Energy Conversion and Management 143 (2017) 188–202

Contents lists available at ScienceDirect

Energy Conversion and Management

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

Thermal resistance analysis and optimization of photovoltaic-thermoelectric hybrid system

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ARTICLE INFO

Article history:
Received 27 December 2016
Received in revised form 27 February 2017
Accepted 1 April 2017

Keywords:
Photovoltaic-thermoelectric hybrid system
Thermal resistance analysis
Solar energy
Optimization
Renewable energy

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.

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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http://dx.doi.org/10.1016/j.enconman.2017.04.004
0196-8904/

Nomenclature

A	area (m^2)
R	thermal resistance (K/W)
k_B	Stefan–Boltzmann'sconstant (1.38×10^{-23} J/K)
T	temperature (K)
T_{in}	inlet temperature of water (K)
T_{out}	outlet temperature of water (K)
T_a	temperature of environment (K)
u	velocity of air or water (m/s)
k	thermal conductivity (W m^{-1} K^{-1})
M	number of thermoelements of TE module
h	convection heat transfer coefficient (W m^{-2} K^{-1})
n	number of fins or channels
A_f	surface area of a fin (m^2)
A_t	total convection surface area of fin (m^2)
W_{fin}	thickness of the rectangular fins (m)
$H_{c,fin}$	corrected fin height (m)
D	diameter of the pin fins or effective diameter of the water cooling channels (m)
L	length of fin (m)
H	height of fin (m)
m	fin constant
Nu	Nusselt number
Re	Reynolds number
Pr	Prandtl number
Gz	Graetz number
v	viscosity of air or water (m^2/s)
V	flow rate of air (m^3/s)
a	height of channels (m)
b	width of channels (m)
l	length of channels (m)
P	output power (W)
Q	heat flux (W)
Q_{in}	all the solar energy getting into PV-TE hybrid system (W)
s	Seebeck coefficient of p-type semiconductor legs or n-type semiconductor legs (V/K)
s_m	Seebeck coefficient of TE module (V/K)
I	output current of TE module (A)
r	loading resistance of TE module (Ω)
r_{TE}	internal resistance of TE module (Ω)
C	optical concentrating ratio
G	solar irradiance (W/m^2)
f	friction factor
C_p	thermal capacity of water (J/kg K)
q	electron charge (1.6×10^{-19} C)
ΔP	pressure drop of air (Pa)
e	electron concentration (cm^{-3})
t	hole concentration (cm^{-3})
N_A	acceptor doping concentration (cm^{-3})
N_D	donor doping concentration (cm^{-3})
N_C	the effective density of electrons (cm^{-3})
N_V	the effective density of holes (cm^{-3})
J	electron and hole current densities (A/cm^2)
Gr	generation rate (cm^{-3} s^{-1})
Z	recombination rate (cm^{-3} s^{-1})
R_{SRH}	Shockley-Read-Hall recombination rate (cm^{-3} s^{-1})
R_{Aug}	Auger recombination rate (cm^{-3} s^{-1})
E_g	band-gap energy (eV)
ni	intrinsic carrier concentration (cm^{-3})
B	Auger recombination coefficients (cm^6/s)
$I_{AM1.5}(\lambda)$	solar irradiance of $AM1.5$
c	speed of light (3×10^8 m/s)

Greek symbols

ε	surface emissivity
a	absorptivity
$a(\lambda)$	absorption coefficient (m^{-1})
τ	transmissivity
δ	thickness (m)
ρ	density of water (kg/m^3)
λ	wavelength of photon (μm)
ω	dielectric constant (Fm^{-3})
φ	electrical potential (V)
ϕ	electron and hole lifetimes (s)
δ_{fc}	thickness of the front cover of water cooling system (m)
γ	structure parameter of the TE legs (m)
$\eta_{0,fin}$	overall surface efficiency of fin
$\eta_{f,fin}$	efficiency of a fin
σ	electrical resistance of the p/n semiconductors (Ω m)
η	total efficiency of PV-TE hybrid system
μ	carrier mobility (cm^2 V^{-1} s^1)
η_{PV}	photo-electric conversion efficiency of PV cell

Subscripts and superscripts

rad	radiation heat loss
PV	photovoltaic cell
g	glass cover
conv	convection heat loss
wind	natural wind
EVA	optical adhesive EVA
ceram	ceramic wafers of TE module
Cu	Cu material and Cu electrodes of TE module
c	connecting interface
ad	thermal conductive adhesive
TE	TE module
n	n-type semiconductor legs of TE module
p	n-type semiconductor legs of TE module
cool	cooling system
b	fin base
fin	pin fin and rectangle fin
air	air
w	water cooling system and water
ch	channels of water cooling system
loss	heat loss from the top side the glass cover
down	all the components below the PV cell
h	hot side of TE module
c	cold side of TE module
e	electron
t	hole

Abbreviations

PV	photovoltaic cell
TE	thermoelectric module
a-Si	amorphous silicon
c-Si	monocrystalline silicon
p-Si	polycrystalline silicon

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