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An efficient hybrid system using a thermionic generator to harvest waste heat from a reforming molten carbonate fuel cell

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ABSTRACT

A new hybrid system consisting of an internal reforming molten carbonate fuel cell (IR-MCFC) and a vacuum thermionic generator (TIG) is constructed. By considering the main irreversible losses in two subsystems and the coupling process, general expressions for the power output and efficiency of the hybrid system are derived. The performance characteristics of the hybrid system are revealed, and the optimal regions, including the power output, efficiency, and load resistances, are determined. It is found that the maximum power output density of the IR-MCFC/TIG system increases by 22% compared to that of a single MCFC, and among the IR-MCFC- and MCFC-based hybrid systems reported in the literature, the present hybrid system can most efficiently harvest the waste heat from the MCFC.

1. Introduction

Fuel cells represent a class of efficient energy converting systems that directly turn chemical energy into electricity [1,2]. To date, various types of fuel cells have been proposed, investigated, and constructed [3–6]. Among them, the molten carbonate fuel cell (MCFC), developed in the 1950s, is one of the most promising fuel cells because of its stationary power output and high efficiency [7,8]. Many comprehensive studies have been performed in both theory and experiment [9–14].

Currently, much attention has been paid to reducing the costs of MCFCs and improving the efficiency of MCFCs [15–17]. Traditional fuel cells fueled by H_2 have the difficulties of hydrogen production, preservation, and transportation. By applying internal [18–23] or external reforming technology [24,25], the MCFCs, working at high temperatures of nearly 600–800 °C, can directly utilize other inexpensive and resourceful gases as fuel, such as natural gas, biogas, landfill gas, and methane [26–31]. This is an attractive business prospect. Moreover, the recovery of the waste heat produced by MCFCs is another significant issue in the investigation of the performance of fuel cells. Coupling MCFCs with different thermodynamic systems, such as gas turbines [32–37] and heat engines [38–42], has been intensively discussed, but the complex structure and low efficiency of these systems may limit their actual use. In comparison, as one type of high-temperature solid state generator, the vacuum thermionic generator uses electrons as the working substance and has advantages that include no mechanically moving parts, a small device size, and high power density [43–46], and it may be a better device for using the waste heat from MCFCs.

In the present paper, we establish a new hybrid model composed of an IR-MCFC and a vacuum TIG. Some irreversible losses in the hybrid system are considered. The expressions of the power outputs and efficiencies for the two subsystems and hybrid system are analytically derived. According to the first law of thermodynamics, an important energy equilibrium equation between the two subsystems is obtained. The graphs of the power output, efficiency, and load resistances, varying with different parameters, are generated. The performance characteristics of the IR-MCFC/TIG hybrid system are revealed, and the optimal regions of some important parameters are determined. The results obtained here are compared with those of other IR-MCFC- or MCFC-based hybrid systems reported in the literature.

2. The hybrid system consisting of an IR-MCFC and a TIG

Fig. 1 shows the hybrid system composed of an IR-MCFC and a vacuum TIG, where P_f and P_t are, respectively, the power outputs of the MCFC and the TIG; q_r is the reforming energy; q_l is the heat loss from the MCFC to the environment; q_c is the heat absorbed by the cathode of the TIG; and q_a is the heat released by the anode of the

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Nomenclature

A_0	Richardson-Dushmann constant ($A\,m^{-2}\,K^{-2}$)
$C_{p,k}$	molar heat capacity of component k at constant pressure ($J\,mol^{-1}\,K^{-1}$)
e	unit charge (C)
E_{act}	activation energy ($J\,mol^{-1}$)
E_0	ideal standard potential (V)
F	Faraday constant ($C\,mol^{-1}$)
Δg	molar Gibbs energy change ($J\,mol^{-1}$)
Δh	molar enthalpy change ($J\,mol^{-1}$)
$\Delta \dot{H}$	enthalpy change rate (W)
i	current density of the TIG ($A\,m^{-2}$)
j	current density of the MCFC ($A\,m^{-2}$)
j_{co}	cut-off current density ($A\,m^{-2}$)
j_{st}	start-work current density ($A\,m^{-2}$)
k_1	area ratio
k_B	Boltzmann constant ($J\,K^{-1}$)
L_m	molar latent heat of H_2O ($J\,mol^{-1}$)
n_e	number of electrons
$\dot{n}_f$	molar rate of fuel flowing ($mol\,s^{-1}$)
$\dot{n}_H$	hydrogen expended rate ($mol\,s^{-1}$)
p_α	partial pressure of constituent α (atm)
P	power output (W)
P^*	power output density ($W\,m^{-2}$)
q_a	heat released by the TIG anode (W)
q_c	heat absorbed by the TIG cathode (W)
q_l	heat loss rate (W)
q_r	reforming energy rate (W)
q_w	waste heat rate (W)
r	load resistance (Ω)
R	universal gas constant ($J\,mol^{-1}\,K^{-1}$)
R_0	reforming energy of methane per mole ($J\,mol^{-1}$)
S	surface area (m^2)
T	working temperature of the MCFC (K)
T_0	environment temperature (K)
T_a	anode temperature of the TIG (K)
U	voltage of the MCFC (V)
U_0	ideal equilibrium potential (V)
U_{ohm}	ohm overpotential (V)
V	voltage of the TIG (V)
V_c	optimal voltage of the TIG (V)

Greek symbols

χ_{CH_4}	molar fraction of methane
ε	thermal emissivity
σ	Stefen-Boltzmann constant ($W\,m^{-2}\,K^{-4}$)
δ_r	heat loss ratio in reforming process
κ	heat conductivity coefficient ($W\,m^{-2}\,K^{-1}$)
η	efficiency
Φ_a	anode work function of the TIG (eV)

Subscripts

a	anode
c	cathode
f	MCFC
l	heat loss
m	maximum power output density
s	hybrid system
t	TIG
1, 2	two states of $P_s^* = P_{fm}^*$

Abbreviations

MCFC	molten carbonate fuel cell
TIG	thermionic generator
GT	gas turbine
IR	internal reforming
SCO_2	supercritical CO_2

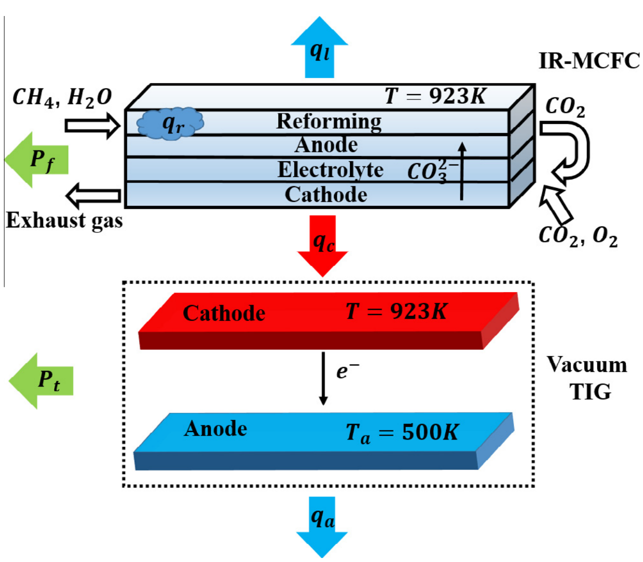

Fig. 1. The schematic diagram of the hybrid system composed of an internal reforming molten carbonate fuel cell and a vacuum thermionic generator.

TIG. Identical TIGs can be set in both the top and bottom sides of the MCFC. For simplicity, we only draw one equivalent TIG, shown in Fig. 1.

2.1. Model description of an IR-MCFC

The IR-MCFC shown in Fig. 1 has no extra supply heat for reforming a reaction and no extra structure for reforming product transportation. During the reforming process, pure methane and steam are utilized as the fuel. The two main reforming reactions are the steam/methane reforming reaction (SMR): $CH_4 + H_2O \leftrightarrow CO + 3H_2$ and the water–gas shift reaction (WGS): $CO + H_2O \leftrightarrow CO_2 + H_2$ [19,23,31]. The overall reforming reaction is written as

$$CH_4 + 2H_2O \leftrightarrow CO_2 + 4H_2. \quad (1)$$

In reality, the fuel utilization and the chemical reactivity in the internal reforming process are incomplete and depend on the size of the fuel cell stack, operating conditions, catalyst activity, etc. Such some incompleteness will reduce the performance of the IR-MCFC system [18,19,47,48]. In the present model, the effect of the fuel utilization and the incomplete chemical reactions on the system performance will be not discussed quantitatively. The methane is assumed to be completely used because we mainly focus on the recovery of the waste heat. Thus, the extra heat provided by the MCFC during the reforming process can be calculated by

$$q_r = \dot{n}_f \chi_{CH_4} \left\{ 4\left[\Delta h_f^0(H_2) + \int_{T_0}^{T} C_{p,H_2} d\tau\right] + \left[\Delta h_f^0(CO_2) + \int_{T_0}^{T} C_{p,CO_2} d\tau\right] - \left[\Delta h_f^0(CH_4) + \int_{T_0}^{T} C_{p,CH_4} d\tau\right] - 2\left[\Delta h_f^0(H_2O) + L_m + \int_{T_0}^{T} C_{p,H_2O} d\tau\right] \right\}, \quad (2)$$