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Parametric study of a hybrid system integrating a phosphoric acid fuel cell with an absorption refrigerator for cooling purposes

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ABSTRACT

A hybrid system that integrates an absorption refrigerator and a PAFC (phosphoric acid fuel cell) is proposed to recover waste heat for cooling purposes. The operating current density interval of the PAFC that enables the absorption refrigerator to cool effectively is determined. The numerical expressions for the equivalent power output and efficiency of the hybrid system are specified at different operating conditions. Calculations show that the maximum power density and corresponding efficiency using the hybrid system can be increased by 2.6% and 3.0%, respectively, compared to system only using a PAFC. The general performance characteristics and optimum criteria for the hybrid system are revealed. Comprehensive parametric analyses were conducted to determine the effects of internal irreversibilities in the absorption refrigerator, some integrated parameters related to the thermodynamic losses, and the operating current density, temperature and pressure of the PAFC on the performance of the hybrid system.

Introduction

A fuel cell enables electrochemical conversion of chemical energy from a fuel, such as hydrogen, into electrical and thermal energies without the need for combustion and without producing noise or pollution [1–3]. Fuel cells can be classified into five major categories based on the electrolyte they use, namely, phosphoric acid, alkaline, molten carbonate, solid oxide, and polymer electrolyte fuel cells [4]. Of the various fuel cell types, phosphoric acid fuel cells (PAFCs) are regarded as one of the most well-established hydrogen-oxygen fuel cell systems and are closest to commercialisation because of their relatively low cost electrolyte, low operating temperature, and high durability [5–8].

The major disadvantages of PAFCs are their lower power density compared to conventional combustion engines, which is a critical factor that restricts the widespread commercialisation of PAFCs [9]. The maximum power density obtained from PAFCs has been improved by a number of advances in recent years, not only because of progress in material fabrication [10–12] and better understanding of electrochemical processes and transport phenomena in the cell [13–16] but also because of the optimization of operating conditions and cell design [14,17–19]. However, the power density of current PAFC systems is still 10–100 times lower than that of combustion engines, which can reach power densities of up to 50 kW/L [9]. As an alternative approach, the maximum power density of fuel cells can be effectively improved by combining them with heating, cooling and power systems to recover the

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waste heat produced in the fuel cell because a large portion of the energy contained in the hydrogen used in the electrochemical reaction is ultimately dissipated as waste heat [20–34]. Hwang et al. [20,21] implemented a heat recovery unit into a proton exchange membrane fuel cell system to produce electricity and hot water simultaneously; they reached a maximum combined power and heating efficiency in excess of 80% based on the lower heating value of hydrogen. Silveira et al. [22] conducted an energy, exergy and economic analysis of a molten carbonate fuel cell cogeneration system for the production of electricity and cold water. The technoeconomic analysis showed that the global efficiency was approximately 86%, and exergy losses in the fuel cell and absorption refrigeration system were significant. The payback period was estimated to be 3 and 5 years for investments in fuel cells of 1000 and 1500 US$/kW, respectively. Chen et al. [23] reported a hybrid power system that coupled a semiconductor thermoelectric generator with a proton exchange membrane fuel cell to convert waste heat into additional electric power. The numerical expressions for equivalent power output and efficiency of the hybrid system were analytically derived. In addition, many researchers have studied integrated fuel cell and micro gas turbine hybrid systems with different fuel sources [24–26], fuel cell electrolytes [27,28], scales [29,30], and analysis approaches [31–33] to increase overall performance.

An absorption refrigerator can be driven by low-grade heat energy, such as waste heat from industrial production, solar energy and geothermal energy, and has a great potential for energy conservation and environmental protection [34]. Compared to conventional compression air-conditioning technology, absorption refrigerators offer many advantages such as being reliable, economical, easy to manufacture, adaptable to various heat sources with moderate temperatures, and having low noise outputs [35]. Recently, Ishizawa et al. [36] experimentally presented a PAFC energy system for a telecommunication cogeneration system in which the PAFC was used to provide electrical power to the telecommunication equipment and the waste heat was used by an absorption refrigerator to cool the telecommunication room. Coupling an absorption refrigerator to a PAFC can be widely used for various applications such as residential projects, computer and telecommunications equipment power and cooling, and so on [37,38]. However, to date, little theoretical modelling has been performed on PAFC/absorption refrigerator hybrid systems, which could provide new, valuable insights into the optimum design and practical operation of these hybrid systems.

In this work, a hybrid system that combines a PAFC with an absorption refrigerator to simultaneously produce electricity and cooling is proposed to improve the overall power output and efficiency. Analytical expressions for the power output and efficiency of the hybrid system are found by considering multiple irreversibilities, such as the external and internal irreversibilities of the absorption refrigerator, electrochemical irreversible losses inside the PAFC, regeneration losses in the regenerator, and heat leakage from the PAFC to the surroundings. The general performance characteristics and optimum criteria of the hybrid system are revealed, and the operating current densities of the PAFC that enable the absorption refrigerator to function will be determined. The effects of some operating conditions and design parameters on the performance of the hybrid system will be discussed through comprehensive parametric analyses.

A PAFC/absorption refrigerator hybrid system

The hybrid system presented in this paper consists of a PAFC, an absorption refrigerator and an auxiliary regenerator, as schematically shown in Fig. 1, where q_h is the heat-transfer rate from the PAFC 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, P_{PAFC} is the electric power output of the PAFC, and q_L is the heat-leakage rate from the PAFC to the environment via convective and/or conductive heat transfer. For such a hybrid system, waste heat dissipated in the PAFC can be readily utilized for cooling purposes without additional electric power inputs, and consequently, the performance of the PAFC can be effectively increased. To conveniently describe the major irreversible losses existing in the system, some simplifications and assumptions are made [39–41]: (1) Both the PAFC and the absorption refrigerator are operated under steady state conditions. (2) The operating temperature and pressure are uniform and constant in the PAFC. (3) The amounts of hydrogen and air are theoretically provided based on the electric current produced. (4) The flow of reactants is steady, incompressible and laminar. (5) The internal current density refers to the electrons transported through the electrolyte and fuel crossover is neglected. (6) The work input required by the solution pump in the absorption refrigerator is negligible. (7) The working fluid in the absorption refrigerator flows constantly and exchanges heat continuously with the three external heat reservoirs. (8) Heat transfers within the system obey Newton's law.

The PAFC

A PAFC is mainly composed of two electrodes and an aqueous phosphoric acid solution that is used as an electrolyte. The anode is supplied with hydrogen, and the cathode is supplied with air. The overall electrochemical reactions that occur in a PAFC can be summarized as $H_2 + 0.5\ O_2 \rightarrow H_2O$ + Electricity + Heat, where the electricity is delivered to the external load and the heat is usually dissipated into the environment via convective and/or conductive heat transfer. As previously demonstrated in Ref. [39], some irreversible losses in the PAFC inevitably occur as a result of the electrochemical reactions, and these irreversible losses can be characterized in terms of the activation overpotential (V_{act}), the concentration overpotential (V_{con}), and the ohmic overpotential (V_{ohm}). By considering these three overpotentials, the power output of a stand-alone PAFC at a given operating current density can be expressed as [39,40]:

$$P_{PAFC} = IV = jA(E - V_{act} - V_{con} - V_{ohm}), \tag{1}$$