Energy 101 (2016) 359–365

Contents lists available at ScienceDirect

Energy

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

A study of double functions and load matching of a phosphoric acid fuel cell/heat-driven refrigerator hybrid system

Xiaohang Chen [a, *], Yuan Wang [a], Yingru Zhao [b], Yinghui Zhou [a, *]

[a] Department of Physics, Xiamen University, Xiamen 361005, People's Republic of China
[b] School of Energy Research, Xiamen University, Xiamen 361005, People's Republic of China

ARTICLE INFO

Article history:
Received 7 October 2015
Received in revised form
19 January 2016
Accepted 6 February 2016
Available online 24 March 2016

Keywords:
Hybrid system
Phosphoric acid fuel cell
Heat-driven refrigerator
Double function
Load matching

ABSTRACT

A generic model of the hybrid system consisting of a phosphoric acid fuel cell (PAFC) and a heat-driven refrigerator is originally established. On the basis of the models of PAFCs and three-heat-source refrigerators, the equivalent power output and efficiency of the hybrid system are obtained. The performance characteristic curves of the hybrid system are plotted through numerical calculation, showing that the performance of the hybrid system in the whole operating region is better than that of a single PAFC. The maximum equivalent power output density and the corresponding efficiency of the hybrid system are calculated. It is found that compared with the maximum power output density and the corresponding efficiency of a single PAFC, the maximum equivalent power output density of the hybrid system increases 938 W/m^2 and the equivalent efficiency of the hybrid system at the maximum equivalent power output density increases 5.86%. The optimal ranges of the equivalent efficiency of the hybrid system and the current density of the PAFC are determined. The effects of the refrigeration temperature on the performance of the hybrid system are discussed in detail. Two different loads of the hybrid system are optimally matched.

1. Introduction

Phosphoric acid fuel cells (PAFCs) operating at moderate temperatures [1–6] have been considered as one of the most advanced technologies because they have simple construction and no special requirements for the high temperature properties of materials. Unlike solid oxide fuel cells [7–11] and molten carbonate fuel cells [12–14] being operated at high temperatures, PAFCs do not have a high working temperature so that the waste heat produced in PAFCs cannot be effectively used to drive a heat engine or a thermionic generator. However, the operating temperatures of PAFCs are higher than those of proton exchange membrane fuel cells [15–17] and alkaline fuel cells [18–20] and the waste heat produced in PAFCs includes a considerable number of available energy. Therefore, PAFCs can be more appropriately and efficiently used in cogeneration systems than proton exchange membrane fuel cells [21–24] and alkaline fuel cells [25].

Cogeneration may be defined as the simultaneous production of electric power and useful heat from the burning of a single fuel. This technique of combined heat and power production has been applied in both the industrial and tertiary sectors [26]. It can be used in both the power generation and the production of steam, hot or cold water, or hot or cold air, depending on the associated recuperation equipment. Many experimental and theoretical studies have been finished on this research. For example, Silveira et al. [26] carried out energy, exergy, and economic analyses for a fuel cell cogeneration system and pointed out that the high efficiency and the low emission of pollutants in comparison with other technologies makes the fuel cell cogeneration system an attractive technology of energy generation. Liu and Leong [27] investigated a cogeneration system that incorporates a natural gas fed internal-reforming solid oxide fuel cell and a zeolite/water adsorption chiller and the main aim is to determine the performance of this combined system under different operating conditions and design parameters. Yu et al. [28] analyzed the performance of an integrated solid oxide fuel cell and absorption chiller tri-generation system. Ishizaw et al. [29] conducted an experiment and PAFCs were used to provide electrical power to the telecommunication equipment, where heat energy was used by absorption refrigerators to cool the telecommunication rooms throughout the year. These previous studies play a solid foundation for the further research of PAFC-based cogeneration systems.

* Corresponding authors. Tel./fax: +86 592 2182428.
E-mail addresses: chenxh@xmu.edu.cn (X. Chen), yhzhou@xmu.edu.cn (Y. Zhou).

http://dx.doi.org/10.1016/j.energy.2016.02.029

In the present paper, we will establish a cogeneration system consisting of a PAFC (phosphoric acid fuel cell) and a heat-driven refrigerator. Based on the models of PAFCs and heat-driven refrigerators, the equivalent power output and efficiency of the hybrid system are derived. The general performance characteristics of the PAFC-refrigerator hybrid system are determined, and consequently, the advantages of the hybrid system are revealed. The matching problem of loads is discussed so that the hybrid system can be operated at the optimum states. Finally, some important conclusions are summarized.

2. The model description of a new hybrid system

Fig. 1 shows the schematic diagram of a new hybrid system composed of a PAFC, a regenerator, and a heat-driven refrigerator, where the PAFC operated at temperature T acts as the high-temperature heat reservoir of the heat-driven refrigerator, P_f is the electric power output of the PAFC, $q_r$is the rate of refrigeration, $T_c$is the temperature of the cold reservoir, q_h is the heat flow from the PAFC to the refrigerator, q_o is the heat flow between the refrigerator and the environment at temperature T_o, and q_l is the heat leak rate directly from the PAFC to the environment. The regenerator works as a heat exchanger, heating the inlet reactants from the ambient temperature to the cell temperature by using the high-temperature outlet gas of the fuel cell. By using such a hybrid configuration, the waste heat produced in the PAFC can be instantly utilized to provide additional cooling and realize the double functions of the power output and refrigeration of the hybrid system. In the following sections, we will analyze the performance of individual components and then synthetically investigate the performance characteristics of the hybrid system.

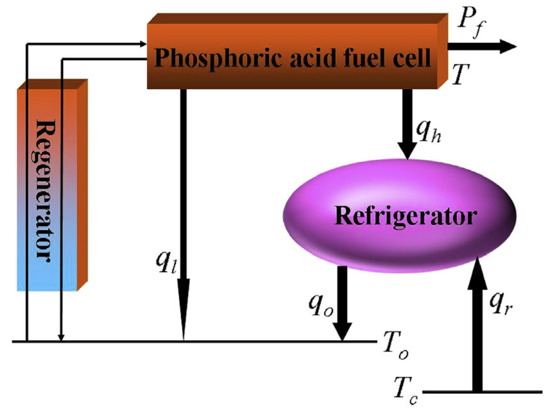

Fig. 1. The schematic diagram of a PAFC/heat-driven refrigerator hybrid system.

2.1. The coefficient of performance of a heat-driven refrigerator

The refrigeration cycle in the hybrid system is a refrigerator driven directly by heat rather than work. Such a heat-driven refrigerator is operated among three heat sources and often referred to as the three-heat-source refrigerator [30,31], which is the theoretical model of absorption refrigerators, adsorption refrigerators, etc. These refrigerators can efficiently exploit low-level heat sources such as solar energy, geothermal energy, and waste heat produced in some devices. In the last decades, the performance of three-heat-source refrigerators affected by irreversible heat transfer has been widely investigated and some significant results have been obtained. For example, when the finite-rate heat transfer between the three-heat-source cycle and the heat reservoirs is assumed to obey Newton's law, the coefficient of performance of the refrigerator for a given rate of heat input q_h may be expressed as [32–34].

$$\varepsilon = \left\{\frac{1}{4}g^2 - \frac{T_c}{T}\left[\frac{(a-1)^2}{a^2} - \frac{T-T_o}{q_h b}\right]\right\}^{\frac{1}{2}} - \frac{1}{2}g \tag{1}$$

where $g = 1 + \frac{(a-1)^2 T_c - T_o}{Ta^2} - \frac{T_c - T_o}{q_h b}$, $a = \left(\frac{1}{\sqrt{U_c}} + \frac{1}{\sqrt{U_o}}\right)\left(\frac{1}{\sqrt{U_c}} - \frac{1}{\sqrt{U_h}}\right)^{-1}$, $b = \frac{1}{A}\left(\frac{1}{\sqrt{U_c}} + \frac{1}{\sqrt{U_o}}\right)^2$, U_h, U_c, and U_o are, respectively, the heat transfer coefficients between the working substance in the cycle and the three heat reservoirs at temperatures T, T_c, and T_o, and A is the total effective heat transfer area of the refrigeration cycle.

2.2. The power output and efficiency of a phosphoric acid fuel cell

The PAFC shown in Fig. 1 is operated by feeding hydrogen to the anode and air to the cathode, respectively. The overall reaction is $H_2 + 0.5O_2 \rightarrow H_2O$ + electricity + heat. The performance of PAFCs has been widely investigated [35–39]. When the main irreversible losses resulting from the activation overpotential $V_{act} = \frac{RT}{\alpha n_e F}\ln\left(\frac{i}{i_0}\right)$, concentration overpotential $V_{con} = m\exp(ni)$, and ohmic overpotential $V_{ohm} = i\frac{t_{ele}}{\kappa}$ are considered, the output voltage V_{cell} of a PAFC can be expressed as [5,35].

$$\begin{aligned} V_{cell} &= V_{rev} - V_{act} - V_{con} - V_{ohm} \\ &= \frac{1}{n_e F}\left\{-\Delta g^0 + RT\ln\left[\frac{p_{H_2}(p_{O_2})^{0.5}}{p_{H_2O}}\right] - \frac{RT}{\alpha}\ln\left(\frac{i}{i_0}\right) \right. \\ &\quad \left. - n_e F m\exp(ni) - n_e F\frac{i t_{ele}}{\kappa}\right\}, \end{aligned} \tag{2}$$

where $V_{rev} = -\frac{\Delta g^0}{n_e F} + \frac{RT}{n_e F}\ln\left[\frac{p_{H_2}(p_{O_2})^{0.5}}{p_{H_2O}}\right]$ is the reversible potential of the PAFC, Δg^0 is the Gibbs free energy change at standard state, n_e is the number of electrons, F is Faraday's constant, R is the universal gas constant, and $p_j (j = H_2, O_2$, and $H_2O)$ are the partial pressures of species j, i_0 is the exchange current density, i is the operating current density, α is the charge transfer coefficient, which depends on the nature of the reaction and electrode materials, m and n are two constants [35,40], and t_{ele} and κ are, respectively, the thickness and specific conductivity of the aqueous phosphoric acid solution. The ohmic overpotential is mainly caused by the resistance contributed by the electrolyte because the resistance of electrodes can be negligible compared with that of electrolyte. Using Eq. (2), one can calculate the power output P_f and efficiency η_f of the PAFC as

$$P_f = V_{cell} I = \frac{iA_f}{n_e F}\left\{-\Delta g^0 + RT\ln\left[\frac{p_{H_2}(p_{O_2})^{0.5}}{p_{H_2O}}\right] - \frac{RT}{\alpha}\ln\left(\frac{i}{i_0}\right) - n_e F m\exp(ni) - n_e F\frac{i t_{ele}}{\kappa}\right\} \tag{3}$$