



Thermal resistance analysis and optimization of photovoltaic-thermoelectric hybrid system



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ABSTRACT

The thermal resistance theory is introduced into the theoretical model of the photovoltaic-thermoelectric (PV-TE) hybrid system. A detailed thermal resistance analysis is proposed to optimize the design of the coupled system in terms of optimal total conversion efficiency. Systems using four types of photovoltaic cells are investigated, including monocrystalline silicon photovoltaic cell, polycrystalline silicon photovoltaic cell, amorphous silicon photovoltaic cell and polymer photovoltaic cell. Three cooling methods, including natural cooling, forced air cooling and water cooling, are compared, which demonstrates a significant superiority of water cooling for the concentrating photovoltaic-thermoelectric hybrid system. Influences of the optical concentrating ratio and velocity of water are studied together and the optimal values are revealed. The impacts of the thermal resistances of the contact surface, TE generator and the upper heat loss thermal resistance on the property of the coupled system are investigated, respectively. The results indicate that amorphous silicon PV cell and polymer PV cell are more appropriate for the concentrating hybrid system. Enlarging the thermal resistance of the thermoelectric generator can significantly increase the performance of the coupled system using amorphous silicon PV cell or polymer PV cell.

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1. Introduction

Photovoltaic (PV) technology is one of the highly competitive technologies to convert the solar energy into electric energy. However, the reported commercial PV modules have very low conversion efficiency within the range of 12–18% [1] and decreasing as the increase of temperature. A significant part of solar energy converts into heat and is wasted [2]. Therefore, improving the photoelectric conversion efficiency and combining PV cell with heat recovery-utilization system, such as thermoelectric (TE) module, are in demand for further utilization of solar energy. Thermoelectric module (TE) can generate electricity based on the Seebeck effect when the hot side and the cold side exist a temperature difference [3–9]. Thus, combining PV cell and TE devices can not only increase the output power but also utilize the unwanted heat that may weaken the performance of the PV cell.

One of combining approaches is directly attaching the TE generator to the back of the PV cell. Numerous theoretical and experimental researches in the hybrid system have been carried out recently. Most of the researching results pointed that this

combining method can improve the utilization of the solar spectrum [10–18]. Zhang et al. [11] studied the concentrating PV-TE coupled system with a forced air cooling method. The coupled system achieved an increase in efficiency of 1–30% comparing to the pure photovoltaic system. Park et al. [13] provided a novel hybrid approach named lossless coupling which matched the resistance of TE modules with PV circuits. The coupled system achieved great improvement in the efficiency of PV cell (~30% when the TE generator maintained a 15 °C temperature difference). Zhu et al. [14] considered an optimal thermal management for the coupled system. The new coupled system achieved a significant increase (~25%) in conversion efficiency compared to the PV cells. Wang et al. [15] designed a PV-TE system combining dye sensitized PV device (DSSC), solar selective absorber (SSA) and TE generator which demonstrated an obvious increasing on the total conversion efficiency of the hybrid systems comparing to the pure PV system. The overall efficiency was 13.8% for the DSSC-SSA-TE hybrid device, 12.8% for the DSSC-TE coupled device whereas the efficiency was 9.26% for the pure PV system.

However, there were also some different results that pointed out the capability of the coupled system was worse than the pure photovoltaic system [19,20]. Bjørk et al. [19] theoretically investigated the hybrid systems with four types of PV cells and a

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Nomenclature

A	area (m^2)	B	Auger recombination coefficients (cm^6/s)
R	thermal resistance (K/W)	$I_{AM1.5}(\lambda)$	solar irradiance of AM1.5
k_B	Stefan–Boltzmann's constant ($1.38 \times 10^{-23} \text{ J/K}$)	c	speed of light ($3 \times 10^8 \text{ m/s}$)
T	temperature (K)	Greek symbols	
T_{in}	inlet temperature of water (K)	ε	surface emissivity
T_{out}	outlet temperature of water (K)	α	absorptivity
T_a	temperature of environment (K)	$\alpha(\lambda)$	absorption coefficient (m^{-1})
u	velocity of air or water (m/s)	τ	transmissivity
k	thermal conductivity ($\text{W m}^{-1} \text{ K}^{-1}$)	δ	thickness (m)
M	number of thermoelements of TE module	ρ	density of water (kg/m^3)
h	convection heat transfer coefficient ($\text{W m}^{-2} \text{ K}^{-1}$)	λ	wavelength of photon (μm)
n	number of fins or channels	ω	dielectric constant (Fm^{-3})
A_f	surface area of a fin (m^2)	φ	electrical potential (V)
A_t	total convection surface area of fin (m^2)	ϕ	electron and hole lifetimes (s)
W_{fin}	thickness of the rectangular fins (m)	δ_{fc}	thickness of the front cover of water cooling system (m)
$H_{c,fin}$	corrected fin height (m)	γ	structure parameter of the TE legs (m)
D	diameter of the pin fins or effective diameter of the water cooling channels (m)	$\eta_{0,fin}$	overall surface efficiency of fin
L	length of fin (m)	$\eta_{f,fin}$	efficiency of a fin
H	height of fin (m)	σ	electrical resistance of the p/n semiconductors ($\Omega \text{ m}$)
m	fin constant	η	total efficiency of PV-TE hybrid system
Nu	Nusselt number	μ	carrier mobility ($\text{cm}^2 \text{ V}^{-1} \text{ s}^{-1}$)
Re	Reynolds number	η_{PV}	photo-electric conversion efficiency of PV cell
Pr	Prandtl number	Subscripts and superscripts	
Gz	Graetz number	rad	radiation heat loss
ν	viscosity of air or water (m^2/s)	PV	photovoltaic cell
V	flow rate of air (m^3/s)	g	glass cover
a	height of channels (m)	$conv$	convection heat loss
b	width of channels (m)	$wind$	natural wind
l	length of channels (m)	EVA	optical adhesive EVA
P	output power (W)	$ceram$	ceramic wafers of TE module
Q	heat flux (W)	Cu	Cu material and Cu electrodes of TE module
Q_{in}	all the solar energy getting into PV-TE hybrid system (W)	c	connecting interface
s	Seebeck coefficient of p-type semiconductor legs or n-type semiconductor legs (V/K)	ad	thermal conductive adhesive
s_m	Seebeck coefficient of TE module (V/K)	TE	TE module
I	output current of TE module (A)	n	n-type semiconductor legs of TE module
r	loading resistance of TE module (Ω)	p	p-type semiconductor legs of TE module
r_{TE}	internal resistance of TE module (Ω)	$cool$	cooling system
C	optical concentrating ratio	b	fin base
G	solar irradiance (W/m^2)	fin	pin fin and rectangle fin
f	friction factor	air	air
C_p	thermal capacity of water (J/kg K)	w	water cooling system and water
q	electron charge ($1.6 \times 10^{-19} \text{ C}$)	ch	channels of water cooling system
ΔP	pressure drop of air (Pa)	$loss$	heat loss from the top side the glass cover
e	electron concentration (cm^{-3})	$down$	all the components below the PV cell
t	hole concentration (cm^{-3})	h	hot side of TE module
N_A	acceptor doping concentration (cm^{-3})	c	cold side of TE module
N_D	donor doping concentration (cm^{-3})	e	electron
N_C	the effective density of electrons (cm^{-3})	t	hole
N_V	the effective density of holes (cm^{-3})	Abbreviations	
J	electron and hole current densities (A/cm^2)	PV	photovoltaic cell
Gr	generation rate ($\text{cm}^{-3} \text{ s}^{-1}$)	TE	thermoelectric module
Z	recombination rate ($\text{cm}^{-3} \text{ s}^{-1}$)	$a\text{-Si}$	amorphous silicon
R_{SRH}	Shockley–Read–Hall recombination rate ($\text{cm}^{-3} \text{ s}^{-1}$)	$c\text{-Si}$	monocrystalline silicon
R_{Aug}	Auger recombination rate ($\text{cm}^{-3} \text{ s}^{-1}$)	$p\text{-Si}$	polycrystalline silicon
E_g	band-gap energy (eV)		
ni	intrinsic carrier concentration (cm^{-3})		

universal bismuth telluride TE module. For c-Si, CIGS and CdTe PV cells, the hybrid system achieved a worse performance compares to the pure PV system. The output power of the coupled system

got a tiny increase only when the a-Si PV cell was employed. Vorobiev et al. [20] investigated the hybrid system with concentrator of solar radiation. For existing thermoelectric

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