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Numerical simulation of a photovoltaic thermoelectric hybrid power generation system

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ABSTRACT

In this study, three dimensional numerical models for a PV module and a TEG device are developed. The objective is to investigate the performance of hybrid PV + TEG power generation systems composed of thermoelectric generators attached to the backside of a PV module. The proposed numerical model ignores the inner structural complexities and considers the device as a homogeneous medium. The electric power output is modeled as an internal energy sink. The governing energy equations are solved by finite volume method. User defined functions are developed to account for the electrical behavior of PV and TEG. Results show that the hybrid system can generate more power than the simple PV in certain environmental conditions. However, the increase is marginal due to the insufficient temperature difference for the TEG device. Also, the presence of TEG may have undesirable effects on cooling of PV module. Simulations are performed for different number of TEG modules and also various optical concentration ratios. It is revealed that the maximum power generation occurs at a certain concentration ratio which depends on the heat sink characteristics.

1. Introduction

Today, with the increasing importance of global climate change, application of novel and renewable energy technologies with less environmental effects has gained an important role in different countries. Energy resources are the most important factors of sustainable development. Deployment of renewable energy can reduce the dependency on fossil fuels and greenhouse gas emissions. Among different clean energy technologies, solar energy has a great potential to meet the future needs of the world. Up to now, different solar power generation methods have been developed including photovoltaic (PV) technology. Therefore, share of PV power generation is increasing drastically in recent years (Chow, 2010).

When a photovoltaic module is exposed to solar radiation, not all of the incident irradiation but a small fraction is converted to electricity. The remaining energy is absorbed and dissipated as heat. If a part of this thermal energy can be converted to electricity, the efficiency of the system improves. A photovoltaic cell mostly uses ultraviolet and visible range of the solar spectrum (200–800 nm), while a thermoelectric generator may use the infrared range (800–3000 nm). Combining photovoltaic and thermoelectric can widen the effective range. In fact, the temperature difference between the photovoltaic cell and the surroundings can be used to generate power by means of a thermoelectric generator. Thermoelectric generators (TEG) are based on Seebeck effect found by Tomas Seebeck in 1821 (Seebeck, 1822). This effect indicates that by creating a temperature difference on the sides of a connection of two non-similar metals, a voltage proportional to the temperature difference is induced.

Many studies have been reported on modeling and improving the performance of PV + TEG hybrid systems. A concentrator can increase the radiation intensity on the system. It can be installed either on the PV or between the PV and TEG. Vorobiev et al. (2005) developed one-dimensional models for comparison of two hybrid systems; one with the concentrator on the PV and another between PV and TEG. Liao et al. (2013) studied a theoretical one dimensional model for a hybrid system consisting of a low concentrating photovoltaic cell and a thermoelectric generator. The maximum power output of the hybrid device was calculated numerically and the optimal electric load of the CPV and TEG were determined. By considering a constant surrounding temperature, they concluded that a hybrid CPV-TEG system is more preferable than a simple CPV or a TEG alone but did not mention the specifications of the comparison. Also, Deng et al. (2013) fabricated a model of a solar-driven hybrid generation system consisting of a silicon thin film solar cell, TEG and a heat collector. Solar cell absorbs a part of the incident solar energy and directly converts it into electric energy. The undesired waste heat from the solar cell and parts of solar energy are conducted

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Nomenclature

A	area (m^2)
c_p	specific heat capacity (kJ/kg K)
G	irradiance (W/m^2)
h	convection heat transfer coefficient (W/m^2 K)
I	electrical current (A)
K	thermal conductance (W/K)
L	length (m)
n	number of p-n units
P	power generated (W)
$\dot{P}$	power generation per volume (W/m^3)
Q	heat rate (W)
$\dot{q}$	volumetric energy absorption (W/m^3)
R	electric resistance (Ω)
T	temperature (K)
V	volume (m^3)
Z	figure of merit (K^{-1})
ΔT	temperature difference between cold surface and hot surface of TEG

Abbreviations

EVA	ethylvinylacetate
PV	photovoltaic
TEG	thermoelectric generator
TPT	tedlar/PET/tedlar
UDF	user defined function

Greek letters

α	absorptivity
β	temperature coefficient (K^{-1})
ε	Seebeck coefficient (V/K)
η	efficiency
λ	thermal conductivity coefficient (W/m K)
μ	ratio of load resistance to internal resistance of TEG
ρ	reflectivity
ρ	density (kg/m^3)
σ	electrical conductivity coefficient ($\Omega^{-1}\,m^{-1}$)

Subscripts

abs	absorbed
C	cold surface of TEG
gen	generation
H	hot surface of TEG
L	load
m	mean
n	n-type semiconductor
p	p-type semiconductor
rec	received
ref	reference
sol	solar
TEG	thermoelectric generator
TPT	tedlar/PET/tedlar

by the heat collector to TEG for power generation. Two cooling methods were studied and results show a better performance for the integrated design. A numerical simulation was also performed on TEG to obtain the distribution of heat flux. Lamba and Kaushik (2016) investigated a thermodynamic model of a concentrated photovoltaic–thermoelectric generator (CPV–TEG) and found the optimum concentration ratio corresponding to maximum power output of the hybrid system. They indicated that the hybrid PV–TEG system generates more power than the PV system alone. Also, Mahmoudinezhad et al. (2018) studied the transient response of a hybrid CPV-TEG system by using numerical simulations. They indicated that efficiency of the TEG and CPV varies diversely versus changing the solar radiation. Besides, Lamba and Kaushik (2018) developed an analytical model for a concentrated PV-TEG hybrid system and iteratively solved the thermodynamic energy balance equations to find the PV and TEG temperatures. They showed that the maximum power output of the hybrid system increases by 5% as compared to the corresponding values of the concentrated PV system.

Several researchers studied the influence of the cooling system. They pointed that a good cooling system can increase the total hybrid system output power. Wu et al. (2015) established a theoretical model for assessing the performance of glazed/unglazed photovoltaic-thermoelectric hybrid system. To enhance the heat removal, nanofluids were served as heat sink. The results showed that compared to the forced air cooling method, cooling the hybrid system with nanofluid can significantly improve the efficiency of the hybrid system. Cui et al. (2016) also designed a hybrid system including phase change material (PCM). The results indicate that the performance of the PV–PCM–TE system is superior to single PV cells and/or PV–TE systems. Moreover, Yin et al. (2017) proposed a thermal resistance analysis to optimize the design of the coupled system in terms of optimal total conversion efficiency. Three cooling methods, including natural cooling, forced air cooling and water cooling, were investigated, which demonstrated a significant superiority of water cooling for the concentrating photovoltaic-thermoelectric hybrid system. The results showed that enlarging the thermal resistance of the thermoelectric generator can significantly increase the performance of the coupled system. Recently, Soltani et al. (2017) experimentally showed that the performance of a hybrid PV + TEG system can be improved by nanofluid cooling.

Bjork and Nielsen (2015) examined the performance of a combined solar photovoltaic and thermoelectric generator system using an analytical model for four different types of commercial PVs and a bismuth telluride TEG. They indicated that for three types of PV, the combined system has lower production than the PV alone but for a-Si cells the total system performance has slightly improved. On the other hand, Van Sark (2011) showed that thermoelectric materials with figure of merit of $0.004\,K^{-1}$ lead to efficiency enhancement of up to 23%. He investigated a hybrid generation system in two different cities with various values of figure of merit. During the study, cold side of the TEG was assumed to have constant temperature equal to ambient. Lin et al. (2015) also presented a thermodynamic analysis of a one dimensional hybrid system consisting of photovoltaic modules and multi-couple thermoelectric elements. This study shows that the PV–TEG hybrid system has the advantage of increasing the electric power output compared with the conventional PV system. Kossyvakis et al. (2016) made an experimental setting to investigate the performance of a tandem PV-TEG hybrid, employing poly-Si as well as dye-sensitized solar cells. Thermoelectric devices of different thermoelement geometry were used in order to identify the corresponding performance effects. The cold side temperature was maintained at constant temperature during the entire experimental process. This analysis indicated that the performance enhancement obtained due to hybridization becomes more notable for PV cell operating in elevated temperatures. Besides, Hajji et al. (2016) investigated a new concept based on an indirect photovoltaic and thermoelectric coupling. In this model, a concentrator was placed between photovoltaic and thermoelectric systems without any physical contact of the three components. Also, a one dimensional thermodynamic model for analyzing the features of photovoltaic-thermoelectric hybrid systems was proposed by Li et al. (2017). They discussed the effects of the concentration ratio and the PV cells technology