Energy 112 (2016) 520–527

Contents lists available at ScienceDirect

Energy

journal homepage: www.elsevier.com/locate/energy

Performance assessment of a hybrid system integrating a molten carbonate fuel cell and a thermoelectric generator

Sijie Wu [a], Houcheng Zhang [a, b, *], Meng Ni [b]

[a] Department of Microelectronic Science and Engineering, Ningbo University, Ningbo, 315211, China
[b] Department of Building and Real Estate, The Hong Kong Polytechnic University, Hong Kong, China

ARTICLE INFO

Article history:
Received 6 April 2016
Received in revised form
22 June 2016
Accepted 24 June 2016

Keywords:
Molten carbonate fuel cell
Thermoelectric generator
Hybrid system
Irreversible loss
Performance assessment

ABSTRACT

A hybrid system consisting of an MCFC (Molten Carbonate Fuel Cell), a TEG (Thermoelectric Generator) and a regenerator is proposed. In this system, the MCFC produces electricity and heat from fuels and the TEG utilizes the heat for additional power generation. A numerical model is developed to evaluate the performance of the proposed system. The relationship between the operating current density of the MCFC and the dimensionless current of the TEG is theoretically derived and the operating current density region of the MCFC that allows the TEG to function is determined. Numerical expressions of the power output and efficiency for the hybrid system are specified under different operating conditions. The general performance characteristics and optimum criteria for the hybrid system are revealed. It is found that the hybrid system is superior to the stand-alone MCFC system as the bottoming TEG can effectively increase the maximum power density. In addition, the effects of the operating current density, operating temperature, operating pressure, heat conductivity, integrated parameters and dimensional figure of merit on the performance characteristics of the hybrid system are investigated. The results obtained are useful for the design and optimization of novel MCFC system to achieve a better performance.

1. Introduction

Due to their potentially lower greenhouse gas emissions and primary energy consumptions, fuel cells have been considered as next generation power sources to replace conventional thermal power technologies [1–7]. Based on electrolyte types, fuel cells can be classified into five major categories: proton exchange membrane fuel cell (PEMFC), alkaline fuel cell (AFC), phosphoric acid fuel cell (PAFC), solid oxide fuel cell (SOFC), and molten carbonate fuel cell (MCFC) [8]. Among the various fuel cells, MCFC is fuel flexible, long-term stable, and suitable for stationary applications [9–12]. The MCFC is a natural carbon capture system that enables to separate carbon dioxide from the original cathodic flow via the CO_3^{2-} transit through the electrolyte [13]. Unlike some carbon capture and storage technologies such as calcium looping [14,15], the MCFC does not consume but provide power while operating as a CO_2 separator and concentrator [16]. Nowadays, MCFCs are commercially available in some countries such as USA, Germany, Japan, Italy and South Korea [17].

Although progress has been made in MCFCs to prolong the lifetime, improve the stack capacity and lower the manufacturing and running cost [18–20], the relatively low power density is still a major drawback that restricts the wide commercialization of MCFCs [21]. The power density of MCFC can be improved by optimizing the operating conditions or by developing more effective catalyst materials to reduce the activation loss. From engineering point of view, the MCFC performance can also be improved by recovering the waste heat released in MCFC for additional power generation or for combined heat and power (CHP) cogeneration [22–28]. Zhang et al. [22,23] proposed two MCFC-gas turbine (MCFC-GT) hybrid systems with different fuels and investigated effects of some operating conditions and irreversible losses on the performance of the hybrid systems. Sánchez et al. [24] presented a reciprocating engine with three bottoming thermal cycles to recover the waste heat from an MCFC and showed that the Stirling engine was an alternative choice for conventional gas turbines. Angelino et al. [25] considered an ORC (Organic Rankine Cycle) with different working fluids to recover the waste heat from an MCFC. The power and efficiency gain of about in the range 10–15% can be obtained with reference to MCFC plant in the capacity range of 2–5 MW. Baronci et al. [26] studied the integration of an MCFC and

* Corresponding author. Department of Microelectronic Science and Engineering, Ningbo University, Ningbo, 315211, China.
E-mail address: zhanghoucheng@nbu.edu.cn (H. Zhang).

http://dx.doi.org/10.1016/j.energy.2016.06.128
0360-5442/

a Brayton cycle using supercritical carbon dioxide as working fluid. The boost in electrical efficiency was found to be twice that of a recovery system based on an ORC. Mamaghani et al. [27] proposed an MCFC-GT and ORC hybrid plant, 4E (energetic, exergetic, economic and environmental) analyses were performed and a multi-objective optimization method was utilized to build a set of Pareto optimal solutions. The optimum solutions showed that the exergetic efficiency of the MCFC-GT-ORC system was about 55%, about 5% larger than that of the sole MCFC-GT system. Silveira et al. [28] carried out energy, exergy and economic analyses of an MCFC integrated with an absorption refrigeration system for cold water production. A global efficiency of 86% and the payback period of about 3 and 5 years for investments in MCFCs of 1000 and 1500 US/kW were estimated.

Thermoelectric generators (TEGs) use thermal energy to create a temperature gradient across the hot and cold junctions of a thermoelectric material which is used to generate voltage as per the principle of Seebeck effect [29–31]. TEGs can be operated in a quiet way compared with other power generation technologies since TEGs are solid-state heat engine and do not contain any moving part. In addition, TEGs offer many other advantages such as compact, environmentally friendly, highly reliable and adapting to different kinds of heat reservoirs [32,33]. Owing to these advantages, TEGs have drawn more and more attention for waste heat recovery [34–37]. With the rapid developments of thermoelectric materials, the working temperatures of some thermoelectric generators beyond 600 °C have already been reported [38–40]. It creates an opportunity to directly integrate a TEG with an MCFC for converting the waste heat into electricity to increase the power output and efficiency of the MCFC system.

In this work, a new hybrid system integrating an MCFC and a TEG is proposed to improve the energy efficiency for power generation. The layout of the hybrid system will be described and each component in the hybrid system will be numerically characterized. Some important parameters for assessing the performance of the hybrid system will be formulated by taking the main irreversible losses of the system into account. The general performance characteristics and optimum criteria for the hybrid system will be investigated and discussed. Effects of some designing parameters and operating conditions on the hybrid system performance will be specified. Some possible problems for the practical operation of the hybrid system are also discussed.

2. Model description

The hybrid system composed of an MCFC, a TEG and a regenerator, as schematically shown in Fig. 1 (a). The MCFC converts the chemical energy in reactants into electricity and waste heat, and the electricity is delivered to external loads. The waste heat, one part is transferred to the bottoming TEG for additional electricity generation, another part is used to compensate the regenerative losses in the regenerator, and the last part is dissipated into the environment. In Fig. 1 (a), P_{MCFC} stands for the electric power output of the MCFC, q_1 is the heat-transfer rate from the MCFC at temperature T to the hot junction of TEG at temperature T_1, q_2 is the heat-transfer rate from the cold junction of TEG at temperature T_2 to the environment at temperature T_0, P_{TEG} is the additional power output from the TEG, q_r is the heat-transfer rate from the MCFC to the regenerator, q_L is the heat-leak rate from the MCFC to the environment.

For simplification of analyses, the following assumptions are invoked [41–47]:

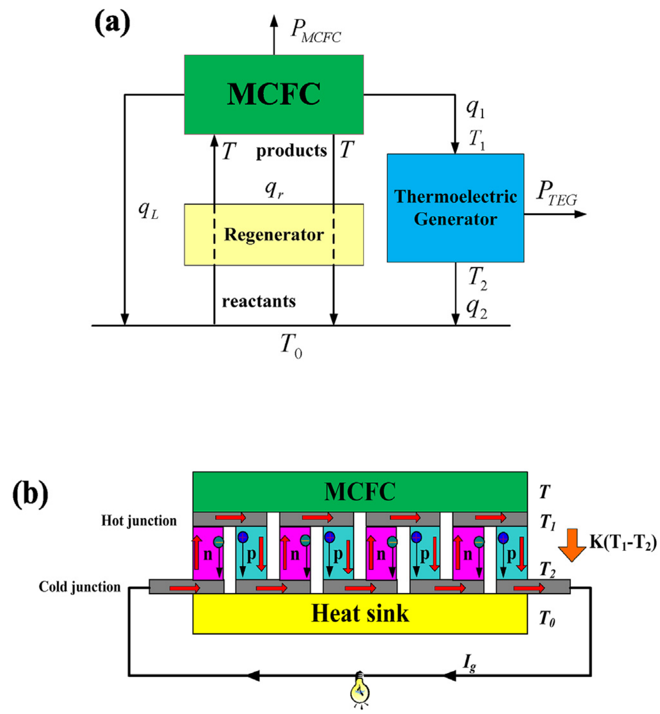

Fig. 1. Schematic diagrams of (a) an MCFC-TEG hybrid system and (b) a TEG.

- Both the MCFC and the TEG are operated under steady state conditions;
- Operating temperature and pressure are uniform and constants in the MCFC;
- All reactants are all consumed in MCFC;
- Internal electric current through the electrolyte is neglected;
- Geometric configuration of the TEG is in the optimum form;
- Heat leakage from the TEG to the surroundings is neglected;
- Heat transfers within the system obey Newton's law;
- Electric current generated by the TEG flows along the arm of the device;
- TEG is closely attached to the MCFC, temperatures of the hot and cold junctions equal to that of the MCFC and the environment, respectively;
- Seebeck coefficient, electrical resistance, thermal conductance, and dimensional figure of merit of the TEG are independent of temperature.

2.1. The MCFC

The MCFC is a core element in the hybrid system, which simultaneously produces electricity and heat through electrochemical reactions. In the normal operation of MCFC, some other heat is also generated due to irreversible losses such as anode overpotential, cathode overpotential and ohmic overpotential. According to the theory of chemical thermodynamics [48] and the semi-empirical electrochemical model developed by Yuh and Selman [49], the power output P_{MCFC} and efficiency η_{MCFC} of an MCFC can be, respectively, expressed as

$$P_{MCFC} = jA(E - U_{an} - U_{cat} - U_{ohm}), \quad (1)$$

and