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Performance evaluation of an alkaline fuel cell/thermoelectric generator hybrid system

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ABSTRACT

A hybrid system consisting of an AFC (Alkaline Fuel Cell), a TEG (Thermoelectric Generator) and a regenerator is put forward, where the AFC converts the chemical energy in the hydrogen into electrical energy and thermal energy, and the released thermal energy is subsequently converted into electrical energy through the bottoming TEG. The main irreversible losses in each element of the hybrid system are characterized, and numerical expressions for the efficiency and power output of the AFC, TEG and hybrid system are respectively derived. The fundamental relation between the operating current density of the AFC and the dimensionless current of the TEG is obtained, from which the region of the operating current density of the AFC that the TEG exerts its function is determined. By employing such a hybrid system, the equivalent maximum power density of the AFC can be increased by up to 23%. The effects of the operating current density, operating temperature, heat conductivity, and integrated parameter on the performance of the hybrid system are revealed. The results obtained in the present paper will provide some theoretical guidance for the performance improvement of the AFC.

Introduction

Fuel cells have the potential to lower the environmental burden of meeting domestic energy needs, particularly greenhouse gas emissions and primary energy consumption [1]. Low-temperature fuel cells, can be widely used in the fields such as power generation, transportation, and portable power, which constitute an important element in pollution-free energy conversion [2,3]. Because the predicted low cost and high durability in PEMFCs remain problematic, a resurgence of interest in the AFC (Alkaline Fuel Cell) has been attracted in recent years [4–9]. AFCs can be manufactured from relatively standard materials and do not need precious metals or energy intensive sintering, and their balance of plant is less complicated than that of other type fuel cell systems.

However, the major drawback of an AFC is its comparative low power density, which becomes a critical factor that restricts the widely commercialization of AFCs [10]. The maximum power density obtained from AFCs has undergone many advances in recent years not only due to the progresses in catalysts and electrode materials but also due to the optimized operating conditions and fuel cell design [11]. As an

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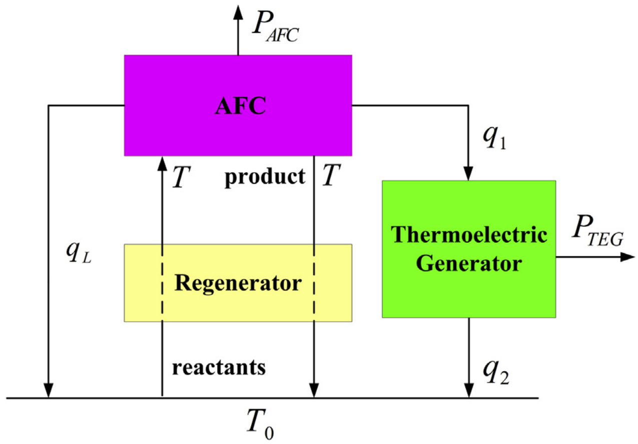

Fig. 1 – The schematic diagram of an AFC-TEG hybrid system.

alternative approach, the equivalent maximum power density of low-temperature fuel cells can be also effectively elevated by employing cogeneration systems to recover the waste heat produced in the fuel cell for other applications [12–18]. Zhang et al. [12] established a new three-heat-reservoir cycle based AFC hybrid system and found that the waste heat produced in the AFC can be readily used in such a system. Hwang et al. [15,16] developed a heat recovery unit and implemented it in a PEM fuel cell cogeneration system to produce electricity and hot water simultaneously. Ishizawa et al. [17] presented a PAFC (phosphoric acid fuel cell) energy system for telecommunication cogeneration systems, where the PAFCs are applied to provide electrical power to telecommunication equipment and the waste heat is used by absorption refrigerators to cool the telecommunication rooms. Zhao et al. [18] carried out the parametric studies on a hybrid power system by integrating a PEM fuel cell stack with an organic Rankine cycle to recover the waste heat from PEM fuel cell stack.

TEG (Thermoelectric Generator) can convert thermal energy into electricity due to the Seebeck effect, which is regarded as one of the potential candidates for renewable energy conversion [19,20]. Besides being environmentally friendly, TEGs have many other advantages such as being highly reliable, adapting to different kinds of heat reservoirs and having no moving parts. Therefore, TEGs have received more and more attention in scientific community especially in the aspect of low-level waste heat recovery [21]. Obviously, the waste heat generated in the AFC can be further converted into electricity through a bottoming TEG and thus the equivalent maximum power density of AFC can be effectively enhanced.

In the present paper, a hybrid system mainly composed of an AFC, a TEG and a regenerator is put forward to increase the equivalent maximum power density of the AFC. The performance of the hybrid system is evaluated by taking the main irreversible losses in each element of the system into account. The availability of the hybrid system will be validated and the effects of some operating conditions and designing parameters on the performance of the hybrid system will be revealed. Some possible problems that should be aware in the practical operation of the hybrid system are posed.

An AFC-TEG hybrid system

The hybrid system established here consists of an AFC, a TEG and a regenerator, where the TEG is closely attached to the AFC, as schematically shown in Fig. 1. The AFC acts as the high-temperature heat reservoir of the TEG which generates an additional power generation, and the regenerator is applied to preheat the incoming fuel and oxidant with the comparative high-temperature exhaust product from the AFC. By using such a hybrid system, the heat produced in the AFC can be effectively harvested, and consequently, the equivalent maximum power density of the AFC can be improved. Below, each component in the hybrid system will be analyzed, and then the performance characteristics of the global system will be synthetically investigated.

The AFC

The AFC directly converts the chemical energy of the incoming hydrogen into the electrical and thermal energies, it is mainly composed of an anode and a cathode with KOH solution as an electrolyte sandwiched between the two electrodes. The AFC is operated by introducing hydrogen as fuel and oxygen as oxidant to the anode and cathode, respectively. At the anode, hydrogen reacts with hydroxyl ions available in the KOH solution into water and releases electrons to the external electric circuit. At the cathode, oxygen reacts with water into hydroxyl ions with the help of the reaching electrons. The overall electrochemical reaction is

$$H_2 + \frac{1}{2}O_2 \rightarrow H_2O + \text{Heat} + \text{Electricity}. \tag{1}$$

As previously described in Ref. [22], some irreversible losses in the AFC are inevitably when the above electrochemical reaction is occurred, and these irreversible losses can be characterized in terms of activation overpotential (V_{act}), concentration overpotential (V_{con}) and ohmic overpotential (V_{ohm}). By considering these three overpotentials, the power output and efficiency of an AFC can be, respectively, expressed as [22]

$$P_{AFC} = jA(E - V_{act} - V_{ohm} - V_{con}), \tag{2}$$

and

$$\eta_{AFC} = \frac{P_{AFC}}{-\Delta\dot{H}} = \frac{n_e F}{-\Delta h}(E - V_{act} - V_{con} - V_{ohm}), \tag{3}$$

where $E = [-\Delta g_f^0 + (T - T_0)\Delta s^0 + RT\ln(p_{H_2}\sqrt{p_{O_2}}/p_{H_2O})]/n_e F$ is the equilibrium potential; Δg_f^0 is the standard molar Gibbs free energy change at reference condition ($T_0 = 298$ K, $p_0 = 1$ atm), Δs^0 is the standard molar entropy change, both of them can be founded in Ref. [22]; R is the universal gas constant; T is the operating temperature of the AFC; n_e is the number of mole electrons transferred per mole hydrogen; F is the Faraday's constant; p_{H_2}, p_{O_2} and p_{H_2O} are respectively the partial pressures of H_2, O_2, and H_2O, and the water produced is assumed to be in liquid phase, such that $p_{H_2O} = 1$ atm; j is the electric current density; A is the polar plate area of the AFC; $(-\Delta\dot{H}) = -jA\Delta h/(n_e F)$ is the total energy released per unit