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Analysis and discussion on the impact of non-uniform input heat flux on thermoelectric generator array

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ABSTRACT

The study on thermoelectric generator combined with the solar concentrator has increased rapidly in recent years. However, the solar concentrator inevitably causes the uneven distribution of the heat flux, which would significantly impact the performance of the thermoelectric generator array. This work presented the models of thermoelectric generators in series connection and parallel connection. Furthermore, series of experiments were made to verify the rationality of the model. In addition, the discussion based on the model was conducted to optimize the output power. The results indicated that for the thermoelectric generator array with the large heat flux gradient, which may be more effective and efficient to obtain higher output power through giving up lower heat flux part, which also can reduce the number of the thermoelectric generator modules. This work can be as a hint for the optimization of the solar thermoelectric generator.

1. Introduction

One of biggest challenge human faced in 21st century is energy crisis. With the ever decreasing reserve of the fossil energy, the new technology and the clear renewable energy seem to be promising ways. Solar energy used as heat source for thermoelectric generator (TEG) can be a nice try. Zhang et al. [1] have proposed a solar thermoelectric co-generator comprising evacuated tubular solar collectors and thermoelectric modules. Wu et al. [2] have analyzed the performance of a photovoltaic–thermoelectric hybrid system with and without glass cover. He et al. [3] have designed a solar heat pipe thermoelectric generator unit, and the parameters of this system were investigated. Then He et al. [4] have also made the simulation and experiment on the evacuated-tube heat-pipe solar collectors with thermoelectric modules. The results showed that that system has the electrical efficiency of 1–2%.

However, the direct use of the solar energy has a disadvantage of the low heat flux. In order to increase the input heat flux, the solar concentrator is a good choice. Chen et al. [5] have studied a thermal-concentrated solar thermoelectric generator. The result shows that a maximum system efficiency of 4.15% can be obtained with the thermal concentration ratio of 190×. And the performance can be improved by decreasing the cross-sectional area of the thermoelectric element. Muthu et al. [6] have analyzed a solar parabolic dish thermoelectric generator with acrylic cover. An efficiency of 1.68% is achieved at the solar beam radiation of 1050 W/m^2. Li et al. [7] have investigated the influence of environmental factors on the conversion efficiency of solar thermoelectric co-generators comprising parabola trough collectors and thermoelectric modules. The results show that solar insolation, atmospheric temperature and wind velocity have great impact on the performance and the solar conversion efficiency decreases with those factors increase. Kraemer et al. [8] have studied the solar thermoelectric generators with an optical concentrator system for terrestrial applications. The results illustrate that a peak efficiency of 5% can be obtained at the standard spectrum AM1.5G. Xiao et al. [9] have analyzed and optimized the performance of a solar thermoelectric generator. The results show that with the temperature difference increasing from 0 °C to 200 °C, the conversion efficiency rises from 0% to 10.82%, respectively. Olsen et al. [10] have proposed a prototype of solar thermoelectric generator which declares to have an efficiency of 15% at the temperature across TH–TC = 1000–200 °C. Amatya et al. [11] have studied a solar thermoelectric generator with the solar concentrator of Fresnel lens for micro-power applications. The result shows that a system efficiency of 3% can be obtained by a commercial Bi_2Te_3 module with output power of 1.8 W. Fan et al. [12] have designed an electric power generation from thermoelectric cells using a solar dish concentrator. Nia et al. [13] have combined thermoelectric module and Fresnel lens for the cogeneration solar system which has 2–3% the electrical efficiency.

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Nomenclature

Symbols		*Subscripts*	
A	area, m^2	1	TEG#1
Q	heat flux, W	2	TEG#2
T	temperature, °C	3	TEG#3
I	current, A	*oc*	open circuit
V	voltage, V	*in*	internal resistance
α	seebeck coefficient, V/°C	*load*	load resistance
λ	thermal conductivity, W/(m °C)	*H*	hot side
R	resistance, Ω	*L*	cold side
L	length, m	*am*	ambient

However, whatever the type of the common solar concentrator is, it inevitably causes the non-uniform of the radiation which makes the uneven heat fluxes, such as the dish concentrator, the trough concentrator and Fresnel concentrator. Many researchers have investigated these features based on different optical structures. Johnston et al. [14] analyzed the optical performance of the spherical reflecting elements for use with paraboloidal dish concentrators. Li et al. [15] used the Monte-Carlo ray-tracing method to predict the radiation flux distributions of the concentrator–receiver system. Huang et al. [16] predicted the performance of the parabolic solar dish concentrator with sphere receiver using analytical function. Reddy et al. [17] proposed the suitable design of absorber/receiver based on the focal image characteristics of the solar dish. Cooper et al. [18] indicated the flux distribution of the compound parabolic concentrators with series of polygonal apertures. Li et al. [19] presented the optical analysis of the parabolic dish solar concentrator with a cavity receiver. Tang and Liu [20] analyzed the optical performance of V-trough concentrators for photovoltaic applications. Bojić et al. [21] analyzed the optical performances of sea-shell trough solar concentrators. Wirz et al. [22] improved the optical and thermal efficiencies of parabolic trough concentrators. Kunnemeyer et al. [23] also indicated the performance of a V-trough photovoltaic/thermal concentrator. Guiqiang et al. [24] investigated the non-uniformity of the flux distribution of the CPCs. Abbas et al. [25] studied the solar radiation concentration features in Linear Fresnel Reflector arrays which showed the specific different radiation intensity on the receiver. Chemisana et al. [26] also indicated the characterization of Fresnel lens optical performances using an opal diffuser. Zhu and Huang [27] revealed that the uniformity of the radiation distribution is stronger for the focus length 3000 mm compared with that of focus length 1700 mm based on the semi-parabolic linear Fresnel reflector solar concentration collector. And the non-uniform of the heat flux usually would further affect the performance of the TEGs. In addition, it also needs to be mentioned that the TEGs should be in arrays of series connection and/or parallel connection to satisfy the current and/or voltage of the load requirement. Thus the study on the effect of mismatch input heat flux on thermoelectric generator modules arrays with different kinds of interconnection ways is very important for the assessment and optimization of the TEGs array, but there are still few researches on it.

Therefore, in this paper, the models of TEGs in arrays of series and parallel connection under different heat fluxes have been constructed respectively. In order to certify those models, a preliminary experiment is setup to compare to the simulation results. Then the certified model is employed to compare the performance of TEGs array under different heat flux condition. Eventually an optimization of the number of the TEG modules in array under the inhomogeneous heat flux condition has been obtained via the comparison. This work can be as a hint for the optimization of the solar thermoelectric generator (STEG).

2. Model

The thermoelectric generator can directly convert the heat into electricity based on Seebeck effect. The TEG array usually consisted by many TEG modules that appears as the integrated unit. To obtain the current and/or the voltage required, the modules are in arrays of series connection and/or in parallel connection. The type of the interconnection is determined by the load.

2.1. Single TEG module

Fig. 1(a) is a schematic diagram of the TEG module. The hot side gains the Q_H from the heat sources. The cold side rejects the heat flux, named Q_L, to the environment. The internal resistance of the TEG is considered to be $R_{in.}$ Eq.(1) is the heat balance of the hot side of the TEG. Eq. (2) is the heat balance of the cold side of the TEG [28].

$$Q_H = \alpha T_H I + \frac{\lambda A}{L}\Delta T - \frac{1}{2}I^2 R_{in} \tag{1}$$

$$Q_L = \alpha T_L I + \frac{\lambda A}{L}\Delta T + \frac{1}{2}I^2 R_{in} \tag{2}$$

The waste heat rejected from the cold side are eventually dissipated which can be described as Eq. (3)

$$Q_L = K(T_L - T_{am}) \tag{3}$$

where ΔT is the temperature difference across the hot side and cold side of the TEG module.

$$\Delta T = T_H - T_L \tag{4}$$

The current in the module can be expressed by;

$$I = \frac{V_{oc}}{R_{in} + R_{load}} \tag{5}$$

The voltage of the open circuit can be calculated via;

$$V_{oc} = \alpha \Delta T \tag{6}$$

The maximum power transfer theorem shows that maximum output power can be obtained if the load resistance R_{load} equals to the internal resistance R_{in}.