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Inconsistent phenomenon of thermoelectric load resistance for photovoltaic–thermoelectric module

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ABSTRACT

Combing PV with Thermoelectric (TE) would be dominant because it can employ the solar fully spectrum to produce electricity. But the TE efficiency is significantly lower than PV efficiency and the coupling effect between them will limit the performance of PV and TE. The analyze and comparison on the different characteristics among the hybrid module, the PV alone and TE alone is significant to obtain the highest the electrical efficiency. In this paper, the attention was paid to the inconsistent phenomenon of thermoelectric load resistance for photovoltaic–thermoelectric modules. The model of PV-TE was built and verified based on two types of PV cells. The load resistance of TE for the maximum power output was also analyzed under different working conditions for the TE alone, TE in the PV-TE and PV-TE. The results showed that the load resistance of TE for the maximum power output of the TE alone, TE in the PV-TE and PV-TE are all different. For example, the PV-TE module based on the c-Si cell attains its peak value at the load electrical resistance of TE of 0.75 Ω, while the internal electrical resistance of the TE is 0.47 Ω. The PV-TE module based on the GaAs cell shows a maximum efficiency of PV-TE with a load resistance of approximately 1.6 Ω, while the internal electrical resistance of the TE is 2.0 Ω. Referring to the load resistance of TE alone is not suitable for PV-TE maximum power output. In addition, the TE maximum power output does not correspond to the PV-TE maximum power output since the TE load resistances in these two conditions are also different. The study will provide the reference for attaining the correct load resistance for the actual maximum power output of PV-TE module.

1. Introduction

Photovoltaic (PV) is one of the most common and commercialized ways for electrical generation [1]. With the PV technology development, PV efficiency has been increased significantly, but it is still limited since the conventional materials can only effectively convert photons of energy close to the semiconductor band gap. Therefore, researchers are paying more attention on ways of utilizing a wider solar spectrum to produce more electricity.

Thermoelectric (TE) technology can directly convert heat into electricity due to the Seebeck effect. Similar to PV, it has the advantages of no noise, no pollution, no moving parts, etc. [2]. In fact, by contrast the solar energy that cannot be absorbed by PV will be converted into the heat and even negatively affect PV efficiency. Thus the combination the PV and TE may be a good way to produce more electricity based on the full solar spectrum. Van Sark analyzed the feasibility of hybrid PV-TE modules, and found the overall efficiency and annual energy yield would all increase [3]. Lamba and Kaushik built a model and indicated the performance of a concentrated PV-TE hybrid power generation system [4]. Wang et al. designed a novel PV–TE hybrid device employing the dye-sensitized solar cell (DSSC), which gave rise to an overall conversion efficiency larger than 13% [5].

However, it is also possible that the efficiency of the PV-TE is lower than that of the PV alone [6]. The higher temperature will increase the TE efficiency but decrease the PV efficiency, so the coupling relationship between the PV and TE is complex, which can affect the performance of PV and TE. Pang et al. studied the impacts of the heat sink for PV-TE [7]. Zhu et al. optimized the thermal management for the high-performance photovoltaic-thermoelectric hybrid power generation system [8]. Zhang and Chau proposed a PV–TE hybrid system for automobiles and optimized the power output with maximum power point tracking (MPPT) technique [9,10]. Zhang et al. described the integration of polymer solar cell and TE module for doubling energy harvesting and increasing the open-circuit voltage [11]. Park et al. simulated and tested a lossless hybrid design through matching the internal resistance of TE to convey photocurrents without sacrificing the PV fill factor, and results showed an increase of conversion efficiency by ∼30% [12].

Generally speaking, for the TE alone, when the load electrical

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Nomenclature

A	area of PV (m^2)
C	concentration ratio
C_p	specific heat of air (KJ/(kg K))
E_{pv}	power of the solar cell (W)
E_{in}	incident solar energy (W)
G	solar radiation (W/m^2)
h_{rad}	coefficient of radiation heat transfer (W/(m^2 K))
h_{wind}	coefficient of radiation heat transfer (W/(m^2 K))
H	height of heat sink (m)
I	current (A)
K	total thermal conductance of a TE module (W/K)
K_{fin}	thermal conductivity of the fin (W/K)
L	length of the heat sink (m)
P_{teg}	power of the load resistance (W)
Pr	Prandtl number
Q_{flow}	energy that flowed from solar cell to hot side of the TEG
Q_h	energy that passed in hot side of the TEG (W)
Q_l	energy that passed in cold side of the TEG (W)
R_{conv}	thermal resistance of convection heat transfer between heat sink and ambient air (K/W)
R_{conf}	thermal resistance of the heat conduction in heat sink(K/W)
R_{fin}	thermal resistance of the heat sink (K/W)
R_{ct1}	thermal contactresistance between solar cell and TEG (K/W)
R_{ct2}	thermal contactresistance between heat sink and TEG (K/W)
R_{TE}	electric resistance of TE (Ω)
S_1	cross section area of the heat sink (m^2)
S_2	total area of the fin (m^2)
T_a	temperature of ambient air (K)
T_c	temperature of PV (K)
T_h	temperature of the hot side of TEG (K)
T_l	temperature of the cold side of TEG (K)
T_{sky}	temperature of sky (K)
u_f	wind speed (m/s)
α	Seeback coefficient (V/K)
σ	Stefan-Boltzmann constant (W/(m^2 K^4))
ε	emissivity of the PV
η_c	photoelectric efficiency at standard condition
ϕ_c	solar cell temperature coefficient
ρ	density of air (kg/m^3)
μ	kinematic viscosity (m^2/s)

resistance equals to or is slightly higher than the internal electrical resistance, the maximum power output can be obtained [13–15]. However, for the hybrid PV-TE module, it may be different from the TE alone operation, and the optimized working temperature may not match the load resistance as the same as that with which the TE alone has the maximum power output, since the factors of PV efficiency and the effect each other need to be considered. In addition, for the PV-TE module, even if the load resistance matches the TE maximum power output, one may not match the PV-TE maximum power output, and the inconsistent phenomenon of the TE load resistance may occur. Therefore, the verification of the inconsistent phenomenon and the analysis on it would be of befit for distinguishing the load resistances in different conditions, and for obtaining the actual PV-TE maximum power output. However, at present, there are few studies on the inconsistent phenomenon of the load resistances in the hybrid module.

Therefore, in this paper, the inconsistent phenomenon of TE load resistance for PV-TE maximum power output is introduced. The model of the PV-TE is built then the simulation outcome is verified and the migration phenomenon is indicated. In addition, based on two types of the PV cells, the migration phenomenon on different environmental conditions is also discussed. The paper also provides the reference on the load resistance optimization to obtain the higher efficiency for PV-TE application.

2. Mathematical model

2.1. PV-TE module description

The PV-TE module is shown in Fig. 1. The sunlight can be concentrated by the solar concentrator, then part of this energy will be absorbed by the PV. The excess energy can be converted into the heat to be transferred to the TE. This creates a temperature gradient across the TE module, thus resulting in a thermal to electrical conversion. At last, the remaining thermal energy will be dispatched to the heat sink.

This study is intended to analyze the steady state performance of the PV-TE module, and the following assumptions are adopted to simplify the problem.

- The energy balance equations are all on the steady state conditions.
- The analysis is based on the one dimensional heat transfer.
- The solar flux distribution and temperature distribution on the PV top surface are uniform.
- The energy loss through around the side of the module is ignored.
- The internal electrical resistance of the TE is considered as an approximate constant [16–18].

2.2. Model

The energy transfer process of the PV-TE module is shown in Fig. 2. According to the energy balance, the energy balance equation of the PV can be expressed as below,

$$E_{in} = E_{pv} + h_{rad}A(T_c - T_{sky}) + h_{wind}A(T_c - T_a) + Q_{flow} \quad (1)$$

where E_{in} is the solar energy absorbed by the PV-TE module. E_{pv} is the PV electrical output. h_{rad} is the radiation heat transfer coefficient. h_{wind} is the convective heat transfer coefficient. Q_{flow} is the thermal energy transferred from the PV into TE.

E_{in} can be expressed as

$$E_{in} = CGA\alpha_c \quad (2)$$

where C is the solar concentration ratio, and G is the solar radiation. A is the area of PV. α_c is the absorptivity of PV.

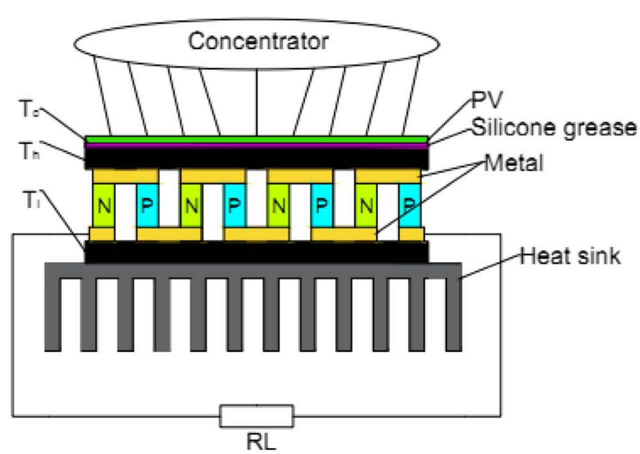

Fig. 1. Schematic diagram of the PV-TE module.