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Performance assessment of an integrated molten carbonate fuel cell-thermoelectric devices hybrid system for combined power and cooling purposes

Mengmeng Wu [a], *Houcheng Zhang* [a,*], *Tianjun Liao* [b,**]

[a] *Department of Microelectronic Science and Engineering, Ningbo University, Ningbo 315211, China*
[b] *Department of Physics, Xiamen University, Xiamen 361005, China*

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ABSTRACT

In order to recover the waste heat produced in molten carbonate fuel cells (MCFCs), a new hybrid system mainly consisting of an MCFC, a thermoelectric generator, and a thermoelectric cooler is integrated for performance enhancement. The irreversible losses in each subsystem are fully considered. The relationship between the dimensionless electric current of the thermoelectric element and the electric current density of the MCFC is discussed in detail. Based on non-equilibrium thermodynamics, the analytical formulas for power density and efficiency of the hybrid system are specified under different operation conditions. The general performance characteristics of the hybrid system are revealed and the optimum regions for several parameters are given. Numerical calculations show that the power density and efficiency of the hybrid system are 3.4% and 4.0% larger than that of the stand-alone MCFC, respectively. The effects of some main operating and design parameters on the performance of the proposed system are discussed through parametric analyses. Abundant numerical calculation examples are provided to show how to improve the system performance. The results obtained may provide some theoretical bases for the MCFC performance improvement through heat management method.

Introduction

With the rising energy demands and the increasing depletion of fossil fuels, it is urgent to find alternative energy sources such as solar energy, wind turbine, fuel cell, etc. Fuel cells enable to directly and efficiently convert chemical energy of a fuel into electricity without pollutants, which are regarded as one of the most promising technologies [1–6]. Among various fuel cells, MCFCs have attracted considerable interests because of many advantages such as low emissions, fuel flexibility, possibility for CO_2 capture and storage and etc [7–10]. To now, a number of investigations on MCFCs have focused attention on aspects such as fabrication of cathode and anode materials [11–13], stack modeling and dynamic simulation [14,15], and theoretical modeling of a single MCFC [16,17].

The high-grade waste heat generated in MCFCs provides the opportunity for additional power generation or for combined heat and power (CHP) cogeneration [18–21]. Recently,

* *Corresponding author.*
** *Corresponding author.*
E-mail addresses: zhanghoucheng@nbu.edu.cn (H. Zhang), tianjunliao@163.com (T. Liao).
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many researchers have employed various thermal devices to recover the waste heat from MCFCs for various applications using various analysis approaches [22–33]. Wu et al. [22] proposed a hybrid system coupling a TEG to an MCFC to recover the waste heat produced in the MCFC. They evaluated the performance of the system by considering the thermo-electrochemical losses within the system and discussed the effects of some designing and operating parameters on the hybrid system performance. Yang et al. [23] introduced an MCFC-based hybrid system that bottomed with a thermo-photovoltaic cell. They systematically evaluated the performance characteristics of the MCFC-thermophotovoltaic cell hybrid system and demonstrated the superiority of the introduced system over other similar hybrid systems. Huang et al. [24] performed the thermodynamic analyses of an MCFC-thermionic generator (TIG) hybrid system which includes a reforming MCFC and a TIG. They considered the effects of irreversible losses in the reforming and electrochemical reaction processes and then revealed the generic performance characteristics and obtained the optimal regions of the proposed system. The results showed that the maximum power density of the MCFC-TIG system is about 22% larger than a stand-alone MCFC. Açıkkalp performed the ecologic and sustainable objective thermodynamic analyses of an MCFC-supercritical CO_2 Brayton cycle hybrid system [25] and an MCFC-heat engine hybrid system [26]. The results obtained are helpful to design more environmental-friendly MCFC-based hybrid systems. Mehrpooya et al. [27] introduced and analyzed a hybrid system composed of an MCFC and a supercritical carbon dioxide Brayton cycle for additional power production. This kind of hybrid system not only improved the efficiency and reduced the cost but also enabled to reduce the harmful emissions and negative impact on the environment. Duan et al. [28] used Aspen Plus to investigate a coal-fired power plant that captures CO_2 by integrating a molten carbonate fuel cell, and showed that the total efficiency the proposed system is increased by 4.05% compared with that of the coal-fired power plant without CO_2 capture system. Zhang et al. [29] used an absorption refrigerator to recover the waste heat from an MCFC for combined power and cooling applications. It is found that the maximum power density and efficiency of the proposed system are increased by 3.2% and 3.8% compared with that of the sole MCFC.

Thermoelectric devices are kinds of energy conversion devices that convert waste heat directly into electricity (i.e., thermoelectric generator, TEG) or convert electrical energy into thermal energy for cooling (i.e., thermoelectric cooler, TEC) or heating (i.e., thermoelectric heat pump, THP) [34]. Thermoelectric devices can be used in a significant of amount of fields such as aerospace, military, industrial, and vehicle applications as they are structure-compacted, quiet, environmental-friendly, highly reliable and flexible to various heat sources [35]. To improve thermoelectric devices performance, a number of studies have done on aspects including geometric configuration design [36–38], advanced materials fabrication [39,40], and system integration and optimization [41–43]. Alternatively, the TEG, TEC and THP could be readily connected in a multistage way to enhance their performance [44–46]. Furthermore, different kinds of thermoelectric devices can be cascaded to achieve specific purposes such as heat to cooling, power/cooling cogeneration, and power/heating cogeneration [47,48]. The combination of TEGs and TECs offers the possibility to convert the heat to cooling using electricity as agent [49]. Obviously, the thermoelectric devices TEG-TEC can be used to recover the waste heat in MCFCs for additional cooling production, and thus the performance of MCFCs can be improved.

In this study, a new hybrid system that integrates a thermoelectric generator and a thermoelectric cooler with an MCFC to simultaneously produce electricity and cooling is proposed. Based on the theories of electrochemistry and non-equilibrium thermodynamics, the multi-irreversible losses in each component are described. The problem how to design and operate the cascading thermoelectric devices will be solved. Expressions for equivalent power output and efficiency of the MCFC, thermoelectric devices and hybrid system are derived, from which the generic performance characteristics of the proposed system will be revealed. Finally, parametric studies will be used to discuss the effects of some designing parameters and operating conditions on the proposed system performance.

Description of the hybrid system

Fig. 1 shows the schematic diagram of the proposed hybrid system that mainly consists of an MCFC, a TEG, a TEC, and a regenerator. Fuel and air are supplied to the fuel cell and participate in electrochemical reactions to produce electric power P_{MCFC} and waste heat. A part of the waste heat, Q_H (J s^{-1}), is transferred from the MCFC at temperature T to the TEG for electricity generation via Seebeck effect. The generated electrical current I_g is flowed to TEC for extracting heat Q_C (J s^{-1}) from the cooled space at temperature T_C via Peltier effect. Another part of the produced waste heat, Q_L (J s^{-1}), is directly leaked from the MCFC to the environment at temperature T_0 via convection or conduction heat-transfer. The rest part of waste heat, Q_R (J s^{-1}), is used to compensate the regenerative loss in the regenerator. The regenerator utilizes the heat in high-temperature exhaust products to preheat the reactants from T_0 to T. Q_1 (J s^{-1}) and Q_2 (J s^{-1}) are, respectively, heat-transfer rates between the environment and the TEG and the TEC.

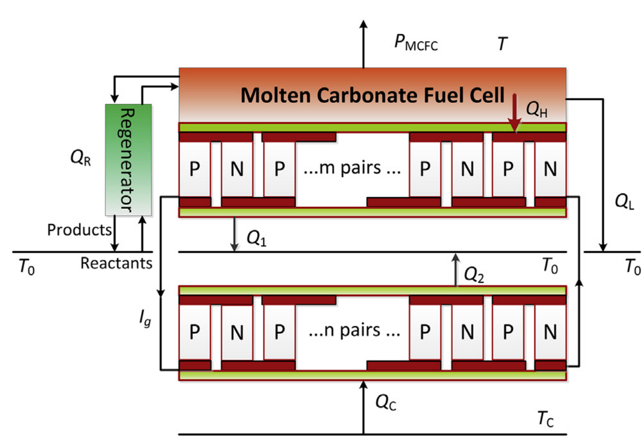

Fig. 1 – Schematic diagram of an MCFC/thermoelectric devices hybrid system.

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