Energy Conversion and Management 112 (2016) 49–60

Contents lists available at ScienceDirect

Energy Conversion and Management

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

Design of a novel concentrating photovoltaic–thermoelectric system incorporated with phase change materials

Tengfei Cui [a], Yimin Xuan [a,b,*], Qiang Li [a]

[a] School of Energy and Power Engineering, Nanjing University of Science & Technology, China
[b] College of Energy and Power Engineering, Nanjing University of Aeronautics & Astronautics, China

ARTICLE INFO

Article history:
Received 7 October 2015
Accepted 5 January 2016
Available online 13 January 2016

Keywords:
Solar energy utilization
Photovoltaic cells
Thermoelectric modules
Phase change material
PV–PCM–TE system

ABSTRACT

Since the solar irradiance within a day is varying, the temperature of the photovoltaic–thermoelectric (PV–TE) system becomes fluctuant with the change of the incident solar irradiance, which exerts a significant influence on the efficiency of the total system. In this paper, the phase change material (PCM) is introduced into the PV–TE system to construct a novel PV–PCM–TE hybrid system. The purposes of applying PCM are to mitigate the temperature fluctuations of the PV cell and the TE modules and keep the hybrid PV–TE system operating under a fixed operating condition. A theoretical model of evaluating the efficiency of the concentrating PV–PCM–TE hybrid system is presented. The feasibility of the PV–PCM–TE system with four types of PV cells, c-Si, CIGS, single-junction GaAs, and GaInP/InGaAs/Ge (III–V), are investigated. The optimum operating conditions which indicate that the PV–PCM–TE system has the highest total efficiency are discussed to determine the melting temperatures of PCMs. A series of structure parameters are designed to obtain the optimized parameters for the PV–PCM–TE system, and the influences of these parameters on the PV–PCM–TE system are investigated. The results indicate that the performance of the PV–PCM–TE system is superior to single PV cells and/or PV–TE systems.

1. Introduction

Solar energy which is currently one of the most renewable and potential energy sources has been widely focused and investigated. However, only a limited solar energy incident on a photovoltaic (PV) cell can be converted into electricity; the remaining absorbed solar energy has to be transformed into heat, which is not only a waste of energy but also an adverse influence factor for the PV cell converting solar energy into electricity [1]. Therefore, reutilization of this part of exhaust heat and further improving the efficiency of utilizing solar energy becomes an attractive problem and receives more and more attentions.

Recently, a so-called hybrid photovoltaic–thermoelectric (PV–TE) system has been proposed, which implies enhancement on the total efficiency of utilizing solar energy [2–12]. Wang et al. [6] measured the conversion efficiency of a hybrid PV–TE system which was combined by the series-connected dye-sensitized solar cell (DSSC), a solar selective absorber (SSA), and a TE generator. They found that compared with the referenced efficiency 9.39% of the DSSC, the maximum entire efficiency of the entire PV–TE system amounted to 13.8%. Hsueh et al. [7] investigated the performance of the PV–TE system formed by the CuInGaSe2 (CIGS) PV cell and a TE generator, the maximum total efficiency of the whole hybrid system increased from 16.5% to 22.02%. Zhang et al. [8] developed a theoretical model of the concentrating PV–TE hybrid system. By using fins as cooling device, the enhancement of 1–8% on the total efficiency of utilizing solar energy was realized compared with the pure PV system. A similar simulation was found in the work of Liao et al. [9], the difference between their work and the studies from Zhang's group [8] was that the matched load resistances in the PV–TE system were discussed. Moreover, Dallan [10] experimentally investigated the viability of a PV–TE system. The experimental results showed that the output power of the PV–TE system increased up to 39% under the fixed thermal input conditions compared with the PV module's operating performance in the absence of the TE module. For most of the aforementioned investigations, the PV–TE systems were mostly tested or simulated under the laboratory environment (AM 1.5) which implies a constant solar irradiance 1000 W/m^2. At this situation, the operating temperature of the PV–TE system may be kept at a constant value. In fact, the solar irradiance during a day changes along the time and the operating temperature of the PV–TE system varies with the changes of solar irradiance as consequence. Wu et al. [11] studied the performance of a PV–TE system by using the nanofluid as

---

* Corresponding author at: School of Energy and Power Engineering, Nanjing University of Science & Technology, China. Tel.: +86 025 84890688.
E-mail address: ymxuan@mail.njust.edu.cn (Y. Xuan).

http://dx.doi.org/10.1016/j.enconman.2016.01.008
0196-8904/

Nomenclature

A	area (mm^2)
h	height (mm)
l	the length of channels (mm)
A_c	the cross sectional area of channels (mm^2)
T	temperature (K)
T_{wi}	temperature of water at the inlet (K)
T_{wo}	temperature of water at the outlet (K)
T_{wm}	mean temperature of the water (K)
m	the number of channels
c_p	thermal capacity (J/kg K)
R	thermal resistance (mm^2 K/W)
R_c	thermal contact resistance (mm^2 K/W)
h_w	convection heat transfer coefficient of water (W/mm^2 K)
h_{air}	convection heat transfer coefficient of air (W/mm^2 K)
$1/h_r$	radiation thermal resistance (mm^2 K/W)
P	power (W)
t	time (s)
C	optical concentrating ratio
C_{th}	thermal concentrating ratio
G	optical generation rate
J	current density (mA cm^{-2})
N_A	acceptor doping concentration (cm^{-3})
N_D	donor doping concentration (cm^{-3})
N_C	the effective densities of electrons (cm^{-3})
N_V	the effective densities of holes (cm^{-3})
$I(\lambda)$	the solar irradiance spectrum (cm^2 s^{-1})
c	speed of light (m/s)
k_B	Boltzmann constant (1.38 × 10^{-23} J K^{-1})
E_g	the band-gap energy (eV)
k	thermal conductivity (W/m K)
n_i	the intrinsic carrier concentration (cm^{-3})
p	free hole concentration (cm^{-3})
n	free electron concentration (cm^{-3})
R_{re}	carrier recombination rate (cm^{-3} s^{-1})
R_{SRH}	Shockley–Read–Hall recombination
R_{Aug}	Auger recombination
T	temperature (K)
ZT	the dimensionless thermoelectric coefficient
E	heat absorbed by phase change material
H	the latent heat of phase change material
T_m	the melting temperature of phase change material

Nu	Nusselt number
Re	Reynolds number
Pr	Prandtl number
D_h	the hydraulic diameter of channels (mm)
f	friction factor
R_q	root mean square roughness of the channels (μm)
u, v, w	velocity (m/s)
x, y, z	coordinate (m)

Greek letters

$\hbar$	Planck constant (6.63 × 10^{-34} J s)
$\alpha(\lambda)$	absorption coefficient (m^{-1})
β	temperature coefficient (K^{-1})
δ_{SB}	Stefan–Boltzmann constant (5.67 × 10^{-8} W m^2 K^4)
ε	dielectric constant (F m^{-1})
η	efficiency (%)
λ	wavelength of photon (μm)
μ_n	carrier mobility (cm^2 V^{-1} s^{-1})
ϕ	electrostatic potential (V)
τ	relaxation time (s)
μ	viscosity (mm^2/s)
ρ	density (kg/m^3)

Subscripts

lens	Fresnel lens
PV	photovoltaic cell
PCM	phase change material
TE	thermoelectric generators
hs	heat sink
pump	pump
n	electron or the *n*-type material
p	hole or the *p*-type material
w	water
air	air
r	radiation
L	liquid phase of phase change material
S	solid phase of phase change material
up	up side surface
down	down side surface

the coolant in the PV–TE system under a daily changed solar irradiance. The results showed that compared with the forced air cooling method, cooling the PV–TE system with the nanofluid can significantly improve the efficiencies of the PV–TE system. However, the efficiency and the temperature of the PV–TE system were still fluctuant due to the changes of solar irradiance, which induced a series of questions related to the practical applications of the PV–TE system in a realistic situation, such as the designs of structure sizes of the PV–TE systems, the matching of the load resistance [12], and the controls of the cooling system of the PV–TE system [11]. Therefore, it is necessary to weaken the influence of fluctuant solar irradiance on the PV–TE system, and make sure that the PV–TE system operates under the optimal operating status.

To suppress the temperature fluctuation of a PV–TE system induced by the fluctuant solar irradiance, one of alternative methods is using phase change materials (PCM). This is because that PCM can absorb a large amount of energy as latent heat at a constant phase transition temperature, and thus be widely used for passive heat storage and temperature control of electronics [13]. Recently, PCMs are more and more incorporated with photovoltaic devices to improve their conversion performance. Huang et al. [14–16], Maiti et al. [17] and Aelenei et al. [18] numerically and experimentally investigated the performance of a PV–PCM system. All these efforts indicated that using PCM can maintain the system operating under a steady-state and low temperature fluctuation during the day time, and then generate a greater electrical power output. In addition, Malvi et al. [19] proposed the concept of a combined photovoltaic thermal (PVT)–PCM system. By using water cooling, they found that the PCM further mitigated the temperature rise of the PV cell, so that the PV cell operated at a steady-state temperature during a day.

Therefore, in order to eliminate the influence induced by the fluctuant solar irradiance on the PV–TE system, PCM is introduced into the PV–TE system in this paper to construct a novel hybrid PV–PCM–TE system. A theoretical model of the PV–PCM–TE hybrid system is presented to evaluate its performances under different conditions. The feasibility of a PV–PCM–TE system operating under