with that from the TE generator. Thus, total amount of the generated power would be the sum of the power generated by the PV cell and the TE generator.

$$P_{total} = P_{PV} + P_{TE} \tag{1}$$

Here, the generated power of the PV cell is dependent on an efficiency of the PV cell (defined as η_{PV}) as given in equation (2), and G which is solar irradiance.

$$P_{PV} = \eta_{PV} \cdot G \tag{2}$$

However, efficiency of the PV cell is a function of the PV cell temperature (T_{PV}), and their relationship is generally described by equation (3) [5–7].

$$\eta_{PV} = \eta_{PV(25\ ^{\circ}\mathrm{C})} \cdot [1 - \beta \cdot (T_{PV} - 25\ ^{\circ}\mathrm{C})] \tag{3}$$

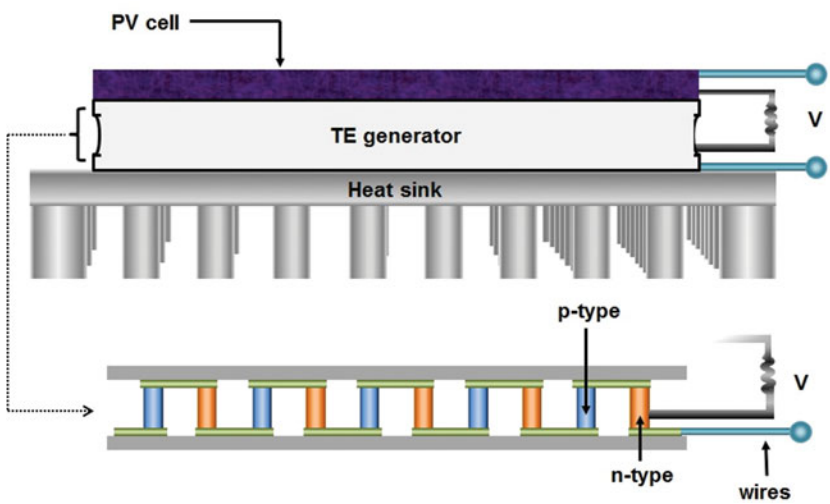

Figure 1. Schematic diagram of the hybrid PV-TE system.

where β is a temperature coefficient of efficiency, and $\eta_{PV\,(25\,^\circ C)}$ is the efficiency at T = 25 °C (standard test condition).

$$P_{TE} = (1 - \eta_{PV} - R) \cdot (1 - r_{loss}) \cdot \eta_{TE} \cdot G \tag{4}$$

Considering introduction of heat flux to the hot side of the TE generator, the reflectance (R) and radiation loss (r_{loss}) at the front side of the PV cell should be taken into account for practical use. This approach is different from van Sark's approach [3]. Thus, the generated power from the TE generator can be theoretically obtained from equation (4), where η_{TE} is the efficiency of the TE generator. The efficiency of a TE generator can be expressed as the below equation [1,3].

$$\eta_{TE} = \left(1 - \frac{T_C}{T_{PV}}\right) \cdot \frac{\sqrt{1 + ZT_{ave}} - 1}{\sqrt{1 + ZT_{ave}} + \frac{T_C}{T_{PV}}} \tag{5}$$

ZT_{ave}, the figure of merit, is determined by Seebeck coefficient α, thermal conductivity κ, and electrical resistivity ρ, and Z is defined as $Z = \alpha^2\kappa/\rho$. T_{ave} is the average temperature of the TE generator, and defined as $T_{ave} = (T_C + T_{PV})/2$, where T_C is the temperature at the cold side of the TE generator [3]. Thus, the overall efficiency of the hybrid system can be expressed as follows:

$$\eta_{Total} = \eta_{PV} + (1 - \eta_{PV} - R) \cdot (1 - r_{loss}) \cdot \eta_{TE} \tag{6}$$

Results and Discussion

For a crystalline silicon photovoltaic cell, confirmed terrestrial module efficiency measured under the global AM1.5 spectrum (1,000 W/m^2) at a cell temperature of 25 °C ($\eta_{PV\,(25\,^\circ C)}$) was about 23% [8]. There are many different temperature coefficients of efficiency [5–7], but $\beta = 0.45\%\ K^{-15}$ which was smaller one among them was chosen. Also, R and T_C were set to 0.1 [5] and 25 °C, respectively. The material used at temperature between 200 and 400 K has value of $ZT_{ave} \sim 1$ [3]. In this study, thermal radiation loss was set to 50% since the front side of the PV cell is opened to the outer environment. Figure 2 shows the PV cell and TE generator efficiency as a function of the PV cell temperature. Total efficiency which is the sum of the PV cell efficiency and the TE generator efficiency is also shown in Fig. 2. Figure 2(a) shows the efficiencies without considering reflectance and thermal radiation loss that was suggested by van Sark [3]. For this calculation, R and r_{loss} were set to 0 in equation (6). At high irradiation, the PV cell can reach 80 °C. In this graph, overall efficiency at temperature of 80 °C was 0.387, and the contribution of the TE generator to the overall efficiency was 55.3% which is higher than that of the PV cell (44.7%). The efficiencies of the TE generator and PV cell were 0.214 and 0.173, respectively. At the temperature around 58–60 °C, both PV and TE efficiencies were almost the same. The maximum overall efficiency (0.390) was obtained at temperature of 65 °C. Figure 2(b) shows the efficiencies without considering thermal radiation loss but with considering reflectance. In this case, only r_{loss} was set to 0 in equation (6). In this figure, the overall efficiency at operating temperature of the PV cell (80 °C) was 0.361, and still the contribution of the TE generator to the overall efficiency is more than that of the PV cell. The efficiencies of the TE generator and PV cell were 0.188 and 0.173, respectively. At the temperature around 71–72 °C, both PV and TE efficiency contributions were almost the same. The maximum overall efficiency was 36.5% at the temperature of 62 °C. In the above two cases, the TE generator more

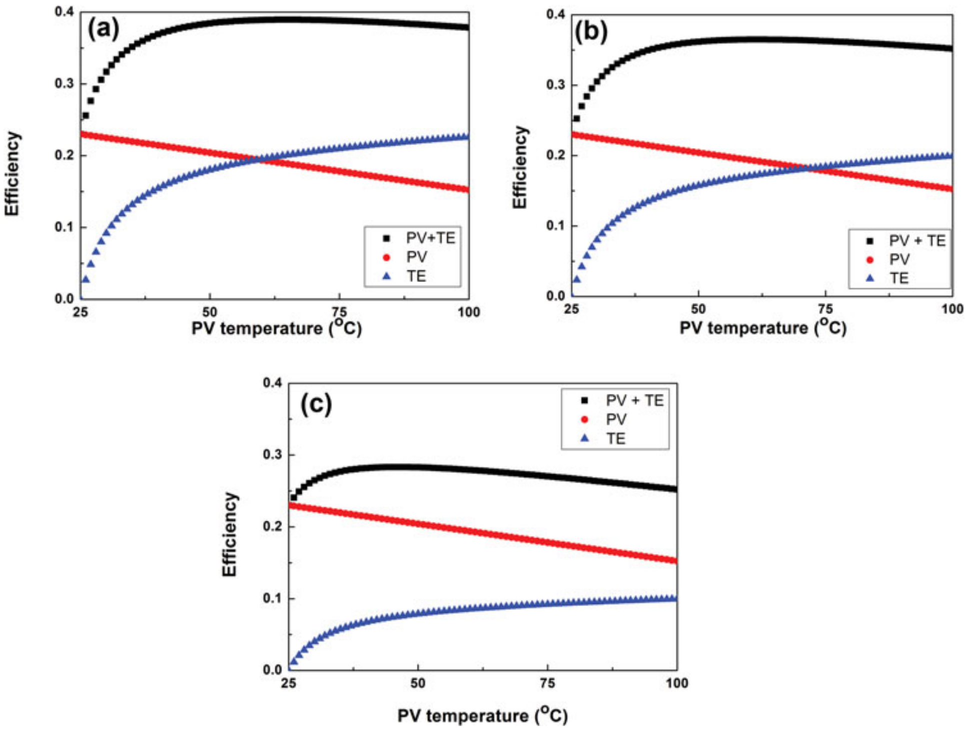

Figure 2. Efficiencies of PV cell, TE generator and their sum as a function of temperature at PV cell (a) without considering reflectance and thermal radiation, (b) with considering reflectance and without considering thermal radiation, and (c) with considering reflectance and thermal radiation.

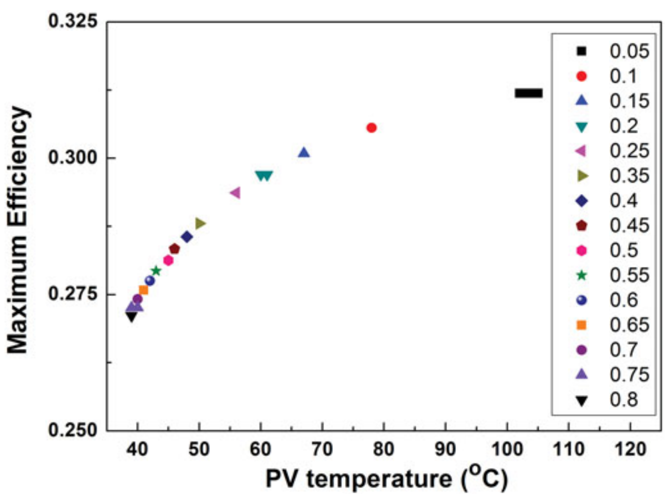

Figure 3. Maximum efficiency of the simple hybrid system with various β in the range between 0.05–0.8%.

Table 1. Efficiency at the PV cell operating temperature and maximum efficiency of the simple hybrid system with various ZT_{ave} in the range between 1.0–1.25

	ZT_{ave}			
Efficiency	1.0	1.1	1.2	1.25
Efficiency [%] at temperature 80 °C	30.56	31.01	31.42	31.62
Maximum efficiency [%] (Temperature [°C])	30.56 (78 °C)	31.01 (80–83 °C)	31.43 (84–85 °C)	31.63 (85–87 °C)

effectively converted solar energy into electricity at the PV cell operating temperature. However, it has not been reported so far that the TE generator was installed into the hybrid system. The realistic result may not agree well with the above two simulated results. When considering thermal radiation loss and reflectance as shown in Fig. 2(c), the maximum efficiency was obtained at the temperature of 46 °C, and its value was 28.3% from equation (6). At temperature of 80 °C, the overall efficiency was 26.7%. The PV cell efficiency was 17.3%, and the overall efficiency increased by 9.4% by adding the TE generator. The contribution of the TE generator to the overall efficiency was 0.352 of the overall efficiency which is less than that of the PV cell. As shown in Fig. 2(c), the efficiency was always less than that of the PV cell. This result could be drawn from the fact that the introduction of the energy into the hot side of the TE generator decreased that is different from the other result [3]. However, the TE generator still impacts the solar energy conversion efficiency.

The influence of material properties of the hybrid system on the efficiency was investigated to find the optimum design of the hybrid system. Firstly, the material aspect of the PV cell was investigated since the efficiency of the PV cell is higher than that of the TE generator at temperature between 25 °C–125 °C as shown in Fig. 2(c). Maximum efficiency of the simple hybrid system was obtained by varying the temperature coefficient of efficiency in the range between 0.05 and 0.8% as shown in Fig. 3. For this calculation, equations (3), (5) and (6) have been used. If $\beta = 0.1\%$, the maximum efficiency was obtained at temperature of 78 °C close to 80 °C which is assumed to be the normal operating temperature of the PV cell. Thus, the PV cell with β less than 0.1% can obtain their maximum efficiency at the PV cell operating temperature or higher. When β was set to be 0.1%,

Table 2. Efficiency at the PV cell operating temperature and maximum efficiency of the simple hybrid system with various reflectance (R) in the range between 0.05–0.15

	R (Reflectance)				
Efficiency	5%	7.5%	10%	12.5%	15%
Efficiency [%] at temperature 80 °C	31.20	30.88	30.56	30.23	29.91
Maximum efficiency [%] (Temperature [°C])	31.20 (80–81 °C)	30.88 (79–80 °C)	30.56 (78 °C)	30.24 (76–78 °C)	29.92 (75—76 °C)

Table 3. Efficiency at the PV cell operating temperature and maximum efficiency of the simple hybrid system with various radiation loss (r_{loss}) in the range between 0.3–0. 5

	r_{loss} (Radiation loss)		
Efficiency	30%	40%	50%
Efficiency [%] at temperature 80 °C	34.09	32.32	30.56
Maximum efficiency [%]	34.13	32.33	30.56
(Temperature [°C])	(91–93 °C)	(84–86 °C)	(78 °C)

various ZT_{ave} of the TE generator have been applied to this model to find the relationship between maximum efficiency of the hybrid system and ZT_{ave}. As shown in Table 1, when $ZT_{ave} = 1.1$, the maximum efficiency (31.008%) can be obtained at the PV cell operating temperature. For the calculation of efficiencies in Table 1, equations (3), (5) and (6) have been used. Therefore, as expected a new material for a TE generator which has ZT_{ave} value more than 1.1 may contribute to obtaining the higher solar energy conversion efficiency. In addition, in order for this model to be suit to design the hybrid system, the heat sink should be very effective to cooling down the TE generator. Otherwise, contribution of the TE generator will decrease, and it would not be effective to combine the PV cell and the TE generator to increase the conversion efficiency of solar energy. In addition, the influence of the reflectance (R) and radiation loss (r_{loss}) at the front side of the PV cell on the total efficiency was investigated as seen in Tables 2 and 3. In both cases β and ZT_{ave} were set to be 0.1% and 1, respectively. All other conditions were the same. As seen in Tables 2 and 3, total efficiency increased as both parameters decreased as expected. Comparing with the effect of the reflectance, the radiation loss is more effective to total efficiency.

Conclusion

The overall efficiency of the hybrid PV-TE system to improve conversion efficiency of solar energy has been investigated based on the theories and experimental results. For practical usage, reflectance and thermal radiation loss at the front side of the PV cell were taken into account. The simple structure of the hybrid system does not have any concentrators. Even though the overall efficiency was less than that without considering reflectance and/or thermal radiation loss, efficiency of the TE generator is 9.4%, and its contribution to the overall efficiency was 0.352. The effect of material properties of the PV cell and TE generator on the efficiency was explored to find the optimum design of the hybrid system. To gain higher efficiency at 80 °C, the temperature coefficient of efficiency and figure of merit of the thermoelectric generator were less than 0.1 and more than 1.1, respectively. In practical use, the heat sink should be cautiously designed to maintain the low temperature on the cold side of the TE generator.

Acknowledgements

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