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Parametric characteristics of a solar thermophotovoltaic system at the maximum efficiency

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ABSTRACT

A model of the solar thermophotovoltaic system (STPVS) consisting of an optical concentrator, a thermal absorber, an emitter, and a photovoltaic (PV) cell is proposed, where the far-field thermal emission between the emitter and the PV cell, the radiation losses from the absorber and emitter to the environment, the reflected loss from the absorber, and the finite-rate heat exchange between the PV cell and the environment are taken into account. Analytical expressions for the power output of and overall efficiency of the STPVS are derived. By solving thermal equilibrium equations, the operating temperatures of the emitter and PV cell are determined and the maximum efficiency of the system is calculated numerically for given values of the output voltage of the PV cell and the ratio of the front surface area of the absorber to that of the emitter. For different bandgaps, the maximum efficiencies of the system are calculated and the corresponding optimum values of several operating parameters are obtained. The effects of the concentrator factor on the optimum performance of the system are also discussed.

1. Introduction

Thermophotovoltaic cells (TPVCs) are a class of energy devices that can convert thermal radiation into electricity, which generally consist of an emitter and a photovoltaic (PV) cell [1–3]. When an external heat source or solar energy is supplied, photons with energy above the band-gap of the PV cell material are emitted from the hot emitter and absorbed by the PV cell to generate power output [4–7]. The conventional PV cells directly convert a part of the solar spectrum into electricity. Differently, TPVCs first convert the solar spectrum into the heat and then emit a narrower thermal spectrum to generate electricity. This approach avoids two primary loss mechanisms: the generation of sub-bandgap photons and the thermalization of excitons with energy much greater than the band gap [8]. Especially, the power output density and efficiency of near-field TPVCs can be significantly improved by comparing with the conventional PV cells. However, the actual designs of near-field TPVCs are more challenging than those of far-field TPVCs because the vacuum gap between the emitter and the PV cell is required at nanoscale. Moreover, the mismatch between the gap frequency of the PV cell and the frequency of surface polaritons supported by the emitter limits the development of near-field TPVCs. At present, far-field TPVCs have more practical applications than near-field TPVCs [9–23].

Apparently, it is significant to further investigate the optimum performance of far-field TPVCs, especially for solar thermophotovoltaic systems (STPVSs) because solar energy is one of the cleanest energy sources [24,25]. In the STPVS, the important components between the solar concentrator and the PV cell are the absorber and emitter, which can convert the broad solar spectrum to a narrower thermal spectrum absorbed by the PV cell to generate electron-hole pairs. Many important researches of STPVSs have been reported in the last years [5–7,10,14,21,22,26–30]. However, in the previous works, the temperatures of the emitter and the PV cell were directly given but not determined by solving the energy balance equations of the absorber, emitter, and PV cell. What's more, parametric optimum analyses, structure designs, and material selections were not discussed and investigated in detail.

In the present paper, the model of an STPVS is proposed. The difference and innovation between this paper and the previous works is that the maximum efficiency of the system is calculated under different conditions, and consequently, the optimum values of the ratio of the front surface area of the absorber to that of the emitter and the bandgap and the output voltage of the PV cell are determined. Moreover, the effects of the different concentrator factors on the performance of the STPVS are also discussed.

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Nomenclature

A	area (cm^{-2})
C	concentrator factor
c	speed of light ($cm\ s^{-1}$)
d	vacuum gap (cm)
E	photon energy (eV)
E_g	bandgap (eV)
h	Planck constant (eVs)
J	current density ($A\ cm^{-2}$)
K_B	Boltzmann constant ($eV\ K^{-1}$)
P	power output (W)
q	heat flow (W)
e	elementary positive charge (C)
T	temperature (K)
T_L	temperature of the heat sink (K)
U	heat transfer coefficient ($W\ K^{-1}\ cm^{-2}$)
V	voltage (V)

Greek symbols

α	absorptance
η	efficiency
λ	radiation wavelength
ε	emissivitiy

Subscript

E	emitter
P	PV cell
e	emitter
a	absorber
ref	reflect
opt	optimum
op	optical
max	maximum
H	hot side
inc	incident
T	thermal emission
L	cold side

Abbreviations

PV	photovoltaic
TPVC	thermophotovoltaic cell
STPVS	solar thermophotovoltaic system

2. Model description

In order to develop and improve the theory of steady state far-field TPVCs, we propose a model of the far-field TPVC driven by solar energy, which consists of an optical concentrator, an absorber, an emitter, and a PV cell and is simply referred as to the far-field STPVS, as shown in Fig. 1, where A_A and A_E are the front surface areas of the absorber and emitter, T_E, T_P, and T_L are the temperatures of the emitter, PV cell, and ambient, $q_{loss,a}$ and $q_{loss,e}$ are the thermal radiation losses from the absorber and emitter to the surrounding, q_{ref} is the reflected solar radiation of the absorber, q_H is the heat flow from the absorber to the emitter, q_L is the heat flow from the PV cell to the heat sink, q_T is the thermal emission flow transferred to the PV cell, R is the load resistance of the PV cell, and d is the distance of the vacuum gap between the emitter and the PV cell. Generally, the emitter and PV cell are, respectively, made of refractory materials (e.g., Tungsten [22] or photonic crystal [14,16,21,31]) and low bandgap semiconductor materials (e.g., InGaAsSb, InAs, or InSb [32]). The intrinsic working mechanism of such an STPVS is that the optical concentrator focuses the broad solar spectrum on the absorber, which is converted into narrowband thermal emission matched closely to the low bandgap of the PV cell [22,31]. The infrared photons are then absorbed by the PV cell that simultaneously excites electron-hole pairs. These electrons generated in the PV are extracted to transfer to the external load to produce the power output. In order to conveniently investigate the performance of the STPVS, it is assumed that the distance d of the vacuum gap is larger than the characteristic wavelength of thermal radiation (i.e., only the dominant far-field contribution of the propagating mode is taken into account) and that the temperature of the emitter and absorber is considered uniform [22,31].

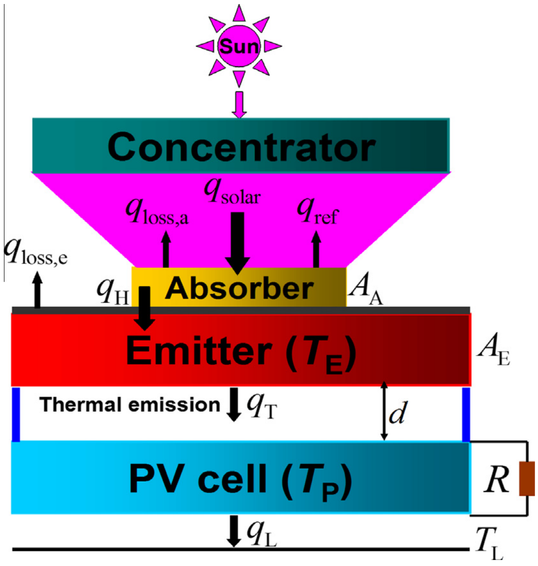

Fig. 1. The schematic diagram of an STPVS.

3. Power output and efficiency of the STPVS

By considering the thermal losses of the surfaces of the absorber and emitter, two energy conservation equations for both the absorber and the emitter are given by [22,28,31]

$$q_{solar} = q_H + q_{loss,a} + q_{ref} \tag{1}$$

and

$$q_H = q_{solar}\eta_a = q_{loss,e} + q_T, \tag{2}$$

where $q_T = q_H\eta_e$, η_a and η_e are the thermal efficiencies of the absorber and the emitter, q_{solar}, $q_{loss,a}$, $q_{loss,e}$, and q_{ref} are, respectively, calculated by [22,28,31]

$$q_{solar} = \eta_{op} C A_A \int_0^\infty q_{solar,inc}(\lambda) d\lambda, \tag{3}$$

$$q_{loss,a} = A_A 2\pi \int_0^\infty \varepsilon_a(\lambda) \frac{hc^2}{\lambda^5}\left[\exp\left(\frac{hc}{\lambda K_B T_E} - 1\right)^{-1} - \exp\left(\frac{hc}{\lambda K_B T_L} - 1\right)^{-1}\right] d\lambda, \tag{4}$$