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Using electrochemical cycles to efficiently exploit the waste heat from a proton exchange membrane fuel cell

Xin Zhang [a,1], Yuzhuo Pan [b,1], Ling Cai [c], Yingru Zhao [d], Jincan Chen [a,*]

[a] Department of Physics, Xiamen University, Xiamen 361005, People's Republic of China
[b] College of Physics and Information Engineering, Quanzhou Normal University, 362000, People's Republic of China
[c] Third Institute of Oceanography of State Oceanic Administration, Xiamen 361005, People's Republic of China
[d] School of Energy Research, Xiamen University, Xiamen 361005, People's Republic of China

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ABSTRACT

With the help of the current models of a proton exchange membrane fuel cell (PEMFC) and a thermally regenerative electrochemical cycle (TREC), a novel model of the hybrid system composed of a PEMFC and *N* TRECs is established. The TRECs in the system can effectively exploit the waste heat released form the PEMFC. The expressions for the power output and efficiency of the hybrid system are analytically derived. The effects of some key parameters including the electric current density and electrode area of the PEMFC and the electric current and regenerative efficiency of TRECs on the performance of the system are discussed in detail. It is found that when the regenerative efficiency of TRECs is in the range of 0.2–0.8, the maximum power output density of the hybrid system is about 1.11–1.20 times of that of the PEMFC. The maximum power output densities and corresponding efficiencies of the hybrid system at the differently operating temperatures of the PEMFC are calculated and compared with those of other PEMFC-based hybrid systems, and consequently, it is revealed that the proposed model can more efficiently utilize the waste heat produced in a PEMFC than other PEMFC-based hybrid systems.

1. Introduction

Among several types of fuel cells, proton exchange membrane fuel cells (PEMFCs) [1–5] are one class of the most popular low temperature fuel cells. Contrasted with other fuel cells, PEMFCs have some key advantages such as the low operating temperature, relative simplicity of design and operation, high power density, and so on [6–8] and portable and stationary applications including automotive, laptop computers, and other electronic devices [9–11]. When PEMFCs are operated under steady-state conditions, they supply power output and simultaneously produce a large amount of waste heat. How to recycle the waste heat produced in PEMFCs has become an interesting issue in the development process of PEMFCs [12–21].

During the last years, the related researches to find the various feasible methods to exploit the waste heat of PEMFCs have drawn widely attention. Several theoretical investigations have dealt with the efficiently exploiting problem of the waste heat recycle from PEMFCs. For example, Chen et al. [14] established a hybrid system through the combination of a PEMFC with a thermoelectric generator (TEG) and offered an alternative approach for thermal energy harvesting. Zhang et al. [15] proposed a novel hybrid system by integrating a refrigeration cycle (RC) to a PEMFC to exploit the waste heat for the cooling purpose. Zhao et al. [16] carried out the parametric studies on a hybrid system composed of a PEMFC and an organic Rankine cycle (ORC) to recover the waste heat. Yang and Zhang [17] proposed a hybrid system by integrating a PEMFC with an absorption refrigerator (AR) to simultaneously produce electricity and cooling. Zhang and Chen [18] presented a new hybrid system consisting of a PEMFC and a heat-driven heat pump (HP) and illustrated that the waste heat can be readily used in such a system. However, up to now, the efficiency of the waste heat recovery released from PEMFCs is still at a low level. Besides the - hybrid systems mentioned above, which new device can be used to efficiently utilize the low-grade waste heat in PEMFCs? This is a new worthy topic to be studied.

Recently, the method of thermally regenerative electrochemical cycles (TRECs) for harvesting the low-grade thermal energy has attracted some interest [22–26] due to the development of highly reversible electrode materials. Based on the temperature dependence of electrode voltage, Lee et al. [22] proposed a novel TREC system, which can be used to effectively recycle low-temperature

* Corresponding author.
E-mail address: jcchen@xmu.edu.cn (J. Chen).
[1] The two authors contribute equally to this work.

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Nomenclature

A	area (cm^2)
c_p	specific heat capacity (J g^{-1} K^{-1})
c_q	specific charge capacity (A h g^{-1})
d_m	thickness of aqueous electrolyte (cm)
F	Faraday's constant (Cmol^{-1})
Δg	molar Gibbs energy change (Jmol^{-1})
Δh	molar enthalpy change (Jmol^{-1})
$\Delta \dot{H}$	enthalpy change rate (W)
i_F	current density of PEMFC (A cm^{-2})
i_0	exchange current density (A cm^{-2})
i_L	limiting current density (A cm^{-2})
I	electric current of TRECs (A)
m	cell number charged simultaneously
N	cell number
n_e	number of electrons
p_{H_2}	partial pressure of H_2 (atm)
p_{O_2}	partial pressure of O_2 (atm)
P	power output (W)
P^*	power output density (W cm^{-2})
q_1	heat flow absorbed from PEMFC (W)
q_2	heat flow released to the environment (W)
q_L	heat leak rate (W)
R	universal gas constant (Jmol^{-1} K^{-1})
R_s	internal resistance (Ω)
Δs	molar entropy change (Jmol^{-1})
T	temperature (K)
k	heat leak coefficient (WK^{-1} cm^{-2})
V	voltage (V)

Greek symbols

α	temperature coefficient (V K^{-1})
β	concentration overpotential constant
η	efficiency
λ	charge transfer coefficient
σ	specific conductivity (S m^{-1})

Subscript

A	ambient environment
act	activation
co	cut off
con	concentration
E	TRECs
F	PEMFC
H	hot reservoir
Lb	lower boundary
max	maximum
ohm	ohmic
P	state at maximum power
R	regeneration process
Ub	upper boundary

Abbreviations

PEMFC	proton exchange membrane fuel cell
AR	absorption refrigerator
HP	heat pump
ORC	organic Rankine cycle
RC	refrigerator cycle
TEG	thermoelectric generator
TREC	thermally regenerative electrochemical cycle

heat, and the efficiency of the TREC can be significantly improved to 5.7%. Yang et al. [23,24] further presented charging-free and membrane-free electrochemical systems to harvest waste heat. Compared with semiconductor thermoelectric devices, the electrode materials of the TREC have the advantage characteristics of the opposite temperature coefficient, high charge capacity, low heat capacity, and low polarization [25–30]. Moreover, the TREC at low temperatures has an advantage of high power output and efficiency and is more suitable for constituting a hybrid system together with a PEMFC than other devices.

In the present paper, a novel model of the hybrid system composed of a PEMFC and N TRECs is used to continuously and stably harvest the waste heat produced in the PEMFC. By considering the main irreversible losses of the system, the analytical expressions for the power output and efficiency of the hybrid system are derived. The effects of some important parameters on the performance of the hybrid system are discussed in detail. It is found that when the regeneration efficiency of TRECs is equal to 70%, the maximum power output density of the hybrid system is about 1.19 times of that of the PEMFC. Moreover, the performances of the PEMFC-TREC and other PEMFC-based hybrid systems are compared. The results obtained show that the PEMFC-TREC hybrid system can more efficiently harvest the low-grade heat energy produced in the PEMFC than other PEMFC-based hybrid systems.

2. Model description of a new hybrid system

In Ref. [19], Long et al. presented a hybrid system by using an electrochemical cell to harvest the waste heat from the PEMFC. Wang et al. [31] pointed out that a single TREC cannot continuously absorb heat from a heat reservoir during the whole cycle period. This implies the fact that the hybrid system established in Ref. [19] can only discontinuously absorb the heat produced in a PEMFC so that the operating temperature of the PEMFC is difficult in being kept constant. On the other hand, a single TREC cannot generate continuous power output [19,22–25], and consequently, the hybrid system composed of a TREC and a PEMFC may not work stably and be convenient in practical applications. In addition, the heat leak losses between the subsystems, which must be considered in the performance evaluation of a hybrid system, are not considered in Ref. [19]. Thus, the topic how to establish a new PEMFC-TREC hybrid system is very significant.

The new hybrid system considered here consists of a PEMFC and N TRECs, as shown in Fig. 1, where the PEMFC operating at temperature T_F acts as the heat reservoir of N TRECs, P_F and P_E are, respectively, the power outputs of the PEMFC and TRECs, q_1 and q_2 are, respectively, the heat flows from the PEMFC to the TRECs and from the TRECs to the environment at temperature T_A, and q_L is the heat leak flow from the fuel cell to the environment. In the hybrid system, fuel and air are fed to the PEMFC and participate in electrochemical reactions to produce power. The role of the regenerator is to preheat the incoming fuel and air by utilizing the high temperature exhaust water to ensure that the PEMFC can work at steady-state. The N TRECs are used to harvest the waste heat produce in the PEMFC and generate the continuous power output, where one part of TRECs acts as the hot cells contacting with the hot reservoir, one part acts as the cold cells contacting with the environment reservoir, the rest part carries out the regenerative processes [31]. Since the high thermal conductivity material is usually filled between the PEMFC and the hot side of