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Investigation on the effect of thermal resistances on a highly concentrated photovoltaic-thermoelectric hybrid system

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ABSTRACT

A thermal analysis of a highly concentrated photovoltaic-thermoelectric (PV-TE) hybrid system is carried out in this paper. Both the output power and the temperature distribution in the hybrid system are calculated by means of a three-dimensional numerical model. Three possible approaches for designing the highly concentrated PV-TE hybrid system are presented by analyzing the thermal resistance of the whole system. First, the sensitivity analysis shows that the thermal resistance between the TE module and the environment has a more great effect on the output power than the thermal resistance between the PV and the TE. The influence of the natural convection and the radiation can be ignored for the highly concentrated PV-TE hybrid system. Second, it is necessary to sandwich a copper plate between the PV and the TE for decreasing the thermal resistance between the PV and the TE. The role of the copper plate is to improve the temperature uniformity. Third, decreasing the area of PV cells can improve the efficiency of the highly concentrated PV-TE hybrid system. It should be pointed out that decreasing the area of PV cells also increases the total thermal resistance, but the raise of the efficiency is caused by the reduction of the heat transfer rate of the system. Therefore, the principle of minimizing the total thermal resistance may not be suitable for optimizing the area of PV cells.

1. Introduction

The photovoltaic cell (PV) is one of the dominant approaches of converting solar energy into electricity. However, only photons with energy larger than the bandgap energy can be utilized by the PV [1] and the remainder of the incident solar photons cannot excite electron-hole pairs to generate photocurrent. The lattice can capture energy from the carriers generated by the photons with energy higher than the band-gap energy by the thermalization process. Due to these two reasons, most of the solar energy is converted into heat [2]. The thermoelectric generator (TE) can convert heat into electricity via the Seebeck effect [3,4]. Therefore, the PV-TE hybrid system is an effective way to utilize solar energy in full spectra and can obtain a higher efficiency [5,6].

There have been some literatures about the design of the PV-TE hybrid system. By using a heat collector to collect waste heat from PV and the solar energy reflected by the PV, the total generated power of the PV-TE hybrid system was twice larger than that of the silicon thin-film PV [7]. The analysis of thermal losses for the PV-TE hybrid system revealed that the output power depends on the optical characteristics of the absorber [8]. Embedding a planar fishnet structure in the back passivation layer of the solar cell could enhance the solar thermal absorption, and improve the efficiency of the PV-TE hybrid system [9]. The performance of the hybrid system consisting of $CuInGaSe_2$ (CIGS) PV and TE could be improved by covering the PV with a passive light-trapping structure [10]. The thermal concentration was proved to be a key factor of the PV-TE hybrid system [11]. The introduction of the TE to the photovoltaic system was an effective method to obtain a higher output power [12]. A theoretical analysis showed that the PV-TE hybrid system is more suitable for the regions having high irradiance [13]. Makki et al. [14] used a heat pipe to transfer the waste heat from the PV cells to the TE module. The concentration ratio of the PV-TE hybrid system was optimized by Lamba and Kaushik [15]. Kossyvakis et al. [16] tested the performance of the PV-TE hybrid system under real operating conditions. The phase change material was introduced in the PV-TE hybrid system to mitigate the temperature fluctuations [17]. The geometry factors of the TE module were optimized to improve the efficiency of the PV-TE hybrid system [18]. Lee et al. [19] used highly conductive PEDOT:PSS film as the TE module to increase the output power of the organic solar cell. Da et al. employed the bio-inspired moth-eye nanostructured surface to improve the light absorption of the PV-TE hybrid system [20].

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Nomenclature

A	area (mm^2)
c_p	specific heat ($J\,kg^{-1}\,K^{-1}$)
e	emissivity of the PV
H	height (m)
J	electric current density ($A\,m^{-2}$)
k	thermal conductivity ($W\,m^{-1}\,K^{-1}$)
K	turbulence kinetic energy ($m^2\,s^{-2}$)
m	flow rate ($m^3\,s^{-1}$)
O	optical concentrating ratio
P	output power (W)
p	total pressure (Pa)
q	heat flux ($W\,m^{-2}$)
Q	heat transfer rate (W)
r	thermal contact resistance per unit area ($m^2\,K\,W^{-1}$)
R	thermal resistance ($K\,W^{-1}$)
S	Seebeck coefficient ($V\,K^{-1}$)
T	temperature (K)
u	the velocity of the fluid (m/s)

Greek letters

α	solar absorptivity
β	temperature coefficient (‰ K^{-1})
δ_{SB}	Stefan–Boltzmann constant ($5.67 \times 10^{-8}\,W\,m^2\,K^4$)
ε	dissipation rate of the turbulence ($m^2\,s^{-3}$)
ζ	sensitivity ($W^2\,K^{-1}$)
η	efficiency
μ	viscosity ($kg\,m^{-1}\,s^{-1}$)
ρ	density ($kg\,m^{-3}$)
σ	electrical conductivity ($S\,m^{-1}$)
ψ	electrostatic potential (V)
Ω	electrical resistance (Ω)

Subscripts

a	ambient
C	cooling system
c1	contact between the photovoltaic cell and the copper plate
c2	contact between the copper plate and the upper ceramic plate
c3	contact between the heat sink and the lower ceramic plate
Cu	copper plate
H	natural convection
I	thermal insulator
in	inlet of the cooling system
out	outlet of the cooling system
P1	plate 1
P2	upper ceramic plate
P3	lower ceramic plate
PV	photovoltaic cell
PV_TE	region between the photovoltaic cell and the thermoelectric generator
r	radiant
s	solar
TE	thermoelectric generator
TE_a	region between the thermoelectric generator and the environment

Due to the high potential of the PV-TE hybrid system, much attention has been paid to the model of the hybrid system. A model was developed to study the feasibility of PV-TE hybrid system, the efficiency of the PV was calculated by assuming a linear temperature dependence [21]. A more detailed model was proposed by considering the effect of the heat loss caused by reflection, radiation and convection [22]. The effect of the solar irradiance on the efficiency was modeled by using an equivalent circuit of the PV [23]. The cooling system is important to the hybrid system, therefore the model of the fin was introduced for a more accurate calculation of the hybrid system efficiency [24]. The hybrid system consisting of a dye-sensitized solar cell and a TE was modeled by using a constant temperature coefficient [25]. A model that considers the effect of the energy gap and the working temperature of the solar cell was developed to study the PV-TE hybrid system [26]. Wu et al. [27] established a model to study the effect of the glass cover on the efficiency of the PV-TE hybrid system. The influences of irreversible losses and load resistances were investigated in the model proposed by Lin et al. [28]. Kwan and Wu [29] considered the outer space scenario in their model. The maximum power point tracking system was studied in the model developed by Verma et al. [30].

Most of the previous papers paid their attention to the feasibility of the PV-TE system. However, few people study the influence of the thermal resistances on the performance of the hybrid system. In fact, there are many thermal resistances in the PV-TE hybrid system, for example, the thermal resistances of the natural convection and radiation at the surface of the PV, the thermal resistance between the PV and the TE (R_{PV_TE}), the thermal resistance between the TE and the heat sink (R_{TE_a}). The temperature differences caused by R_{PV_TE} and R_{TE_a} are harmful to the output power of the hybrid system. Increasing the thermal resistance of the natural convection at the surface of the PV and the thermal resistance of the radiation can reduce the heat transferred from the top side of the PV to the environment; as a result, more heat can be utilized by TE. Therefore, it is very important to analyze the thermal resistances of the PV-TE hybrid system and find methods to optimize these thermal resistances.

The performance of the non-concentrated PV-TE hybrid system has been widely studied. However the literatures related with the highly concentrated PV-TE hybrid system are fewer. Because a solar energy concentrating system leads to a high heat flux, the thermal design of the non-concentrated PV-TE hybrid system may not be directly suitable for the highly concentrated PV-TE hybrid system. Therefore it needs to pay some special attentions to the thermal design of the highly concentrated PV-TE hybrid system.

In this paper, a thermal model is developed for the highly concentrated PV-TE hybrid system. The thermal resistance of each part of the hybrid system has been analyzed to find out an effective way to improve the performance of the system. The sensitivity analysis is used to study the influences of different thermal resistances. Some methods of decreasing the thermal resistance are used to improve the output power of the highly concentrated PV-TE hybrid system.

2. Models

Fig. 1 shows the schematic diagram of the PV-TE hybrid system. The hybrid system is consisted of five parts: the PV cell, plate 1, the TE generators, the heat sink and the thermal insulator. The TE is placed between the PV cell and the heat sink. The fluid cooling system is attached to the back of the TE generators. The concentrated sunlight is incident on the PV cell. Part of the concentrated sunlight is absorbed by the PV cell and the remaining part is reflected back