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Optimum operation states and parametric selection criteria of a high temperature fuel cell-thermoradiative cell system

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ABSTRACT

A coupling system composed of a high temperature fuel cell such as a molten carbonate fuel cell (MCFC), a regenerator, and a thermoradiative cell (TRC) is established. The efficiency and power output of the coupling system are analytically derived. The performances of the system are evaluated. The optimum operation states of the system are determined. The optimal selection criteria of some key parameters are provided. It is found that when the MCFC is operated at the temperature of 923 K and the band gap of the TRC equals 0.2 eV, the maximum power output density (MPOD) of the coupling system is approximately 2.020 times of that of a single MCFC and the corresponding efficiency of the coupling system is approximately 1.304 times of that of the MCFC. The percentage improvements of the MPODs of the coupling system and other MCFC-based coupling systems in the existing literatures are compared. The results show that the MCFC-TRC coupling system can exhibit better performance and make use of the waste heat released by the MCFC more effectively in comparison with other MCFC-based coupling systems. Moreover, it is expounded that the TRC is an efficient device which can recycle and utilize the waste heat produced by other high temperature fuel cells such as solid oxide fuel cells and direct carbon fuel cells.

1. Introduction

High temperature fuel cells (HTFCs) [1–4] can directly convert a part of chemical energy from fuels into electricity through electrochemical reactions and be not only used as the main or backup power supply for residential, industrial, and commercial buildings in remote areas, but also applied to power fuel cell vehicles including automobiles, boats, and so on. According to the different fuels and electrolytes, HTFCs can be classified into the solid oxide fuel cell [5], direct carbon fuel cell [6], molten carbonate fuel cell (MCFC) [7], etc. The solid oxide fuel cell is widely used because of its excellence in fuel flexibility and the solid-phase electrolyte that can reduce corrosion [8], but its disadvantages include the long start-up time and various mechanical and chemical compatibility issues [9]. The advantages of the direct carbon fuel cell are abundant fuel sources, low greenhouse gas emissions, and with no need for gasification [10], but short lifespan and the high required purity for carbon are some of its drawbacks [11]. In the MCFC, natural gas, coal gas, and carbon monoxide can be utilized as fuels and the metal catalysts at electrodes are not needed, which thus reduce costs. Unlike alkaline and phosphoric acid fuel cells, the external reformers converting fuels to hydrogen are not required for MCFCs. Such a process called internal reforming can be completed within the MCFC itself due to the high operating temperature, which also reduces costs [12]. The efficiencies of MCFCs can approach 50%, considerably larger than that of phosphoric acid fuel cells [13]. However, a properly operated MCFC simultaneously releases a great deal of waste heat. Investigating a way to exploit the waste heat has become an attractive topic in the development of MCFCs [14–16]. De Escalona et al. [17] presented a comparative analysis of coupling systems based on MCFCs and closed-cycle externally-heated bottoming systems, and found that the two option Stirling engines and supercritical carbon dioxide gas turbines (GT) fit to different output ranges. Baronci et al. [18] proposed a coupling system by combining an MCFC and a Brayton cycle to further produce electricity and illustrated that the boost in electrical efficiency obtained with a Brayton cycle is twice of that of a coupling system with an Organic Rankine cycle. Wu et al. [19] established an MCFC-thermoelectric generator (TEG) coupling system for additional power generation, and derived that the efficiency of the coupling system at the maximum power output density (MPOD) can reach 30%, which is larger than that of the stand-alone MCFC. Yang et al. [20] used a thermophotovoltaic cell (TPVC) and an MCFC to constitute a coupling system and found that the improved percentage of the MPOD of the

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Nomenclature

A	area (cm^2)
c	velocity of light ($cm\,s^{-1}$)
e	elementary charge (C)
$\dot{E}$	energy flux density of photons ($W\,cm^{-2}$)
E_g	energy gap (eV)
F	Faraday's constant ($C\,mol^{-1}$)
Δg	molar Gibbs free energy change ($J\,mol^{-1}$)
h	Planck constant (Js)
Δh	mole enthalpy change ($J\,mol^{-1}$)
$\Delta\dot{H}$	enthalpy change rate (W)
i	current density ($A\,cm^{-2}$)
k_B	Boltzmann constant ($J\,K^{-1}$)
n_e	number of electrons
$\dot{N}$	photon flux density ($cm^{-2}\,s^{-1}$)
p	pressure (atm)
P	power output (W)
P^*	power output density ($W\,cm^{-2}$)
q_L	heat leakage rate ($W\,cm^{-2}$)
R_0	gas constant ($J\,mol^{-1}\,K^{-1}$)
T_A	ambient temperature (K)
V	potential (V)
μ	quasi-Fermi level difference (J)

Greek symbols

α	area ratio
ε	photon energy (J)
ρ	thermal emissivity
σ	Stefan-Boltzmann constant ($W\,cm^{-2}\,K^{-4}$)
κ	heat conductivity coefficient ($W\,cm^{-2}\,K^{-1}$)
ω	percentage improvement
η	efficiency

Subscripts

ano	anode
cat	cathode
F	MCFC
j	H_2, O_2, H_2O, CO_2
m	local maximum
max	maximum
ohm	ohmic overpotential
rev	reversible overpotential
R	TRC

Abbreviations

GT	gas turbine engine
HTFC	High temperature fuel cell
MCFC	molten carbonate fuel cell
MPOD	maximum power output density
POD	power output density
TEG	thermoelectric generator
TIG	thermionic generator
TPVC	thermophotovoltaic cell
TRC	thermoradiative cell

coupling system is changed in the range of 37.30% to 51.14% when the temperature of the MCFC is ranged from 873 K to 923 K. Huang et al. [21] proposed a coupling system made of an internal reforming MCFC and a vacuum thermionic generator (TIG), and evaluated that the MPOD of such a coupling system can be promoted by 22% compared to that of a single MCFC. Despite much progress, however, the efficiencies of the above-mentioned devices for recycling the waste heat of MCFCs still remain at a low level. Therefore, establishing a new device to more efficiently harvest the waste heat released from MCFCs is very meaningful.

Based on the physical principles of photovoltaic cells [22], the thermoradiative cells (TRCs) [23,24] consisting of p-n junctions have attracted much attention because of their excellent characterization on harvesting thermal energy. Unlike the TPVC which is exposed to a hot surface higher than the temperature of the cell itself when operated, TRCs should be kept at a higher temperature than the environment. Contrasted with TPVCs, TRCs hold many advantages, such as relative simple manufacture and operation, low cost, high power output density (POD) and efficiency, etc. The working regimes and theoretical efficiency limits of a single-junction TRC have been analyzed based on the detailed balance method and it is found that when a TRC with an band gap of 0.4 eV is operated at 1000 K and the environment temperature is 300 K, the theoretical efficiency of the TRC can reach 50% when the POD of the cell equals 0.1 $W\,cm^{-2}$ [23]. The concept of thermoradiative energy conversion was also experimentally demonstrated [24]. Subsequently, it was reported that the efficiencies of TRCs can be improved by using near-field radiative heat transfer [25–27]. Fernández [28] put forward the model of a three-level TRC and discussed its performance. Liao et al. [29] studied the solar-driven negative illumination TRC and found that the device can achieve a high efficiency for low concentrating factor. Zhang et al. [30] proposed an updated model of TRCs with sub-band gap and non-radiative losses. Since TRCs can harvest heat energy with relatively high efficiency and POD, the MCFC-TRC coupling system should be established and studied.

In this paper, a coupling system including an MCFC, a regenerator, and a TRC is proposed to harvest the waste heat released from the MCFC. In Section 2, the operating principles of the MCFC and TRC are briefly described, and the expressions of the efficiency and power output of the coupling system are derived. In Section 3, the performances of the coupling system are evaluated and the optimally working regions of some important parameters are given. In Section 4, the percentage improvements of the MPODs of the MCFC-TRC coupling system and other MCFC-based coupling systems at different operating temperatures are compared. In Section 5, a brief conclusion is drawn.

2. Model description

Fig. 1 illustrates the detail configuration of the integrated system consisting of an MCFC, a regenerator, and a TRC, where the inlet and outlet of the various processes are indicated by the corresponding arrowhead. In Fig. 1, P_F and P_R are the power outputs of the fuel cell and TRC operated at temperatures T_F and T_R, respectively, q_F and q_R are the heat flows from the MCFC to the TRC and from the TRC to the

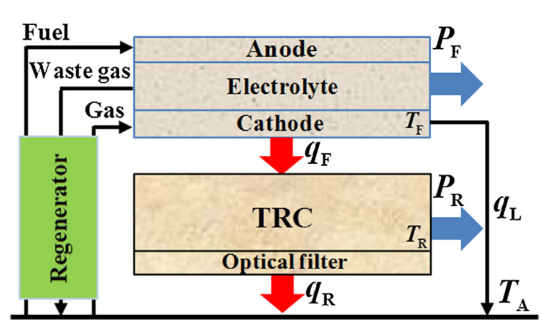

Fig. 1. The diagram of an MCFC-TRC coupling system.