Journal of Power Sources 294 (2015) 430–436

Contents lists available at ScienceDirect

Journal of Power Sources

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

# Maximum power output and load matching of a phosphoric acid fuel cell-thermoelectric generator hybrid system

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## HIGHLIGHTS

- A new model of the phosphoric acid fuel cell system-based hybrid system is proposed.
- The performance characteristics at the maximum power output density are revealed.
- The performances between the hybrid system and the single fuel cell are compared.
- The value ranges of main parameters are reasonably determined.
- The load resistances of two subsystems are optimally matched.

## ARTICLE INFO

*Article history:*
Received 5 February 2015
Received in revised form
30 May 2015
Accepted 15 June 2015
Available online xxx

*Keywords:*
Hybrid system
Phosphoric acid fuel cell
Thermoelectric generator
Irreversible loss
Maximum power output
Load matching

## ABSTRACT

Based on the current models of phosphoric acid fuel cells (PAFCs) and thermoelectric generators (TGs), a new hybrid system is proposed, in which the effects of multi-irreversibilities resulting from the activation, concentration, and ohmic overpotentials in the PAFC, Joule heat and heat leak in the TG, finite-rate heat transfer between the TG and the heat reservoirs, and heat leak from the PAFC to the environment are taken into account. Expressions for the power output and efficiency of the PAFC, TG, and hybrid system are analytically derived and directly used to discuss the performance characteristics of the hybrid system. The optimal relationship between the electric currents in the PAFC and TG is obtained. The maximum power output is numerically calculated. It is found that the maximum power output density of the hybrid system will increase about 150 $Wm^{-2}$, compared with that of a single PAFC. The problem how to optimally match the load resistances of two subsystems is discussed. Some significant results for practical hybrid systems are obtained.



## 1. Introduction

Among various fuel cells, the phosphoric acid fuel cell (PAFC) has been regarded as one of the most advanced technologies [1–9] because it has the relatively low operation temperature and simple construction. Many modeling studies about PAFCs have been carried out, which include the further understanding of materials [10–12], electrochemical processes and transport phenomena [13–16], stack modeling [17–20], hybrid systems for other applications [21,22], and so on [23,24]. The rapid development of novel materials [3,4,25] and new technology [1,3] effectively improve the performance of PAFCs. Recently, some PAFC power units have been commercially developed in USA, Japan, and Europe [26–29]. The research results obtained have laid a foundation for deeply investigating the performance of PAFCs.

Unlike the solid oxide fuel cell [30,31], the PAFC does not have a high working temperature so that the waste heat produced in the PAFC cannot be effectively used to drive a heat engine. However, the operating temperatures of PAFCs are higher than those of proton exchange membrane fuel cells [32–34] and the waste heat produced in PAFCs includes a considerable number of available energy. On the other hand, semiconductor thermoelectric generators can directly convert a part of heat into electricity [35–37]. Especially, they can be conveniently used to recycle the waste heat produced in other devices to generate electrical energy [38–41]. With the development of material technology, thermoelectric devices are playing an important role in the global sustainable energy issue

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http://dx.doi.org/10.1016/j.jpowsour.2015.06.085
0378-7753/

[42,43]. Thus, one possible and simple way of the effective uses for the available energy included in the waste heat of the PAFC is to combine a thermoelectric generator with a PAFC, so that the hybrid system may efficiently enhance the power output.

In the present paper, the concrete contents are arranged as follows. In Section 2, the new model of a PAFC-TG hybrid system is established, based on the models of PAFCs and TGs, and the power outputs and efficiencies of subsystems and hybrid system are derived. In Section 3, the general performance characteristics of the PAFC-TG hybrid system are discussed, and consequently, the advantages of the hybrid system are revealed. In Section 4, the load resistances are optimally matched so that the hybrid system can be operated at the optimum states. Finally, some important conclusions are summarized.

## 2. A new hybrid system consisting of a phosphoric acid fuel cell and a thermoelectric generator

We consider a new hybrid system consisting of a phosphoric acid fuel cell and a thermoelectric generator, as shown in Fig. 1, where $I_f$ and $I_g$ are, respectively, the electric currents flowing through the load resistances $R_f$ and $R_g$ of the PAFC and TG, $T$ is the working temperature of the PAFC, $q_1$ and$q_2$ are, respectively, the heat flows from the PAFC to the TG and from the TG to the environment at temperature $T_0$, $T_1$ and $T_2$ are the temperatures of the hot and cold junctions of the thermoelectric device, $U_1$ and $U_2$ are the overall heat transfer coefficients of heat exchangers at the hot and cold sides of the thermoelectric device, and $A_1$ and $A_2$ are the heat transfer areas at the hot and cold sides of the thermoelectric device. By using such a hybrid system, the PAFC acts as the high-temperature heat reservoir of the TG for a further production of power, one part of the waste heat produced in the fuel cell can be availably utilized by the TG operated between $T$ and $T_0$, and consequently, the conversion efficiency of the fuel can be enhanced [41]. Below, we will analyze the performance of the PAFC and TG and then synthetically investigate the performance characteristics of the hybrid system.

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

The PAFC shown in Fig. 1 is composed of two electrodes which enclose an electrolyte (phosphoric acid solution) [13,14,44] and a regenerator and is operated by introducing 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 basic thermodynamic relationship for the overall reaction can be expressed as $-\Delta H = -\Delta G - T\Delta S$ [5], where $\Delta G$ is the Gibbs free energy change of the reaction, i.e., electrical energy, which is consumed by both the internal dissipation and the external load, and $\Delta S$ is the entropy production of the reaction. $-T\Delta S$ stands for the thermal energy released by the reaction, which may result in a temperature rise inside the fuel cell. To maintain the temperature of the fuel cell constant, the heat produced in the PAFC should be removed by outlet mass flows or by heat transfer. The role of the regenerator in the fuel cell is to heat the inlet reactants from the ambient temperature to the cell temperature by using the high-temperature outlet gas of the fuel cell so that the fuel cell can normally work under the condition of steady-state.

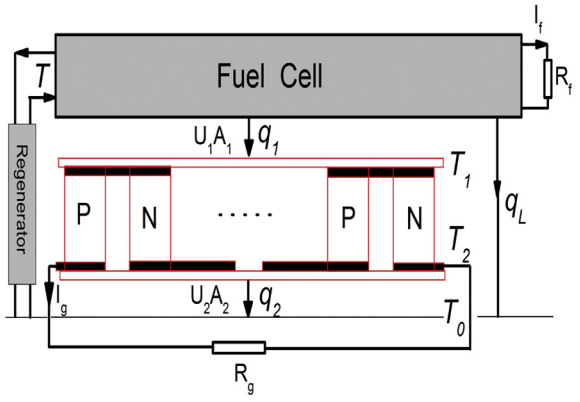


**Fig. 1.** The schematic diagram of a phosphoric acid fuel cell-thermoelectric generator hybrid system.

It is well known that the theoretical maximum potential of a PAFC is its reversible potential, which is determined by Nernst equation [13,14], i.e.,

$$V_{rev} = -\frac{\Delta g^0}{n_e F} + \frac{RT}{n_e F}\ln\left[\frac{p_{H_2}(p_{O_2})^{0.5}}{p_{H_2O}}\right], \tag{1}$$

where$\Delta g^0$ is the Gibbs free energy change at standard state, $R$ is the universal gas constant, $n_e$ is the number of electrons, $F$ is Faraday's constant, and $p_j$ ($j$ = $H_2$, $O_2$, and $H_2O$) are the partial pressures of species $j$. For a practical fuel cell, its output voltage is always smaller than $V_{rev}$ and can be expressed as [5,13].

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

where $V_{act} = [RT/(\alpha n_e F)]\ ln(i/i_0)$ is the activation overpotential, $i$ is the operating current density, $i_0$ is the exchange current density, and $\alpha$ is the charge transfer coefficient, which depends on the nature of the reaction and electrode materials and is in between 0 and 1.0; $V_{con} = mexp(ni)$ is the concentration overpotential, $m$ and $n$ are two constants [13,45] and their typical values are $3.0 \times 10^{-5}$ V and $8.0 \times 10^{-4}$ m$^2$ A$^{-1}$, which are independent of the current density; $V_{ohm} = it_{ele}/\kappa$ is the ohmic overpotential, which is mainly caused by the resistance contributed by the electrolyte because the resistance of electrodes can be negligible compared with that of electrolyte, and $t_{ele}$ and $\kappa$ are, respectively, the thickness and specific conductivity of the aqueous phosphoric acid solution. Eq. (2) includes the main irreversible losses resulting from the activation, concentration, and ohmic overpotentials and shows that the output voltage of a PAFC is a monotonically decreasing function of the current density [5]. Using (2), one can calculate the power output $P_f$ and efficiency $\eta_f$ of the PAFC as

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

and