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Performance evaluation and parametric optimum design of a molten carbonate fuel cell-thermophotovoltaic cell hybrid system

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ABSTRACT

A new model of the hybrid system composed of a molten carbonate fuel cell (MCFC) and a thermophotovoltaic cell (TPVC) is proposed to recovery the waste heat produced by the MCFC. Expressions for the power output and the efficiency of the hybrid system are analytically derived. The performance characteristics of the hybrid system are evaluated. It is found that when the current density of the MCFC, voltage output of the TPVC, electrode area ratio of the MCFC to the TPVC, and energy gap of the material in the photovoltaic cell are optimally chosen, the maximum power output density of the hybrid system is obviously larger than that of the single MCFC. Moreover, the improved percentages of the maximum power output density of the proposed model relative to that of the single MCFC are calculated for differently operating temperatures of the MCFC and are compared with those of some MCFC-based hybrid systems reported in the literature, and consequently, the advantages of the MCFC-TPVC hybrid system are revealed.

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1. Introduction

With increasing fuel consumption and environment pollution, a great number of researchers have devoted to reduce dependence on traditional energy and research renewable energy [1]. Fuel cells can offer a clean, cost-effective, and efficient energy supply and become a strong alternative technology in energy conversion field. Moreover, for high temperature fuel cells, the waste heat recovery is of utmost importance for raising system conversion efficiency [2].

Having many advantages, such as fuel flexibility (carbon monoxide, natural gas, and coal gas can be used as fuel), high efficiency (45–60%), and low-cost (it is not needed to use the noble metals as electrodes), molten carbonate fuel cells (MCFCs) [3,4] are one of the most promising high-temperature fuel cells. In addition, when an MCFC is operated and combined with other power devices such as the gas turbine (GT) [5], heat engine [6], and thermoelectric generator (TEG) [7,8], the high-grade waste heat produced in the fuel cell can be utilized to further increase the conversion efficiency of fuel [9–11]. The performance characteristics of high-temperature fuel cell-based hybrid systems have been investigated and many significant results have been obtained [12–15]. However, there are some disadvantages for the variously existing high-temperature fuel cell-based hybrid systems. For example, the fuel cell-GT hybrid system [16,17] needs more auxiliary devices, leading to larger costs. The fuel cell-heat engine hybrid system [18,19] is not convenient for miniaturization. The primary drawback of the fuel cell-TEG hybrid system [20,21] is that the efficiency of the TEG is low [22,23] so that the high-grade waste heat is not utilized effectively.

Thermophotovoltaic cells (TPVCs) are a class of the high-temperature photovoltaic (PV) cells [24,25] and can efficiently convert the thermal radiation from heat sources such as the sun, fuel combustion, etc. into electricity [26–28]. Besides, the conversion efficiency of TPVCs can even exceed the Shockley–Queisser efficiency limit of a single-junction PV cell [29], and meanwhile TPVCs have many other merits, such as high power and energy densities, stable (non-intermittent), and without moving parts [30]. If we establish a new hybrid system consisting of an MCFC and a TPVC, the TPVC can be utilized to directly recovery the waste heat produced by the MCFC. It can be expected that the conversion efficiency of fuel will be significantly improved and the hybrid system will have a larger power output than the single MCFC.

In the present paper, a new model of the hybrid system consisting of an MCFC and a TPVC is briefly described. Expressions for the power output and the efficiency of the hybrid system are derived. The effects of the current density of the MCFC, voltage output of the TPVC, the area ratio of the TPVC to the MCFC, and energy gap of the material in the PV cell on the performance of the hybrid

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Nomenclature

A	area (cm^2)
c	speed of light ($cm\ s^{-1}$)
E	photon energy (eV)
E_g	energy gap (eV)
e	quantity of electric charge (C)
F	Faraday constant ($C\ mol^{-1}$)
f_{mt}	emitter-to-cell view factor
f_{tt}	cell-to-cell view factor
Δg	molar Gibbs free energy change ($J\ mol^{-1}$)
ΔH	enthalpy change rate (W)
Δh	mole enthalpy change ($J\ mol^{-1}$)
h	Planck constant (J s)
i	current density ($A\ cm^{-2}$)
K_B	Boltzmann constant ($J\ K^{-1}$)
n_e	number of electrons
p	partial pressure (atm)
P	power output (W)
P^*	power output density ($W\ cm^{-2}$)
q_1	heat flows from the MCFC to the emitter (W)
q_2	heat flows from the PV cell to the environment (W)
q_L	heat leakage rate (W)
q_r	net heat flow from the emitter to the PV cell (W)
R	universal gas constant ($J\ mol^{-1}\ K^{-1}$)
T	temperature (K)
U	reversible voltage of fuel cell (V)
V	over-potential/voltage output (V)

Greek symbols

α_A	area ratio
β	reflectivity
λ	refraction index
ε	thermal emissivity
σ	Stefan-Boltzmann constant ($W\ m^{-2}\ K^{-4}$)
κ	heat transfer coefficient ($W\ m^{-2}\ K^{-1}$)
η	efficiency

Subscripts

0	environment
f	molten carbonate fuel cell (MCFC)
j	CO_2, O_2, H_2O, and H_2
L	heat leakage
m	emitter
max	maximum
s	starting
t	thermophotovoltaic cell (TPVC)
x	anode and cathode
ano	anode of the MCFC
cat	cathode of the MCFC
ohm	ohmic loss

Abbreviations

GT	gas turbine
MCFC	molten carbonate fuel cell
PV	photovoltaic
TEG	thermoelectric generator
TPVC	thermophotovoltaic cell

system are analyzed. The lower and upper bounds of optimized parameters are determined. The improved percentage of the maximum power output of the proposed model is compared with those of other MCFC-based hybrid systems.

2. Model description of an MCFC-TPVC hybrid system

A new model of the MCFC-TPVC hybrid system consisting of a MCFC and a TPVC is shown in Fig. 1, where T_f, T_m, T_t, and T_0 are, respectively, the temperatures of the MCFC, emitter, PV cell, and environment, q_1 and q_2 are, respectively, the heat flows from the MCFC to the emitter and from the PV cell to the environment, q_L is the heat leakage rate from the MCFC to the environment, and q_r is the net heat flow from the emitter to the PV cell. The MCFC is mainly composed of the electrolyte, anode, and cathode and usually operated in the range of 600–700 °C [31]. Fuel and oxygen are, respectively, supplied to the anode and cathode by gas channels. The TPVC consists of the emitter, PV cell, and back surface reflector that reflect non-absorbed radiation back to the emitter. The gap between the emitter and the PV cell is much larger than the thermal radiation wavelength given by Wien's law, and consequently, the heat transfer between the emitter and the PV cell may be described by the theory of the far-field thermal radiation.

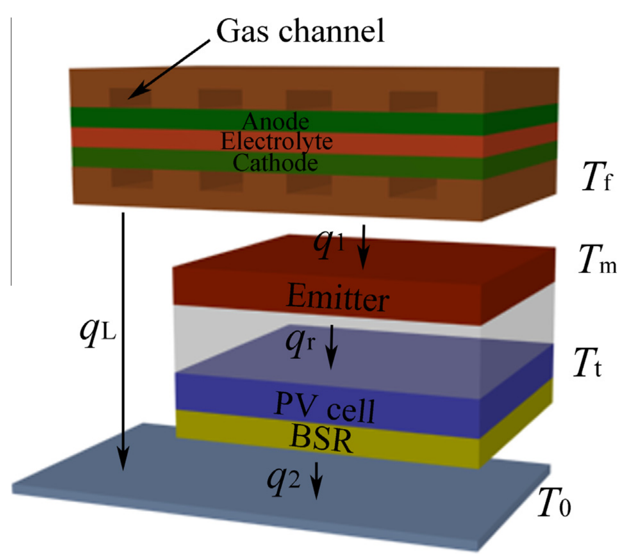

Fig. 1. The schematic diagram of an MCFC-TPVC hybrid system.

2.1. Power output and efficiency of an MCFC

Based on the configuration of the MCFC shown in Fig. 1, the electrochemical reaction in the MCFC can be summarized as: anode reaction $H_2 + CO_3^{2-} \rightarrow CO_2 + H_2O + 2e^-$, cathode reaction $CO_2 + \frac{1}{2}O_2 + 2e^- \rightarrow CO_3^{2-}$, and overall reaction $H_2 + \frac{1}{2}O_2 + CO_2$ (Cathode) $\rightarrow H_2O + CO_2$(Anode) + Electricity + Heat. The reversible potential can be calculated from Nernst equation as [31]

$$U = \frac{-\Delta g}{n_e F} + \frac{RT_f}{n_e F} \ln\left[\frac{p_{H_2,ano}(p_{O_2,cat})^{1/2} p_{CO_2,cat}}{p_{H_2O,ano} p_{CO_2,ano}}\right], \tag{1}$$

where Δg is the molar Gibbs free energy change of the electrochemical reaction at temperature T_f and pressure 1 atm, R is the universal gas constant, F is Faraday's constant, n_e is the number of electrons transferred in reaction, $p_{j,x}$ is the partial pressure, and the subscripts j and x indicate reactants (CO_2, O_2, H_2O, and H_2) and electrodes (anode and cathode), respectively.

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