Energy 85 (2015) 458–467

Contents lists available at ScienceDirect

Energy

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

Parametric analysis of an irreversible proton exchange membrane fuel cell/absorption refrigerator hybrid system

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ARTICLE INFO

Article history:
Received 15 December 2014
Received in revised form
10 March 2015
Accepted 23 March 2015
Available online 18 April 2015

Keywords:
Proton exchange membrane fuel cell
Absorption refrigerator
Hybrid system
Irreversible loss
Parametric analysis

ABSTRACT

A hybrid system mainly consisting of a PEMFC (proton exchange membrane fuel cell) and an absorption refrigerator is proposed, where the PEMFC directly converts the chemical energy contained in the hydrogen into electrical and thermal energies, and the thermal energy is transferred to drive the bottoming absorption refrigerator for cooling purpose. By considering the existing irreversible losses in the hybrid system, the operating current density region of the PEMFC permits the absorption refrigerator to exert its function is determined and the analytical expressions for the equivalent power output and efficiency of the hybrid system under different operating conditions are specified. Numerical calculations show that the equivalent maximum power density and the corresponding efficiency of the hybrid system can be respectively increased by 5.3% and 6.8% compared to that of the stand-alone PEMFC. Comprehensive parametric analyses are conducted to reveal the effects of the internal irreversibility of the absorption refrigerator, operating current density, operating temperature and operating pressure of the PEMFC, and some integrated parameters related to the thermodynamic losses on the performance of the hybrid system. The model presented in the paper is more general than previous study, and the results for some special cases can be directly derived from this paper.

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1. Introduction

Due to the growing concerns on fossil fuel depletion and climate change, fuel cells have received considerable attention in recent years owing to their high efficiencies and low emissions [1–3]. Among the various types of fuel cells, PEMFC (proton exchange membrane fuel cell) is regarded to be the most promising candidate as the next generation power source for stationary, transportation, and portable applications due to some significant advantages such as low operating temperature, fast startup, immediate response ability and high power density [4–7]. In the current literature, most investigations on PEMFC have focused to reach the proton exchange membrane with low electronic conductivity, low electro-osmotic drag coefficient, low permeability to fuel, low cost, good chemical/thermal stability, good mechanical properties and high proton conductivity [8,9]. Relatively, there are fewer studies done on the exhaust heat conversion and management aspect. It has been reported that the PEMFC produces approximately equivalent amount of electric power output and waste heat under normal operating conditions, that is, up to half of the chemical energy in the hydrogen will be finally dissipated as waste heat [10]. On the other hand, the waste heat dissipated in the PEMFC will result in a temperature rise that may affect the normal operation of the PEMFC and should be immediately removed. Thus, it is meaningful to find some feasible methods to utilize the waste heat produced in PEMFC system for other applications, which may further strengthen its position among the various fuel cells.

The waste heat produced in the PEMFC can be effectively harvested by employing CHP (combined heat and power) systems for some applications such as power generation, heating, and cooling [10–20]. Chen et al. [11] reported a hybrid power system by coupling a semiconductor thermoelectric generator to a PEMFC to convert the produced waste heat for additional power production, and the numerical expressions for equivalent efficiency and power output of the hybrid system were analytically derived. Hwang et al. [10,12] developed a heat recovery unit and implemented it in a PEM fuel cell cogeneration system to simultaneously produce electricity and hot water, the maximum efficiency as a combination of power output and heat was found to be larger than 80% based on the lower heating value of hydrogen.

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http://dx.doi.org/10.1016/j.energy.2015.03.104
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Zhao et al. [14] carried out the parametric studies on a hybrid power system by integrating a PEM fuel cell stack with an ORC (organic Rankine cycle) to recover the produced waste heat, the electrical efficiency of the hybrid system can be improved by about 5% compared to that of the single PEMFC. Borello et al. [15] proposed a high temperature PEMFC energy system fueled with reforming ammonia and coupled with a bottoming ORC energy system, they optimized the electric output of the system and improved the overall efficiency. Pilatowsky et al. [16] simulated an air conditioning absorption refrigeration system in a co-generation process combing a PEMFC, their results showed that using the waste heat generated in PEMFC for cooling was feasible and the cogeneration efficiency reached a range of maximum values between 28.6% and 37.3%. Dincer et al. [17] studied on the energy and exergy analyses of a PEMFC integrated with a TEACS (triple-effect absorption cooling system) and investigated the effects of different operating parameters such as pressure, temperature, membrane thickness and current density of the fuel cell on the output of the fuel cell and COP (coefficient of performance) of the cooling system. They also pointed out that integrated PEMFC with a TEACS can be regarded as an attractive and environmentally benign option for cogeneration purposes in sustainable buildings [18]. Zhang et al. [19] presented a hybrid system comprised of a PEMFC and a bottoming endoreversible refrigeration cycle to exploit the waste heat for refrigeration purpose, the optimal operating regions of equivalent power density and efficiency for the hybrid system were determined and the advantages of the hybrid system were shown by numerical results. Among the numerous alternative hybrid systems, coupling an absorption refrigerator to a PEMFC can be promisingly used in some fields such as residential applications, computer and telecommunications equipment power and cooling, and so on [21,22], since it allows production of electricity and cooling in a quiet, decentralized, efficient and environmentally-friendly way. In the literature, some studies have been undertaken to evaluate the performance of absorption cooling systems with PEMFC through numerical simulation, but seldom studies have discussed the effects of various operating conditions and designing parameters on the performance of the hybrid system.

In this work, a hybrid system by integrating a PEMFC with an absorption refrigerator to simultaneously produce electricity and cooling is proposed to improve the overall power output and efficiency. A mathematical model is applied to derive the analytical expressions for the equivalent power output and efficiency of the hybrid system by considering the multi-irreversibilities such as the external and internal irreversibilities of the absorption refrigerator, electrochemical irreversible losses inside the PEMFC, regeneration losses in the regenerator, and heat leakage from the PEMFC to the surroundings. The general performance characteristics and optimum criteria of the hybrid system will be revealed and the operating current density region of PEMFC enable the absorption refrigerator to exert its function will be determined. The effects of some operating conditions and designing parameters on the performance of the hybrid system will be discussed by comprehensive parametric analyses.

2. A PEMFC/absorption refrigerator hybrid system

The hybrid system consists of a PEMFC, an absorption refrigerator and an auxiliary regenerator, the absorption refrigerator is driven by the waste heat produced in the PEMFC and is worked as a so-called three-heat-source refrigerator with reasonable assumptions that the working fluid in the condenser and absorber has the same temperature and exchanges heat with the heat sinks at the same temperature [23–26], as schematically shown in Fig. 1, where

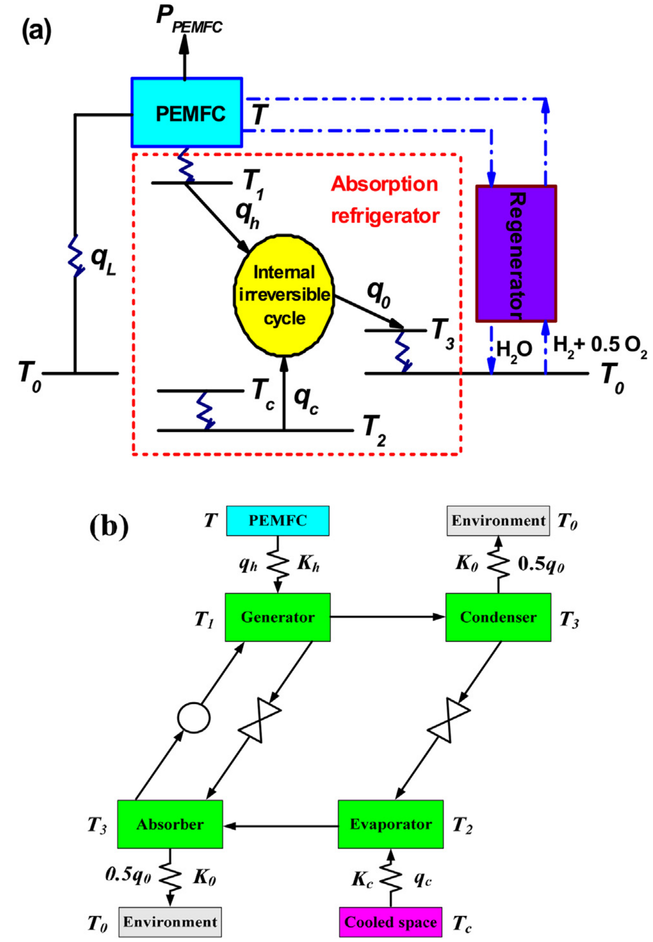

Fig. 1. Schematic diagrams of (a) a PEMFC/absorption refrigerator hybrid system and (b) an absorption refrigerator.

q_h is the heat-transfer rate from the PEMFC at temperature T to the generator, q_c is the heat-transfer rate from the cooled space at temperature T_c to the evaporator, q_0 is the total heat-transfer rate from the condenser and absorber to the environment at temperature T_0, q_L is the rate of heat leakage from the PEMFC to the environment, and P_{PEMFC} is the electric power output of the PEMFC. For such a hybrid system, the waste heat produced in the PEMFC can be readily utilized for cooling purposes without any electric power input, and consequently, the performance of the PEMFC can be improved.

In order to conveniently describe the mainly irreversible losses existing in each component of the hybrid system, several simplifications and assumptions are made as follows [27–29]:

(1) Both the PEMFC and the absorption refrigerator are operated under steady-state conditions;
(2) Operating pressure and temperature are uniform and constants in the PEMFC;
(3) Amounts of hydrogen and air are theoretically provided based on the current produced;
(4) Flow of reactants is steady, incompressible and laminar;
(5) Internal current density referred to the electrons transported through the electrolyte and to the fuel crossover is neglected;
(6) Electrical power required to compress the reactants and air is excluded in the calculations;
(7) Work input required by the solution pump in the absorption refrigerator is negligible;

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