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Study on the Performance of Irreversible Solid Oxide Fuel Cell-Heat Engine Hybrid Power System

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An irreversible solid oxide fuel cell by the hybrid of Stirling heat engine system is built, whose irreversibility in the process of system are considered, such as solid oxide fuel cell irreversible losses, the irreversible loss of the Stirling heat engine working process, and heat conduction between them. Analytical expressions of the key processes are given by electrochemical analysis. Through numerical simulation, various factors affecting the performance of the hybrid system are discussed in detail, and the optimal working range of the hybrid system is deduced. This research shows that the efficiency of the hybrid power system can reach nearly 90% under all the ideal conditions.

Keywords: irreversible solid oxide fuel cell, hybrid power system, performance, optimal working range

1. INTRODUCTION

Fuel cells, due to their low production cost and high maintainability, have become an important solution to global energy depletion [1-3]. In a variety of fuel cells, the operating temperature of solid oxide fuel cell(SOFC) is relatively high, so it belongs to the high temperature fuel cell [4]. In the operating process of the solid oxide fuel cell, it can produce a large amount of high temperature flue gas, which is a kind of natural energy carrier and have the value of utilization. SOFC can not only provide the heat needed for natural gas reforming, but also can be used to produce steam. At the same time, it can also form a combined cycle system with various heat engines, which is very suitable for distributed power generation system [5-8].

There have been a large number of combined power generation systems composed of solid oxide fuel cells, gas turbines and steam turbines, which not only have high power generation efficiency, but also have low pollution environmental benefits. For example, one technique was reported in the paper[9] by Damo that the integration of micro turbine and fuel cell (hybrid power system) can be a practical solution. In engineering, by combining two different systems in a hybrid way, the efficiency of microturbines has been improved from 25-30% to 60-65%. M Moradi[10] designed a new power generation system, it contains a solid oxide fuel cell, solar parabolic dishes, double libro-H_2O absorption refrigeration systems and organic Rankine cycle, the results show that the electrical efficiency of solid oxide fuel cell, the electricity efficiency of joint system and system of total thermal efficiency were 41.49%, 48.73% and 79.49%, respectively. HP Berg and other researchers[11] have built a compact system that takes advantage of the micro-gas turbine cycle to release the heat energy from the injected fuel into the SOFC stack and convert that energy into additional work, which is then converted to electricity through a turbine generator.

In present paper, we will build a hybrid power system, which use the solid oxide fuel cell as a high-temperature heat storage device, and the heat from the exhaust gas to provide further power for the heat engine. Analytical expressions of efficiency and power output of hybrid power system are given by electrochemical and thermodynamic analysis. Finally, the important factors affecting the hybrid power system, such as electrolyte thickness, fuel ratio and operating temperature, are discussed in detail.

2. MODEL OF THE HYBRID SYSTEM

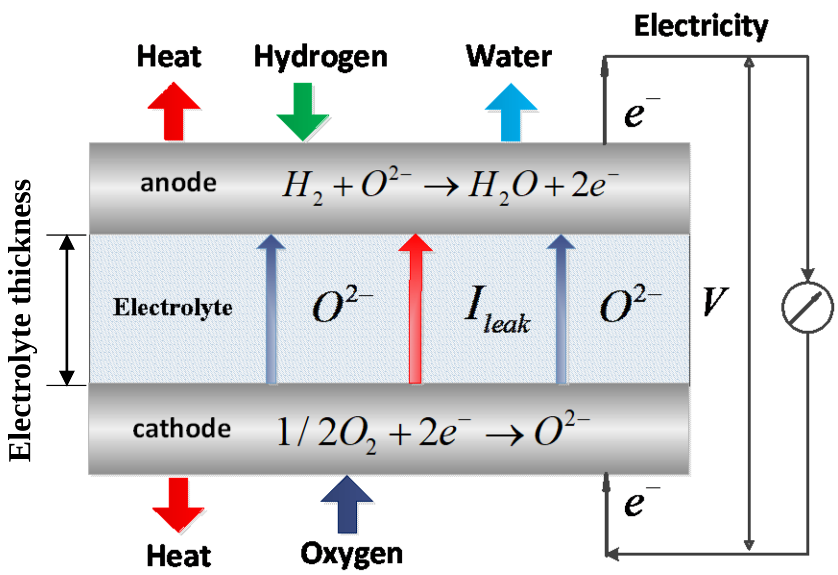

Figure 1. Principle of a solid oxide fuel cell.

Firstly, let's look at the solid oxide fuel cell itself. The solid oxide fuel cell model proposed in this paper has been reported in the paper[12,13]. It is mainly composed of cathode, anode and electrolyte, and with hydrogen as fuel, air as oxidant for work. The electrolyte acts as a barrier between the anode and cathode, allowing only certain types of ions to pass through, while electrons generate a useful current from the anode to the cathode through an external circuit. Its basic working principle is shown in Figure

1. At the cathode, incoming electrons reduce oxygen to oxygen anions, which are then conducted through the electrolyte to the anode, where they electrochemically bind with the adsorbed hydrogen, producing water and hot work as byproducts, and releasing electrons into an external circuit. The whole electrochemical reaction process in the fuel cell can be summarized as H_2 + (1/2) O_2 →H2O +heat+electricity.

Considering several typical irreversibility, the output power and efficiency of the fuel cell can be deduced as

$$P_{cell} = \frac{iA}{n_e F}\left[\beta - \frac{k}{RTd_1}\beta^2\right] \qquad (1)$$

and

$$\eta_{cell} = \frac{1}{-\Delta h}\left[\beta - \frac{k}{RTd_1}\beta^2\right] \qquad (2)$$

Where $\beta = -\Delta g^0(T) + RT\ln(\frac{p_{H_2} p_{O_2}^{1/2}}{p_{H_2O}}) - RTd_1$, R is Universal gas constant , Δg is the Gibbs free energy, T is temperature, p is the partial pressures of various gases, $k = R_{\text{int}} / R_{leak}$, R_{int} and R_{leak} represents internal resistance and leakage resistance respectively, F is Faraday constant, i is the electrical current density, L_{el} is electrolyte thickness, n_e is the number of electron , $d_1 = 2n_e \sinh^{-1}(\frac{i}{2i_{0,a}}) + 2n_e \sinh^{-1}(\frac{i}{2i_{0,c}}) + \frac{i n_e L_{el} F}{R\sigma_0}\exp(\frac{E_{el}}{RT}) - \ln(1-\frac{i}{i_{L,a}}) - \ln(1-\frac{i}{i_{L,c}})$, E_{el} is activation energy.

In actual application, general SOFC power generation systems include a fuel handling unit, a fuel cell power generation unit, and an energy recovery unit. Figure 2 shows a typical power generation system powered by natural gas operating at atmospheric pressure.

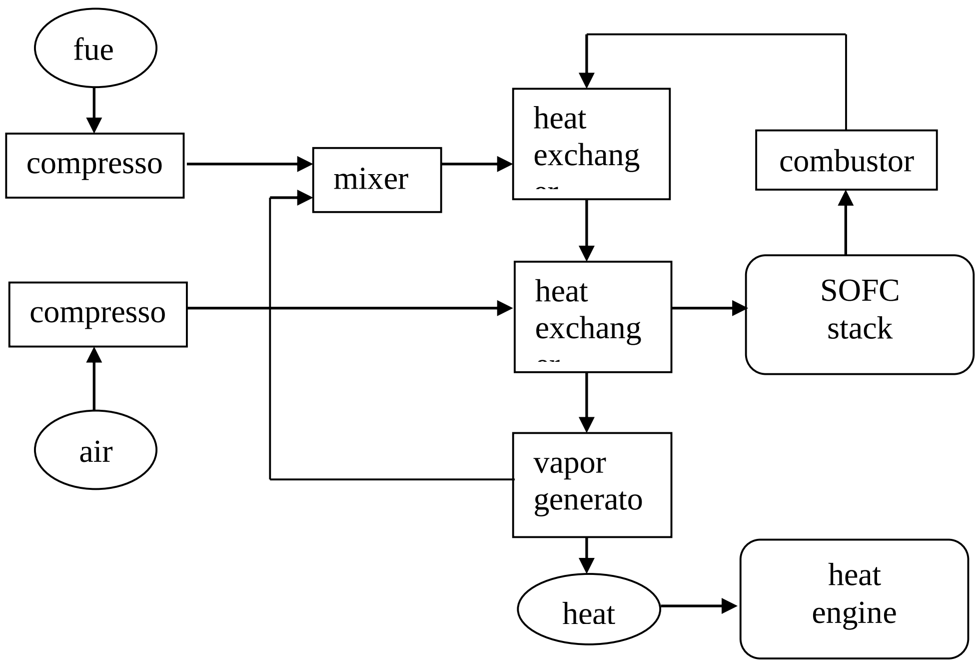

Figure 2. Typical SOFC power generation system operation diagram

In this model, the air is compressed by the compressor and enters the preheater to preheat after overcoming the resistance of the system, and then enters the cathode of the fuel cell. At the same time, the natural gas enters the mixer after compression by the compressor, overcoming the system resistance, and mixes with the superheated steam generated in the steam generator. The mixed fuel gas enters the heater to raise the temperature and then passes into the anode of the fuel cell. The gas between the anode and cathode will undergo electrochemical reaction in the fuel cell.

When the fuel cell generates electric energy, the heat generated in the electrochemical reaction process can be used to heat the gas between the anode and cathode which is not completely reacted. Finally, the unreacted gas of anode and the remaining oxidant of cathode are passed into the burner for combustion. The high-temperature gas produced by combustion is not only used to preheat fuel and air, but also provides the heat required by the steam generator. The heat energy of the combustion products after passing through the steam generator still has utilization value, and can be further utilized through the waste heat recovery device to provide secondary use of energy.

The initial design of a fuel cell-thermo-engine hybrid power system should be as simple as possible to be competitive, but at the same time, it should be highly reliable and practical. Therefore, a simplified Stirling heat engine hybrid system of solid oxide fuel cell is designed in this paper, which mainly consists of solid oxide fuel cell, regenerator and Stirling heat engine. In this system, in addition to its own energy generation, solid oxide fuel cell can also be used as a high temperature heat storage device to further power the heat engine. The regenerator can preheat the fuel and gas that will enter the fuel cell by using the waste heat of high temperature generated in the process of fuel cell operation, so as to ensure that the fuel cell works in a stable state.

Firstly, in order to simplify the model, it is assumed that the whole system works under a stable condition, that all gases are ideal gases, and that the temperature and pressure are uniform in the whole system space. Then, for a typical Stirling heat engine, its efficiency and power can be expressed as:

$$\eta_{engine}=\frac{(\beta_1-1)T-\beta_1T_0+\left[i\beta_2(1-\eta_{cell})-\beta_3(T-T_0)\right]+T_e}{2\beta_1T+\beta_1\left\{(\beta_1-1)T-\beta_1T_0+\left[i\beta_2(1-\eta_{cell})-\beta_3(T-T_0)\right]+T_e\right\}} \quad (3)$$

and

$$P_{engine}=K\left[i\beta_2(1-\eta_{cell})-\beta_3(T-T_0)\right]$$
$$\times\frac{(\beta_1-1)T_h-\beta_1T_0+\left[i\beta_2(1-\eta_{cell})-\beta_3(T-T_0)\right]+T_e}{2\beta_1T+\beta_1\left\{(\beta_1-1)T-\beta_1T_0+\left[i\beta_2(1-\eta_{cell})-\beta_3(T-T_0)\right]+T_e\right\}} \quad (4)$$

where $T_e=\left\{\left[(\beta_1+1)T+\beta_1T_0-q_h/K\right]^2-4\beta_1(\beta_1+1)TT_0\right\}^{0.5}$, $K=\frac{k_1}{(1+b)(1+\sqrt{k_1/k_2})^2}$, $\beta_2=-\frac{A}{n_eFK}\Delta h$ and $\beta_3=\frac{\alpha A_l}{K}$.

Combining Equations (1)-(4), the performance expression of the coupled system can be obtained as follows:

$$\eta_{hybrid} = \frac{P_{hybrid}}{\dot{Q}_{all}} = \frac{P_{cell} + P_{engine}}{-\Delta \dot{H}}$$
$$= \eta_{cell} + \left[1 - \eta_{cell} - \frac{\beta_3}{i\beta_2}(T - T_0)\right] \qquad (5)$$
$$\times \frac{(\beta_1 - 1)T - \beta_1 T_0 + \left[i\beta_2(1-\eta_{cell}) - \beta_3(T - T_0)\right] + T_e}{2\beta_1 T + \beta_1\left\{(\beta_1 - 1)T - \beta_1 T_0 + \left[i\beta_2(1-\eta_{cell}) - \beta_3(T - T_0)\right] + T_e\right\}}$$

and

$$P_{hybrid} = P_{cell} + P_{engine}$$
$$= \left(-\frac{iA}{n_e F}\Delta h\right) \times \left\{ \begin{array}{l} \eta_{cell} + \left[1 - \eta_{cell} - \frac{\beta_3}{i\beta_2}(T - T_0)\right] \\ \times \frac{(\beta_1 - 1)T - \beta_1 T_0 + \left[i\beta_2(1-\eta_{cell}) - \beta_3(T - T_0)\right] + T_e}{2\beta_1 T + \beta_1\left\{(\beta_1 - 1)T - \beta_1 T_0 + \left[i\beta_2(1-\eta_{cell}) - \beta_3(T - T_0)\right] + T_e\right\}} \end{array} \right\} \qquad (6)$$

It can be seen from Equations (5) and (6) that the efficiency and power output of the hybrid power system are closely dependent on the internal structure of the fuel cell, the operating temperature, and the proportion of gas fuel and other factors. In the following discussion section, the characteristic factors affecting the general performance of the hybrid system will be analyzed and discussed in detail.

3. DISCUSSION

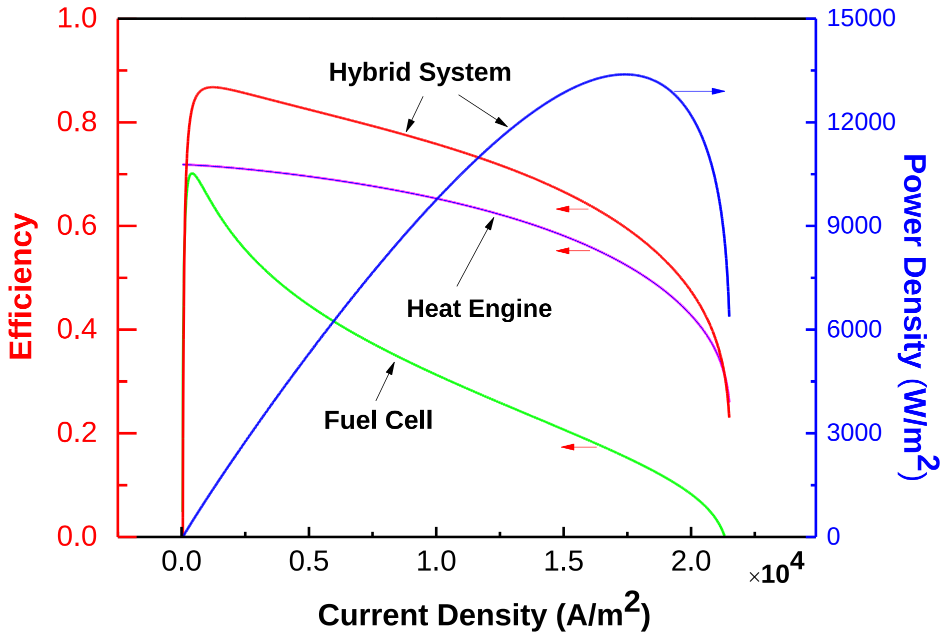

Figure 3. The curves of efficiency and power density as a function of current density.

By using Equations (1)-(6), the efficiency and power density of the hybrid system operating at different current density are presented in Figure 3, where the separate efficiencies in the hybrid system are given and $P^* = P / A$. It can be clearly seen from Figure 3 that the efficiency and power density of the hybrid system first increase and then decrease with the increase of current density. The efficiency value of single system is lower than that of mixed system by coupling the thermal engine, a secondary energy device. The energy efficiency can be greatly improved. Similar conclusions have been found many times in other papers, for example Damo[14] developed an engineered power generation system that combines two different systems in a hybrid way: a micro-turbine and a fuel cell (hybrid power system). The efficiency of microturbines has increased from 25-30% to 60-65%. Kang and Ahn[15] developed a component dynamic modeling of SOFC, engine, external reformer, air blower, and heat exchanger, whose research has confirmed the electrical efficiency of the SOFC-engine hybrid system can be enhanced by about 7.8% compared to the SOFC stand-alone system. All these model are useful to develop the optimal control strategy for the SOFC-engine hybrid system.

To analyze and optimize a system requires a thorough understanding of the various factors that affect its performance. As can be seen from Equations (5) and (6), the performance of the system depends mainly on various electrochemical and thermodynamic parameters, such as electrolyte thickness, fuel mixture ratio, and operating temperature. Next, three typical constraints are discussed in detail to provide useful tools for improving system performance.

3.1 Effect of electrolyte thickness

As a typical factor of fuel cell internal structure, electrolyte thickness must be mentioned. In the model in Fig. 1, the electrolyte layer in the middle of the fuel cell can be observed, and its thickness is the electrolyte thickness. According to Equations (5) and (6), when the working temperature is $1173K$ and the electrolyte thickness is $20, 40$ and $60 \mu m$, respectively, the power density and efficiency of the hybrid system are shown in Fig. 4 and 5. It can be clearly seen from the figure that when the current density is around 1.98×10^{-4} A/m2, that is, the current density corresponding to the maximum power density of the hybrid system, the electrolyte thickness has the greatest influence on the performance of the hybrid system. The thinner the electrolyte thickness, the greater the maximum power density. In other words, its influence on the maximum power density is quite significant under different electrolyte thicknesses. Moreover, the current density corresponding to the maximum power density varies with the thickness of the electrolyte. The smaller the thickness of the electrolyte, the larger the current density corresponding to the maximum power.

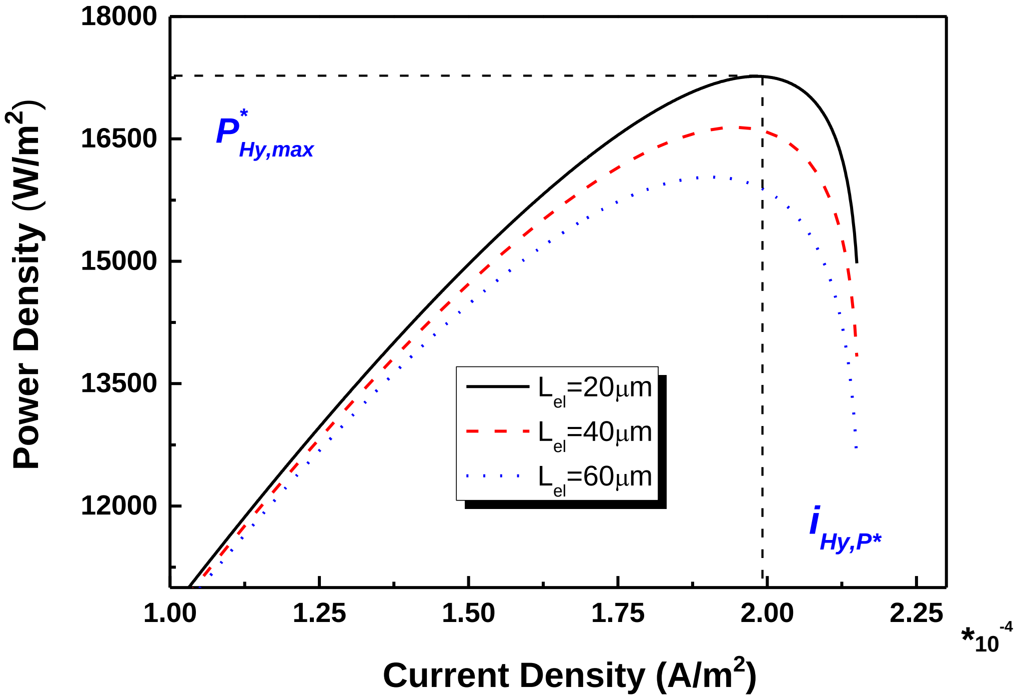

Figure 4. The relationship between the power density of the hybrid system and the current density under different electrolyte thicknesses.

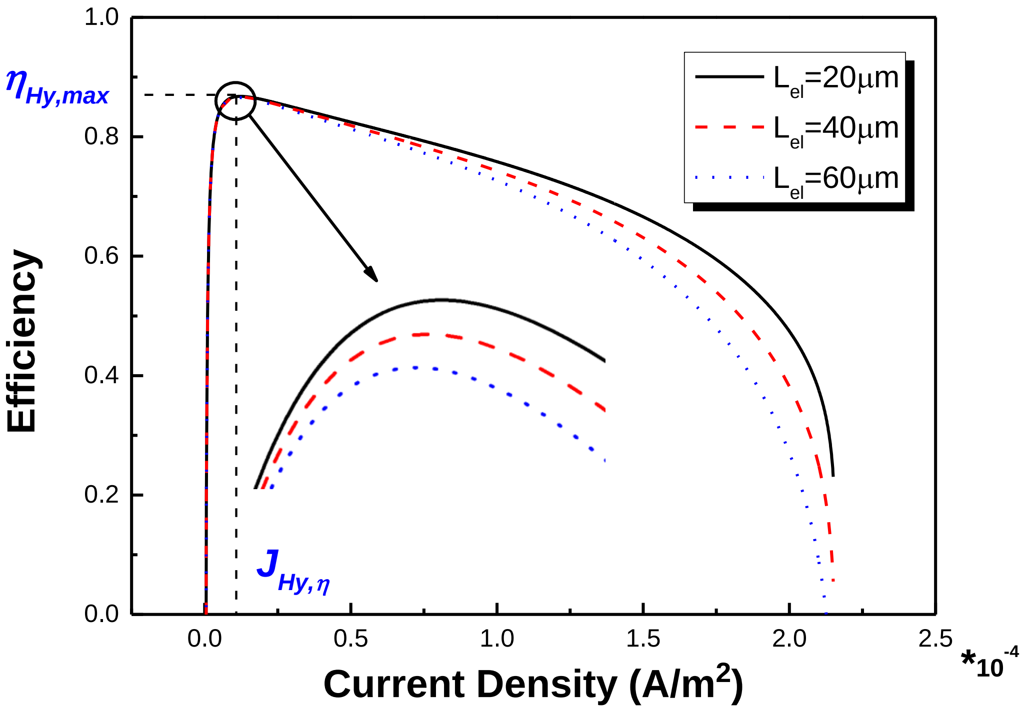

Figure 5. The relationship between the efficiency of the hybrid system and the current density under different electrolyte thicknesses.

However, when the system is operating at maximum efficiency, the effect of electrolyte thickness on maximum efficiency is negligible. But with the increase of current density, the influence of electrolyte thickness becomes more obvious. More importantly, the overall performance of the hybrid system decreases with the increase of electrolyte thickness. This is probably due to the fact that increasing electrolyte thickness increases the ohmic resistance inside the solid oxide fuel cell, which reduces the performance of the fuel cell and thus the performance of the whole hybrid system.

3.2 The influence of fuel mixing ratio

Fig. 6 and Fig. 7 show the performance of hybrid system under different fuel ratios when the operating temperature is $1173K$ and the electrolyte thickness is $20\mu m$ respectively. It is easy to observe that with the increase of hydrogen ratio, the overall performance of the hybrid system, both power and efficiency, has a certain degree of improvement. At the same time, it can also be found that with different fuel mixing ratio, the optimal performance point will be slightly different. Therefore, in practical systems, increasing the concentration of hydrogen and thus improving the overall performance of the system can be pursued by engineers.

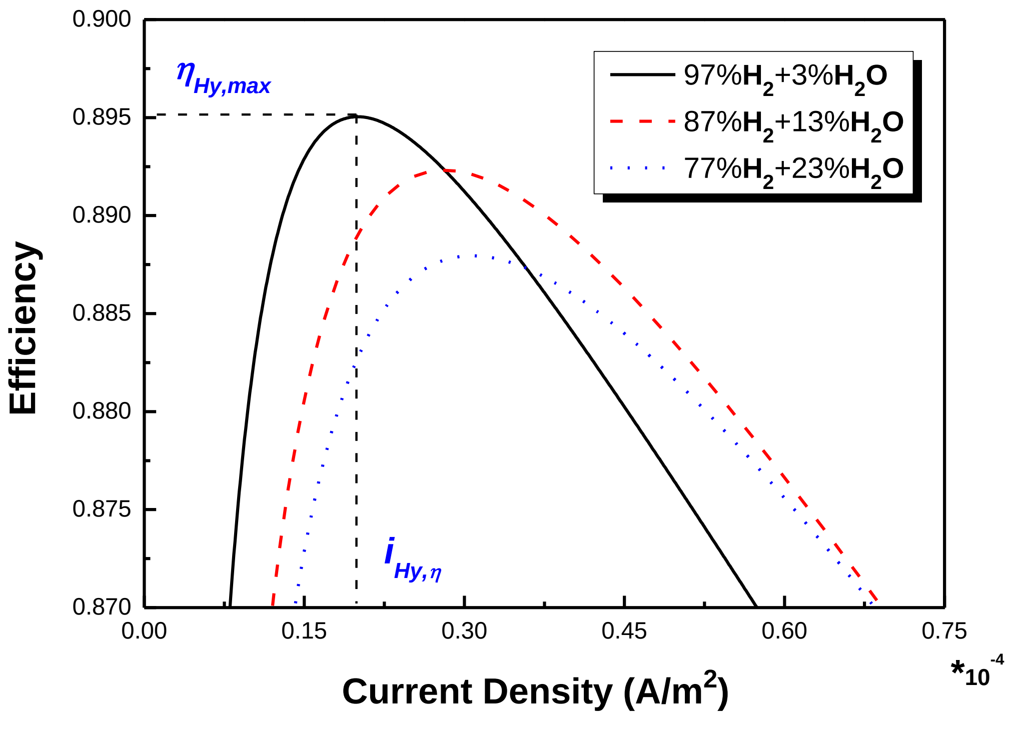

Figure 6. The relationship between the efficiency and the current density of the hybrid system in the case of different fuel mixing ratios

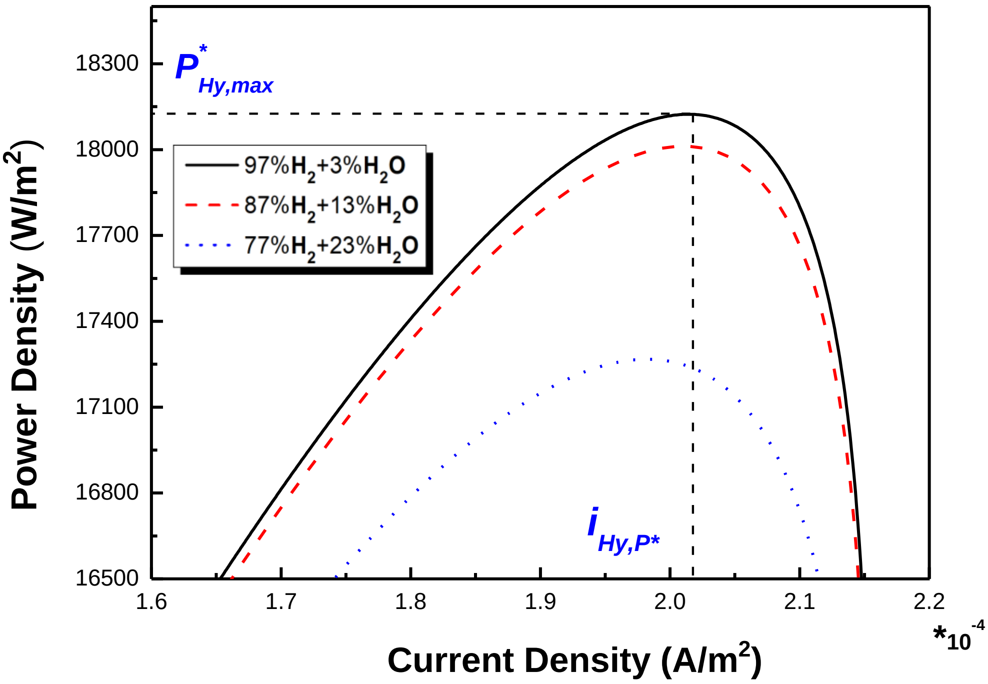

Figure 7. The power density and current density of the hybrid system in the case of different fuel mixing ratios.

3.3 Effect of operating temperature on overall performance

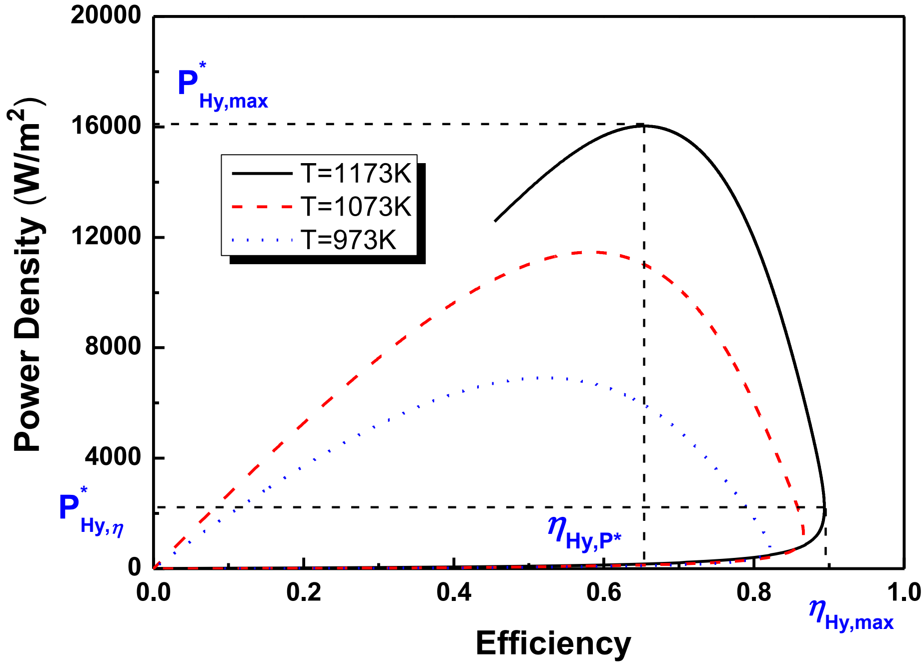

Figure 8. Relationship between power density and efficiency at different temperatures.

As an important performance factor, temperature has an important influence on the performance of hybrid system. Temperature will affect the polarization overpotential, ohmic overpotential and central overpotential of fuel cell. Meanwhile, it will also affect the temperature of the discharged gas, which will lead to the change of the hot heat source of the heat engine. Figure 8 shows the relationship between the efficiency and power of the hybrid system at different operating temperatures. As can be seen from the figure, the higher the temperature is, the better the performance of the hybrid system will be. However, in practical engineering applications, it is impossible to blindly pursue high temperature. On the one hand, excessive temperature may bring performance benefits, but also lead to other engineering costs. Therefore, it is the job of engineers to find a balance between costs and benefits.

4. CONCLUSIONS

In present paper, a solid oxide fuel cell-thermo-mechanical hybrid system is designed. The analytical expressions of the power and efficiency of the hybrid system are given by using electrochemical method under the condition of considering various irreversible losses. Moreover, the influences of three typical characteristics, i.e. electrolyte thickness, fuel mixture ratio and operating temperature, on the performance of the hybrid system are further discussed. The results show that the thinner the electrolyte thickness, the higher the proportion of hydrogen and the higher the operating temperature, the more conducive to improve the performance of the system. The above conclusions have certain guiding significance for practical engineering application.

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