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Behavior of hybrid concentrated photovoltaic-thermoelectric generator under variable solar radiation

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ABSTRACT

Transient response of a hybrid system composed of concentrated photovoltaic (CPV) cell and thermoelectric generator (TEG) is investigated in this study. This research is carried out by using a numerical simulation approach thermally coupled between the CPV and TEG. A transient model is established and solved by finite volume algorithm. In spite of temperatures profile in the hybrid CPV-TEG module, as results of variation of solar irradiation, power generation and efficiency of the CPV and TEG under the transient condition are presented. The results show that efficiency of the TEG and CPV varies diversely versus changing the solar radiation and module temperature. Moreover, the thermal response of the TEG stabilizes temperature fluctuation of the hybrid module when the solar radiation rapidly changes. In this work, impact of the thermal contact resistance on the temperature profile and system efficiency is investigated. The model presented in this study provides a fundamental understanding of the thermal and electrical effect of the TEG in hybrid CPV-TEG module under transient conditions.

1. Introduction

With growing population in the world and progress in technology and industry, additional energy sources are needed to be added to the existing energy reserves. Sun is an infinite source of energy, and fortunately, solar energy is a free, clean and abundant source of energy. Concentrated photovoltaic (CPV) cells are solar-based power generating cells which can convert a fraction of solar radiation into electricity with higher efficiency than conventional photovoltaic (PV) cells. Even CPVs dissipate more than half of the solar radiation as wasted thermal energy. By harvesting the dissipated heat into electricity, the efficiency and power generation of the system can be enhanced.

Due to some particular aspects like having no moving parts and long lifetime, being highly reliable, silent operation and being environment-friendly [1] thermoelectric generators (TEGs) have been a good choice for energy harvesting through the direct recovery of waste heat and conversion into useful electrical energy [2–4]. Most of the studies in the area of hybrid photovoltaic-thermoelectric systems considers integration of conventional PV modules with the TEG [5–8], while charectristics of CPV-TEG hybrid systems are examined less in the literature. Hybrid systems have been investigated using both numerical and experimental approaches [5–7]. Rezania et al. [9] found that a combined PV-TEG system is not an appropriate choice for power generation especially when the PV performance drops with increasing the temperature. They indicated that, with existing thermoelectric materials, the power generation by TEG plays only a small role in power generation in the hybrid PV-TEG panel. However in another investigation, Rezania and Rosendahl [10] showed that by increasing the solar radiation and with optimal geometry and material of the TEG, the hybrid CPV-TEG systems can be suitable, applicable and economically reasonable system. Wu et al. [11] presented a thermal and electric theoretical model for glazed/unglazed PV-TEG hybrid system.

A performance comparison between glazed and unglazed system was given. External parameters, such as wind velocity and nanofluid flow rate were investigated, and it was found that the variation of crucial factors can lead to a different system behavior. They also found that, for certain thermoelectric modules, a higher figure of merit, Z, may still cause a reduction in the system overall efficiency. Different aspects of CPV-TEG hybrid systems have been studied with different methods [12–20]. A hybrid system composed of a multi-junction PV cell and a TEG has been investigated experimentally by Beeri et al. [12].

Multi-physics software e.g. Comsol Multiphysics have been used for estimation of the complete influence of the TEG to the hybrid system performance. A theoretical thermodynamic model of an irreversible CPV–TEG hybrid system has been established by Lamba and Kaushik [13], where ideal concentration ratio based on the maximum power output of the hybrid system has been determined. Performance of different hybrid systems generating electricity and thermal energy using

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Nomenclature

Abbreviation

CPV	concentrated photovoltaic
PV	photovoltaic
SC	solar concentration
TE	thermoelectric
TEG	thermoelectric generator
ZT	figure of merit
EMF	electromotive force
PCM	phase change material
CS	contact surface

Greek script

α	seebeck coefficient, V/K
β	temperature coefficient, $\Delta\eta/\Delta T$, 1/K
ε	emissivity
η	conversion efficiency, %
σ	Stefan-Boltzmann constant, $W/m^2 K^4$
Δ	increment
τ	thomson coefficient, V/K
ρ	density (kg/m^3)
γ	electrical conductivity

Latin script

A	area, m^2
C	specific heat capacity, J/kg K
G	solar radiation, W/m^2
H	heat transfer coefficient, $W/m^2 K$
I	current, A
K	thermal conductivity, W/m K
L	length, m
n	number of thermocouples
P	power, W
q	inner heat source, W
Q	heat loss/heat transfer, W
r	resistance, Ω
T	temperature, K
x	heat transfer direction

Subscripts

1–12	contact surface numbers
a	ambient
c	cold junction
col	conductive layer
cel	ceramic layer
CPV	concentrated photovoltaic
f	cooling fluid
h	hot junction
hx	heat exchanger
ccs	copper conduction strip
max	maximum
rad	radiation
ref	reference
sky	sky
sp	solder paste
TEG	thermoelectric generator

Superscripts

b	the bottom contact surface
t	the top contact surface

TEGs for both non-concentrated and concentrated solar radiation cases has been investigated by Urbiola et al. [14] at relatively low temperatures (below 250 °C).

Ju et al. [15] studied an energy-based numerical model of spectrum splitting applied to PV-TEG hybrid system. Their results indicated that in comparison with the PV-only system the spectrum splitting PV–TE hybrid system is more appropriate for working under high concentration conditions. Energy analysis and exergy analysis approach was used by Li et al. [16] to study the performance of the PV-TE hybrid systems. The energy efficiency, exergy efficiency and the exergy losses of the PV-TE hybrid system were computed. The results showed that at higher concentration ratios and appropriate PV cell used in the PV-TE hybrid system can enhance the system overall conversion efficiency.

A parametric numerical study of the crucial factors in the CPV-TEG hybrid system is presented by Rezania and Rosendahl [10] with an energy cost comparison between CPV and CPV-TEG systems. The results indicated that the contribution of the TEG in power generation increases at high sun concentrations. To minimize energy cost, the optimal value of the heat transfer coefficient in the heat sink was obtained based on the critical design parameters of the CPV and the TEG. Heat flow and temperature distribution in a thermal concentrated PV-TEG hybrid system were investigated theoretically and numerically by Zhu et al. [17] in order to establish a cost and energy lumped model for evaluation of economic practicability of the hybrid technology.

Influence of different parameters like temperature, thermal contact resistance, concentrating ratio and convection heat transfer coefficient were investigated theoretically by Zhang et al. [18] for assessing the efficiency of a CPV-TEG hybrid system. They found that with the increase of cell temperature, the efficiency of polymer PV cell first enhances and then drops, which is appropriate for CPV-TEG hybrid systems. Liao et al. [19] found that the CPV-TEG hybrid system generates more electrical power and also has higher efficiency than a CPV or TEG. Li et al. [20] proposed a concentration solar thermoelectric generator design that used an improved theoretical model to calculate the maximum possible performance of the system.

This paper aims to provide a fundamental understanding of the fast transient behavior of CPV-TEG hybrid module throughout the investigation of the dynamic response of the CPV-TEG components in a hybrid module to the variation of solar radiation under partly cloudy weather conditions. As a matter of fact, since daily solar irradiance is varying with the time, the temperature of the CPV–TEG system, and consequently the power generation and efficiency of the system become unstable. To the best of our knowledge, none of the formerly published studies in this research area considered the transient behavior of the CPV-TEG hybrid system. This paper focuses on the significance of varying weather condition on temperatures, power generation and efficiency of the hybrid CPV-TEG system. This paper proposes an inclusive method to investigate the transient response of components of the hybrid CPV-TEG system to the every time-dependent solar radiation. Since effect of thermal contact resistance between the hybrid module layers can be critical on the system electrical output, influence of the thermal contact resistance at the interfaces between CPV-TEG and TEG-heat sink is, furthermore, evaluated.

2. Modeling and simulation analysis

Fluctuations of the weather condition, especially in the partly cloudy climates, and the effect of the variations on power generation