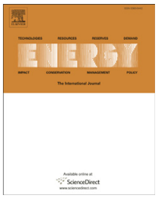
Energy xxx (2014) 1–9

Contents lists available at ScienceDirect

Energy

journal homepage: www.elsevier.com/locate/energy



Performance estimation of photovoltaic–thermoelectric hybrid systems

Jin Zhang, Yimin Xuan*, Lili Yang

School of Energy and Power Engineering, Nanjing University of Aeronautics and Astronautics, Nanjing 210016, China

ARTICLE INFO

Article history:
Received 11 June 2014
Received in revised form
7 October 2014
Accepted 28 October 2014
Available online xxx

Keywords:
Thermoelectric conversion
Photovoltaic module
Hybrid system
Solar energy utilization

ABSTRACT

A theoretical model for evaluating the efficiency of concentrating PV–TE (photovoltaic–thermoelectric) hybrid system is developed in this paper. Hybrid systems with different photovoltaic cells are studied, including crystalline silicon photovoltaic cell, silicon thin-film photovoltaic cell, polymer photovoltaic cell and copper indium gallium selenide photovoltaic cell. The influence of temperature on the efficiency of photovoltaic cell has been taken into account based on the semiconductor equations, which reveals different efficiency temperature characteristic of polymer photovoltaic cells. It is demonstrated that the polycrystalline silicon thin-film photovoltaic cell is suitable for concentrating PV–TE hybrid system through optimization of the convection heat transfer coefficient and concentrating ratio. The polymer photovoltaic cell is proved to be suitable for non-concentrating PV–TE hybrid system.

1. Introduction

The use of solar energy is an important way to alleviate the global energy crisis. It is significant to improve the efficiency of PV (photovoltaic) cell. A lot of research work on improving the efficiency of PV cells has been conducted, however, the conversion performance of PV cells still does not meet industrial requirements because of their relatively lower conversion efficiency [1]. One of the main reasons for the lower efficiency of solar cells is that a type of PV cells can only utilize part of the incident solar energy due to its given bandgap. Although the efficiency of TE (thermoelectric) is less than 10% [2], on the other hand, TE module can directly transform thermal energy of full spectrum into electricity [3]. Generally, a common PV cell converts more than 40% of solar irradiant energy into heat [4]. Therefore, a PV–TE hybrid system may be a prospective way to improve the utilization efficiency of solar energy [5].

One form of PV–TE hybrid systems is the spectrum splitting concentrating system [6]. Photons out of the PV working waveband are incident to the TE modules, electricity can be generated through thermoelectric effect. The system is complex and the heat produced by PV cannot be used by TE. Adding the TE module to the back side is another form of PV–TE hybrid system [7], which is simple and all energy can be used by TE. This paper studies the second form.

PV–TE hybrid system has been investigated during the past years. Yang and Yin [8] pointed out that TE module could potentially enhance the overall efficiency for novel hybrid solar system. Sark [9] proposed a simple model to determine the efficiency of the PV–TE hybrid system. Park et al. [10] demonstrated that resistance matching is important for improving electrical properties. Liao et al. [11] established a theoretical model of a hybrid system, including a low concentrated PV module and a TE module. The models of PV were often simplified and some fundamental features of the PV–TE hybrid system were consciously or unconsciously ignored. For example, the efficiency of PV was often assumed to be temperature-independent or decrease linearly with temperature. However, these assumptions (either constant or linear relationship) may not be suitable for some types of solar cells, especially for polymer PV. On the other hand, the design of TE modules was widely investigated but comprehensive analysis and comparison of the efficiencies of PV–TE hybrid systems with different kinds of PV module are still limited.

A theoretical model for evaluating the efficiency of concentrating PV–TE hybrid system is developed in this paper. The hybrid systems with different PV cells are studied, including c-Si PV (crystalline silicon photovoltaic) cell, p-Si TFPV (polysilicon thin-film photovoltaic) cell, polymer solar cell, and CIGS PV (copper indium gallium selenide photovoltaic) cell. A detailed theoretical

---

* Corresponding author. Tel.: +86 025 84890688.
E-mail address: ymxuan@nuaa.edu.cn (Y. Xuan).

http://dx.doi.org/10.1016/j.energy.2014.10.087
0360-5442/© 2014 Elsevier Ltd. All rights reserved.

Please cite this article in press as: Zhang J, et al., Performance estimation of photovoltaic–thermoelectric hybrid systems, Energy (2014), http://dx.doi.org/10.1016/j.energy.2014.10.087

Nomenclature

B	Auger recombination coefficients ($cm^6\ s^{-1}$)
c	speed of light ($3 \times 10^8\ m\ s^{-1}$)
C	concentrating ratio
C_p	specific heat of air ($kJ\ kg^{-1}\ K^{-1}$)
D_g	fin-to-fin spacing (mm)
E_g	band-gap energy (eV)
G	generation rate ($cm^{-3}\ s^{-1}$)
h	convection heat transfer coefficient (W/m^2K)
H	heat generation ($W\ cm^{-3}$)
H_f	fin height (mm)
$I_{AM1.5}$	solar irradiance *of AM1.5*
J	current density ($A\ cm^{-2}$)
k	thermal conductivity ($W\ m^{-1}\ K^{-1}$)
k_B	Boltzmann constant ($1.38 \times 10^{-23}\ J\ K^{-1}$)
L_{HS}	length of the heat sink (mm)
m_{air}	flow rate of air ($m^3\ s^{-1}$)
n	electron concentration (cm^{-3})
N_A	acceptor doping concentration (cm^{-3})
N_D	donor doping concentration (cm^{-3})
n_f	number of fins
p	hole concentration (cm^{-3})
P	pressure drop (Pa)
q	electron charge ($1.6 \times 10^{-19}C$)
Q	heat flux ($W\ m^{-2}$)
R	recombination rate ($cm^{-3}\ s^{-1}$)
r	thermal contact resistance (mm^2K/W)
S	Seebeck coefficient ($V\ K^{-1}$)
T	temperature (K)
U	velocity of air ($m\ s^{-1}$)
v	viscosity of air ($N\ s\ m^{-2}$)
W_{HS}	width of the heat sink (mm)
x	x-coordinate (m)
Greek letters	
α	absorption coefficient
ε	dielectric constant ($F\ m^{-1}$)
ε_0	vacuum permittivity ($8.85 \times 10^{-12}\ F\ m^{-1}$)
η	efficiency
λ	wavelength of photon (μm)
μ	carrier mobility ($cm^2\ V^{-1}\ s^1$)
σ	electrical conductivity ($S\ m^{-1}$)
τ	carrier lifetime (s)
ψ	electrical potential (V)
$\hbar$	Planck constant ($6.63 \times 10^{-34}\ J\ s$)
Subscripts	
n	electron
p	hole
SRH	Shockley–Read–Hall recombination
Aug	Auger recombination
ie	intrinsic carrier
min	the minimum wavelength
TE	thermoelectric module
PV	photovoltaic module
h	hot side
c	cold side
HS	heat sink
∞	environment
cs	cooling system
f	fan
t	total system
s	incident sunlight

investigation has been carried out to understand the influence of temperature on the PV efficiency. The efficiency of TE is calculated by solving an energy balance equation. The impact of thermal contact resistance, concentrating ratio and convection heat transfer coefficient is also considered.

2. Model

2.1. The system geometry

As shown in Fig. 1, the PV–TE hybrid system consists of an optical concentrator system, PV module, TE module and a heat sink. TE module is attached to the back of PV module. A heat sink is added to the bottom of the system to remove heat from the TE module. The concentrating sunlight is incident on the PV cells, part of the sunlight is transformed into electrical energy and the remaining part is transformed into heat. The TE module can transform the part of heat into electrical energy.

2.2. PV simulation model

The electrical simulation of silicon PV and CIGS PV is conducted based on the semiconductor equations [12]:

$$\nabla(\varepsilon\nabla\psi) = q(p - n + N_D - N_A) \tag{1}$$

$$\nabla J_n = -q(G - R) \tag{2}$$

$$\nabla J_p = q(G - R) \tag{3}$$

$$J_n = -q\mu_n n\nabla\psi + k_B T\mu_n \nabla n \tag{4}$$

$$J_p = -q\mu_p p\nabla\psi - k_B T\mu_p \nabla p \tag{5}$$

$$\nabla(k\nabla T) + H = 0 \tag{6}$$

where ε is the dielectric constant of semiconductor, q is the electron charge, ψ is the electrical potential, n and p are the electron and hole concentration, N_A and N_D are the acceptor and donor doping concentration, J_n and J_p are the electron and hole current densities, G is the generation rate, R is the recombination rate, μ_n and μ_p are the electron and hole mobility, k_B is the Boltzmann constant, k is the thermal conductivity, T is the temperature, and H is the heat generation. Equation (1) is the Poisson's Equation which relates the electrical potential to the space charge density. Equations (2) and (3) are respectively the continuity equations for electrons and holes. Equations (4) and (5) express the current densities in equation (2) and equation (3), respectively. Equation (6) is the thermal energy equation.

The carrier recombination rate can be divided into Shockley–Read–Hall recombination rate (R_{SRH}) and Auger recombination rate (R_{Aug}). The Shockley–Read–Hall recombination rate can be calculated as [12]:

$$R_{SRH} = \frac{np - n_{ie}^2}{\tau_p(n + n_{ie}) + \tau_n(p + n_{ie})} \tag{7}$$

Please cite this article in press as: Zhang J, et al., Performance estimation of photovoltaic–thermoelectric hybrid systems, Energy (2014), http://dx.doi.org/10.1016/j.energy.2014.10.087