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Numerical parametric study on the performance of CPV-TEG hybrid system

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Abstract

The influence of the thermal contact resistance on a hybrid concentrated photovoltaic-thermoelectric generator (CPV-TEG) system has been investigated. A steady-state one-dimensional numerical model is developed. Governing equations are derived using the energy conversion law for each component in the CPV-TEG hybrid system. Power generation and efficiency of the CPV and TEG are obtained for different solar concentrations and heat transfer coefficients, provided by the heat sink, varying between 100 suns to 900 suns and 500 $W/(m^2K)$ to 5000 $W/(m^2K)$, respectively. Thermal contact resistance as a key parameter in real applications is considered in the simulation to check the sensitivity of the output power and efficiency of the system to the thermal resistance. The results show the substantial effect of the heat sink effectiveness, solar concentration and thermal contact resistance on the performance of the hybrid system.

Keywords: Hybrid CPV-TEG System; Thermal Contact Resistance; Solar Concentration, Convective Heat Transfer Coefficient.

1. Introduction

Utilizing solar energy as a clean and unlimited source of energy is one of the promising ways to reduce using traditional fossil fuels that have many environmental and public risks like global warming. Concentrated photovoltaic cells can convert more than 40% of the solar energy to the electricity [1-2]. Even with using the CPV

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cells, more than half of the input energy is wasted. Harvesting this waste heat can be done by TEGs. TEGs have no moving parts and are highly reliable and also have a long lifetime and almost no maintenance cost. These special features make TEGs interesting and suitable for different applications [3-5]. The feasibility of using TEGs in hybrid PV-TEG systems has been investigated in many studies, but the CPV-TEG systems have been considered less in the literature. Urbiola et al. [6] considered the performance of different hybrid systems generating electricity with using the TEGs and under concentrated and non-concentrated solar radiations. They found that with the existing TEG elements some of the hybrid systems can be applicable, but some others can become practical if new TEG and PV materials are developed in future. Rezania et al. [7] developed a thermally coupled model of a PV-TEG hybrid system exposed under different real ambient conditions. The results showed that with the existing TEG materials, the contribution of the TEG in power generation by the hybrid system is not significant while it can be improved by using TEG materials with higher values of the figure of merit.

Sark [8] established a simple model to predict the efficiency of a hybrid PV-TEG system. The results indicate that with attaching a TEG behind a PV module, the efficiency can be enhanced 8-23%. This increment depends on the type of the module integration. Kwan and Wu [9] presented a theoretical analysis of the performance of a hybrid PV-TEG system working in outer space and then optimized the design of the TEG system. They found that in the space applications TEG has a substantial impact on the power generation by the hybrid system. Kossyvakis et al. [10] studied experimentally and theoretically the performance of a hybrid PV-TEG system using poly-Si and dye-sensitized solar cells. TEGs with different thermoelement geometries were used in their study. The results indicated that using shorter thermoelements increases the overall performance of the hybrid system.

The effect of the illumination level and the temperature as two key parameters in a hybrid PV-TEG system is examined by Cotfas et al. [11]. The results indicated that by using the TEG module, the temperature of the PV cell decreases and consequently, the output power by the PV enhances. Lamba and Kaushik [12] presented a numerical study including all primary and secondary effects of the TEG module. The influences of different parameters like concentration ratio, solar irradiance, and the number of thermoelements of the TEG, on the performance of the hybrid system, was investigated. The results showed that the efficiency of the hybrid PV-TEG system is 13.37% more that PV-only system for the concentration ratio 3 and number of thermoelements 127.

A hybrid system including multijunction PV cells, TEGs, and a flat plate solar collector was experimentally studied by Cotfas et al. [13]. The hybrid system was examined under different illumination levels. The results showed that the maximum output power by the TEG decreases significantly when it works under load resistance. A numerical model for the transient response of the CPV-TEG hybrid system was developed by Mahmoudinezhad et al. [14-15]. The results indicate that by increasing the solar radiation, the efficiency of the CPV decreases while the efficiency of the TEG enhances. It is also found that using TEG in such hybrid system leads to having more stable output power. Rezania and Rosendahl [16] presented a steady-state one-dimensional model without considering the thermal contact resistance effect. All the contacts were considered ideal, and the effects of other parameters were considered in this condition. They found that the TEG has a considerable contribution in power generation by the hybrid system, particularly at high solar concentrations.

In this study, a practical CPV-TEG hybrid model that is considering all primary and accessorial effects of the TEG has been developed. The impact of solar concentration and convective heat transfer coefficient in the heat sink as two main external parameters has been investigated. In the real industrial and research applications, thermal contact resistance has a huge effect on the performance of the systems. The efficiency and power generation by the TEG and CPV for the ideal system with no thermal contact resistance is compared with the system with thermal contact resistance varying in a realistic range.

2. Modeling and simulation analysis

Figure 1 shows the schematic of the one- dimensional heat transfer physical model. Energy conservation law is applied to each layer in the hybrid system to obtain the thermally coupled governing equations. The CPV and TEG are assumed to be thermally insulated except the radiative heat loss from the top surface of the CPV. For the top surface of the hybrid system with considering radiative heat loss, the corresponding equation is:

$$SC \times G \times A_{CPV} - Q_{rad} + KA\left(\frac{\partial T}{\partial x}\right) - P_{CPV} = 0 \tag{1}$$

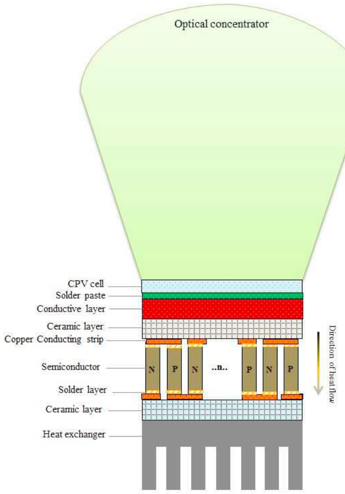

Figure. 1. One-dimensional physical model of the CPV-TEG system.

In this equation Q_{rad} is the radiative heat loss and P_{CPV} is the output power by the CPV and can be obtained as:

$$P_{CPV} = SC \times G \times A_{CPV} \times \eta_{CPV} \tag{2}$$

Where, η_{CPV} is the efficiency of the CPV that can be defined as a linear equation [17]:

$$\eta_{CPV} = \eta_{ref}\left[1 - \beta_{ref}\left(T_{CPV} - T_{ref}\right)\right] \tag{3}$$

η_{ref} and β_{ref} are the electrical conversion efficiency and temperature coefficient of the CPV at the reference temperature ($T_{ref} = 25°C$), respectively.

A Bi_2Te_3-based TEG is used in the simulation. All the TEG material properties are considered temperature dependent. For the equations through the TEG, all the primary and accessorial effects including Seebeck effect, Peltier effect, Thomson effect, Joule effect and Fourier effect have been considered in the equations. Owing to the phenomena of electron and phonon transportation in conductors and semiconductors, electrical current and heat flux are, generally, coupled and linear functions of the electric field and the gradient of temperature [18-19], i.e.:

$$\mathbf{J} = \sigma\mathbf{E} - \sigma\alpha\nabla T \quad \left(\frac{A}{m^2}\right) \tag{4}$$

$$\mathbf{q} = \pi\mathbf{J} - k\nabla T \quad \left(\frac{W}{m^2}\right) \tag{5}$$

Where, **E** and T are the electric field and temperature, respectively. α is the Seebeck Coefficient, π is the Peltier Coefficient, σ is the electrical conductivity and k is the thermal conductivity.

Applying the abovementioned equations for different layers of the TEG leads to having a set of non-linear thermally coupled equations the have to be discretized and solve together. Finite volume method [20] is used to solve these equations. In the heat sink, water is used as the working fluid, therefore, for the contact surface between heat exchanger base and the cooling fluid:

$$k_{hx}A_{hx}\left(\frac{\partial T}{\partial x}\right) + h_f A_f\left(T - T_f\right) = 0 \tag{6}$$

Solving all the obtained equations for different layers lead to having the temperature of different layers of the CPV-TEG hybrid system, and the efficiency and power of the TEG can be achieved as:

$$\eta_{TEG} = \left(\frac{T_H - T_C}{T_H}\right) \cdot \frac{\sqrt{1 + ZT_m} - 1}{\sqrt{1 + ZT_m} + (T_C/T_H)} \tag{7}$$

$$P_{TEG} = \eta_{TEG} \times (SC \times G \times A - Q_{rad} - P_{CPV}) \tag{8}$$

Where η_{TEG} is the efficiency of the TEG, P_{TEG} is the power generation by the TEG, Z is the figure of merit, T_H, T_C and T_m are the hot side, cold side and average temperatures of the TEG, respectively.

3. Results and discussion

The offered numerical model can determine the effect of different parameters on the performance of the CPV-TEG hybrid system. In this study, solar concentration and convective heat transfer of the heat sink as two crucial external parameters along with the thermal contact resistance as a key parameter in industrial design and practical application are considered. Solar concentration is varied between 100 to 900 suns (1 sun$=1000\ W/m^2$) and convective heat transfer and thermal contact resistance are changed between 500 to $5000\ W/m^2K$ and 5×10^{-6} and $5 \times 10^{-4}\ m^2.\text{°C}/W$, respectively.

Convective heat transfer in the heat sink plays a very crucial role in such hybrid system. Figures 2 and 3 show the power generation and efficiency of the CPV and TEG versus convective heat transfer and for the thermoelement length of $L = 1.5mm$ and constant solar concentration $SC = 300$ suns. As it mentioned before, in the real applications thermal contact resistance has a huge effect on the performance of the system. This substantial effect is displayed in the figures. Due to having higher cooling power, by increasing the convective heat transfer, power generation and efficiency of the CPV and TEG enhance as well. The reason is that by increasing the cooling power, the temperature of the CPV drops and consequently the power generation and efficiency increase. For the TEG, increasing the cooling power leads to have a higher temperature gradient across the TEG and therefore having more power and efficiency.

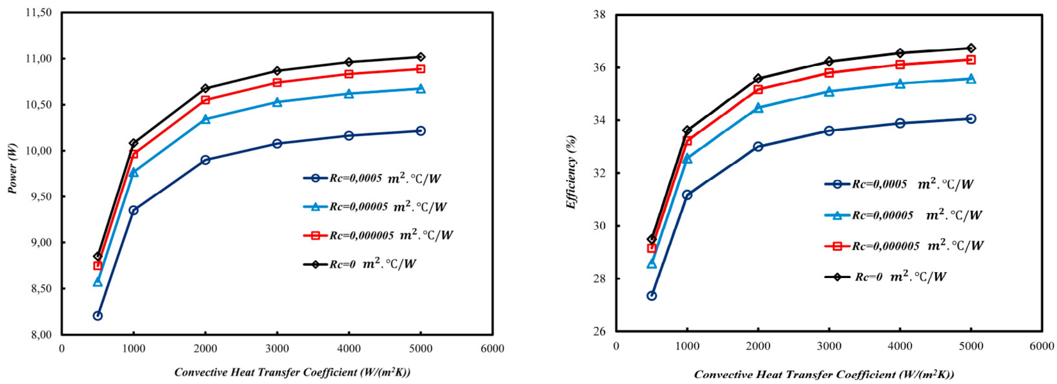

Figure. 2. Power generation and efficiency of the CPV versus convective heat transfer coefficient for different thermal contact resistances.

As can be seen in Figures 2 and 3, the rate of increasing the power and efficiency decrease by enhancing the convective heat transfer. Therefore, to reduce the costs in such this system, it would be better to use an optimum value for the convective heat transfer in the heat sink. Depends on the geometry and material properties and the design of the hybrid system this value can be changed.

Thermal contact resistance has a significant effect on the power generation and efficiency of the CPV and TEG. Comparing the values of the power of the CPV and TEG in Figures 2 and 3 shows that this effect in the TEG is more considerable.

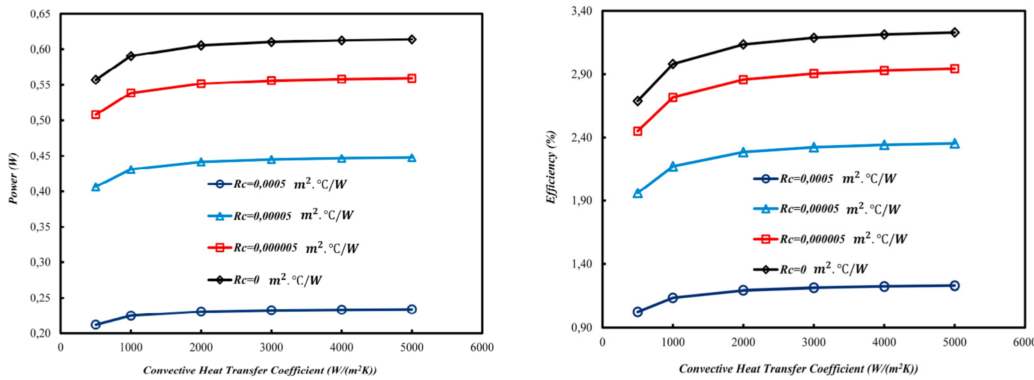

Figure. 3. Power generation and efficiency of the TEG versus convective heat transfer coefficient for different thermal contact resistances.

The impact of the solar concentration on the output power and efficiency of the CPV and TEG can be observed in Figures 4 and 5. In the simulation, the length of the semiconductors are considered $L = 1\ mm$ and convective heat transfer coefficient is $h = 2000\ W/(m^2K)$. Due to the increment of the input energy to the hybrid system, the both output power by the CPV and TEG increase by enhancing the solar concentration. As can be observed, by increasing the solar concentration, the efficiency of the CPV cell will drop dramatically because the temperature of the CPV increases significantly. The negative effect of the thermal contact resistance on the output power and efficiency of the CPV and TEG can be seen in all the figures.

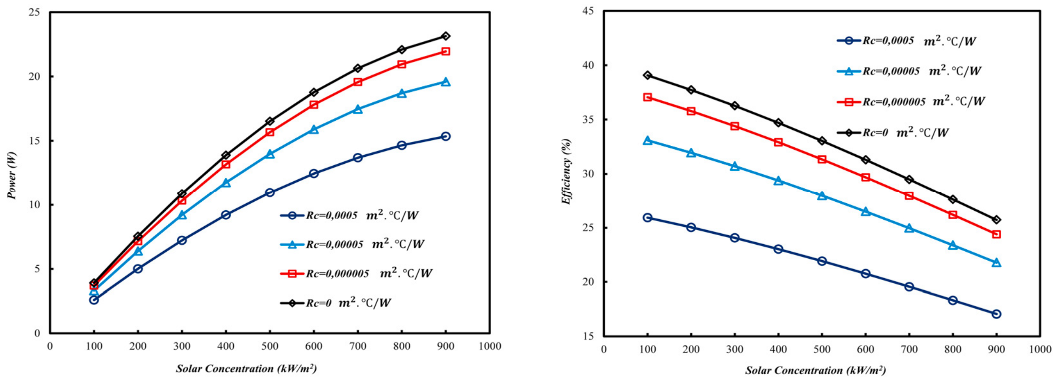

Figure. 4. Power generation and efficiency of the CPV versus solar concentration for different thermal contact resistances.

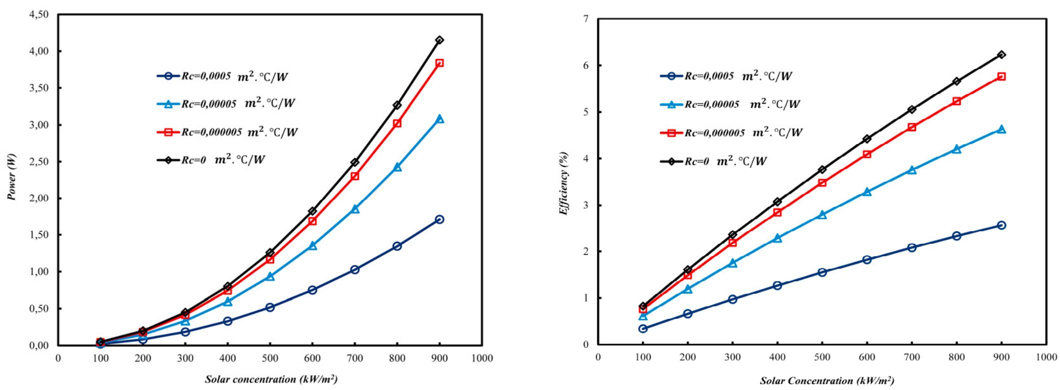

Figure. 5. Power generation and efficiency of the TEG versus solar concentration for different thermal contact resistances.

4. Conclusion

Performance of a hybrid CPV-TEG system is evaluated numerically. Energy conservation law is applied to obtain the governing equations for different components of the system, and the finite volume method is used to discretize and solve the thermally coupled equations. The impact of three vital parameters including convective heat transfer, solar concentration, and thermal contact resistance is examined. The results indicate that increasing the convective heat transfer leads to enhance in power generation and efficiency of the CPV and TEG. The rate of this increment drops in higher convective heat transfers, therefore to reduce the costs an optimum convective heat transfer has to be found. Increasing the solar concentration leads to having higher power for both CPV and TEG while the efficiency of the CPV drops at higher solar concentrations. The results show that the thermal contact resistance has a negative impact on the performance of both the CPV and TEG over studied convective heat transfer and solar concentration values.

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