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Efficiently exploiting the waste heat in solid oxide fuel cell by means of thermophotovoltaic cell

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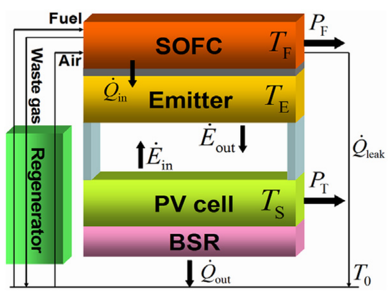
HIGHLIGHTS

- A novel hybrid device exploiting waste heat in solid oxide fuel cells is designed.
- The hybrid device includes a solid oxide fuel cell and a thermophotovoltaic cell.
- The performances of the hybrid device and the single SOFC are compared.
- The optimally operating regions of the hybrid device are determined.
- The advantages of the hybrid device over other SOFC-based hybrid systems are shown.

GRAPHICAL ABSTRACT



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ABSTRACT

Through the combination of the current models of solid oxide fuel cells (SOFCs) and thermophotovoltaic cells (TPVCs), a new model of the hybrid device composed of an SOFC, a regenerator, and a TPVC with integrated back surface reflector (BSR) is proposed. Analytical expressions for the power output and efficiency of two subsystems and hybrid device are derived. The relations between the performance of the TPVC and the operating current density of the SOFC in the hybrid device are revealed. The performance characteristics of the hybrid device are discussed in detail. The maximum power output density is calculated. The optimally operating region of the hybrid device is determined, compared with the performance of the SOFC in the hybrid device. The choice criteria of some key parameters are given. Moreover, it is proved that the proposed model can exploit the waste heat produced in SOFCs more efficiently than other SOFC-based hybrid systems.

1. Introduction

Solid oxide fuel cells (SOFCs) are electrochemical conversion devices that produce electricity directly from oxidizing a fuel. Particularly, SOFCs play an important role in the automotive and efficient distributed power generation systems due to their efficient, clean, environmental friendly, multi-fuel capabilities, and fuel flexibility [1–5]. One of the key problems existing in SOFCs is to produce too much high temperature waste heat. In order to utilize the waste heat in SOFCs, many hybrid systems consisting of an SOFC and a thermoelectric generator (TEG) [6], or various typical thermodynamic cycles such as the Carnot cycle [7], Rankine cycle [8],

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Stirling cycle [9], Braysson cycle [10], gas turbine [11], etc. have been proposed and investigated. It was proved that these hybrid systems can exploit the waste heat produced in SOFCs and enhance the utilization of fuels. Thus, it is important for the performance improvement of fuel cells to continue the investigation on SOFC-based hybrid systems.

Like TEGs, thermophotovoltaic cells (TPVCs) can directly convert a part of the heat absorbed from a high-temperature heat source into electricity [12–18] and have been widely studied [19–25]. Generally, TPVCs consist of an emitter made of the high temperature materials such as hexagonal Boron Nitride (h-BN) and a photovoltaic (PV) cell made of the low band-gap semiconductor materials such as InSb, InAs, Pbs, InGaSb, etc. With the development of material science, the performance of TPVCs can be enhanced by integrating photonic crystals, carbon nanotube, or graphene [14,19–23,26]. The main superiorities of TPVCs are of small-size, no moving part, low noise, easy maintenance, great fuel flexibility, high portability, high power density, high heat-to-electricity conversion efficiency, etc. [18,20,26–28]. TPVCs are more suitable for constituting a hybrid system with other devices operated at high temperature conditions than TEGs, and consequently, it is of very practical significance to establish a novel hybrid system consisting of an SOFC and a TPVC and analyze its performance characteristics.

Based on the existing models of SOFCs and TPVCs, a novel theoretical model of the SOFC-TPVC hybrid device is proposed. The performances of the TPVC and SOFC are briefly introduced. The expressions of the power outputs and efficiencies of two subsystems and the hybrid device are derived. The optimal performance characteristics of the hybrid device are discussed in detail. The results obtained are generalized to be suitable for the differently operating temperatures of SOFCs and compared with those of other SOFC-based hybrid systems.

2. Model description

The SOFC-TPVC hybrid device composed of an SOFC, a regenerator, an emitter, and a PV cell with integrated back surface reflector (BSR) [12,17,18], as shown in Fig. 1, where the SOFC operated at steady temperature T_F acts as the heat source of the TPVC to generate additional power output, the role of the regenerator in the hybrid device is to preheat the incoming air and fuel by using the high-temperature exhaust gas of the SOFC and to ensure that the SOFC works at steady-state [8], T_E is the emitter temperature, T_0 is the environment temperature, P_F and P_T are, respectively, the power outputs of the SOFC and TPVC, $\dot{Q}_{leak}$ is the heat-leak rate released directly from the SOFC into the environment [6], $\dot{Q}_{out}$ is the heat flow from the PV cell to the environment, and $\dot{Q}_{in}$ is the heat flow transferred between the SOFC and the emitter, which are contacted with each other through high thermal conductivity material. The emitter and PV cell are, respectively, made of hexagonal Boron Nitride (h-BN) and low band-gap semiconductor material InGaAsSb. The emitter and PV cell are separated by a vacuum gap, which is larger than the characteristic wavelength of thermal radiation given by Wien's displacement law. Thus, the heat transfer between the emitter and the PV cell obeys the Stefan–Boltzmann law. The intrinsic mechanism of the hybrid device is that when the heat flow $\dot{Q}_{in}$ enters into the emitter, which in turns radiates photons with thermal power density $\dot{E}_{out}$ towards the PV cell at temperature T_S to generate the power output P_T [17]. To achieve a high efficiency, the BSR is placed behind the PV cell, which can control the cut-off spectrum and reflect the sub-bandgap photons with thermal energy density $\dot{E}_{in}$ back to the emitter where they can be reabsorbed to generate heat and additional photons. In this model, it is assumed that the reflectivity ρ_{BSR} in the BSR-PV interface is independent of the photon energy [17].

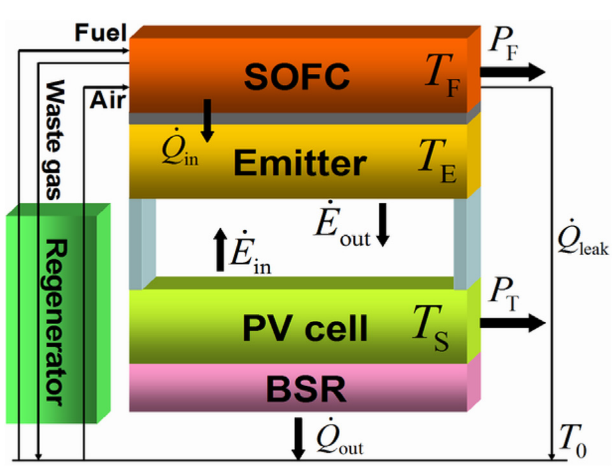

Fig. 1. The schematic diagram of a SOFC-TPVC hybrid device.

2.1. The power output and efficiency of a TPVC

In a TPVC, the total photon flux $\dot{N}$ and energy flux $\dot{E}$ of photons with electrochemical potential μ and energy ε [13,24,29,30].

$$\dot{N}(\varepsilon_1,\varepsilon_2,T,\mu) = \frac{2\pi}{h^3c^2}\int_{\varepsilon_1}^{\varepsilon_2}\frac{\varepsilon^2}{\exp[(\varepsilon-\mu)/(kT)]-1}d\varepsilon \quad (1)$$

and

$$\dot{E}(\varepsilon_1,\varepsilon_2,T,\mu) = \frac{2\pi}{h^3c^2}\int_{\varepsilon_1}^{\varepsilon_2}\frac{\varepsilon^3}{\exp[(\varepsilon-\mu)/(kT)]-1}d\varepsilon, \quad (2)$$

where c is the speed of light, h is the Planck constant, k is the Boltzmann constant, and ε is the energy of the photon, which is located between ε_1 and ε_2.

The photo-current density i_S generated in the TPVC is given by Ref. [15–18].

$$\frac{i_S}{q} = \frac{A_E}{A_S}f_{EC}\dot{N}(\varepsilon_g,\infty,T_E,0) - (1-f_{CC})\dot{N}(\varepsilon_g,\infty,T_S,qV_S) - n^2(1-\rho_{BSR})\dot{N}(\varepsilon_g,\infty,T_S,qV_S), \quad (3)$$

where ε_g is the bandgap of the semiconductor, f_{EC} and f_{CC} denote the emitter-to-cell view factor and cell-to- cell view factor, A_E and A_S represent the areas of the emitter and TPVC, q is the elementary positive charge, n is the refraction index of the TPVC semiconductor, and V_S is the output voltage of the TPVC, which is slightly below the theoretical limit $\tilde{V}_S = [\varepsilon_g(1-T_E/T_S)]/q$ [24].

The energy flux released from the emitter towards the PV is expressed as [15–18].

$$\dot{E}_{out} - \dot{E}_{in} = f_{EC}\dot{E}(\varepsilon_g,\infty,T_S,qV_S) - \dot{E}(\varepsilon_{CE},\infty,T_E,0) + \frac{A_E}{A_S}\frac{\rho_{BSR}f_{EC}^2}{1-\rho_{BSR}f_{CC}}\dot{E}(\varepsilon_{CE},\varepsilon_g,T_E,0), \quad (4)$$

where ε_{CE} is the cut-off energy of the emitter. According to the first law of thermodynamics, we have

$$\dot{Q}_{in} = A_E\left(\dot{E}_{out} - \dot{E}_{in}\right). \quad (5)$$