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Performance analysis of solid oxide fuel cell and micro gas turbine top-level cycle

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Abstract. First, a simulation model of the SOFC-MGT top-level combined cycle was established through Matlab/Simulink, and then the effect of different methane flow rates on the performance of the stack and the SOFC-MGT system was analyzed. The research results show that with the increase of methane flow, the power of the stack and SOFC-MGT system gradually increases, but the efficiency of the SOFC-MGT system gradually decreases with the increase of methane flow.

1 Introduction

The efficiency of traditional gas turbines is limited by the "Carnot cycle", and the fuel utilization rate is only about 30%. Most of the energy is lost in the form of heat. How to improve the efficiency of gas turbines has always been the focus of research. A fuel cell is a device that directly converts the chemical energy of hydrogen energy and other fuels into electrical energy. It has many advantages such as noiseless, high efficiency, and pollution-free[1,2]. Solid oxide fuel cell (SOFC) is a medium-high temperature fuel cell. Its stack working temperature is about 600℃~1000℃, and the exhaust gas emission temperature is about 600℃, and it has high quality can be reused[3]. Because fuel cells are not restricted by the "Carnot cycle", their energy utilization rate is much higher than that of traditional heat engines, usually between 60% and 80%. Therefore, if the two can be effectively combined to form a fuel cell and gas turbine combined cycle system, the operating efficiency of the gas turbine will be greatly improved. The solid oxide fuel cell and micro gas turbine (SOFC-MGT) combined cycle has two main structures: one is the bottom cycle mode; the other is the top cycle mode.

Lv[4] established an IT-SOFC-MGT top-level cycle simulation model to analyze the influence of water vapor content on system performance. Zhan[5] established a dual-reactor SOFC-MGT bottom cycle simulation model, and analyzed the impact of different SOFC reactor connection methods on system performance. Zhu[6] established a SOFC-MGT top-level loop simulation model based on Matlab /Simulink software, and analyzed the impact of high back pressure (1.7kg/cm2) on system performance. Saisirirat[7] used MATLAB simulation software to establish a detailed thermodynamic model of the SOFC-GT hybrid system, and proposed two structures of the SOFC-GT hybrid cycle.

At present, scholars have conducted many researches on SOFC anode catalysts, electrolytes and other materials, but there are few studies on the combination of SOFC-MGT. Therefore, this article combines the existing 1kW SOFC in the laboratory to carry out the top-level circulation structure of SOFC-MGT. The analysis and research provide theoretical support for the industrial application of SOFC-MGT.

2 Modular modelling

2.1. Assumptions

In this paper, the following assumptions are made when modelling the SOFC-MGT dynamics.

-All gases are ideal

-The heat exchange between the system and the outside world is ignored

-The reforming reaction and the water-gas replacement reaction are in equilibrium

-The temperature, gas components and pressure in the system are uniformly distributed.

-The system is modelled using centralised parameters.

The SOFC-MGT top cycle structure is shown in Figure 1.

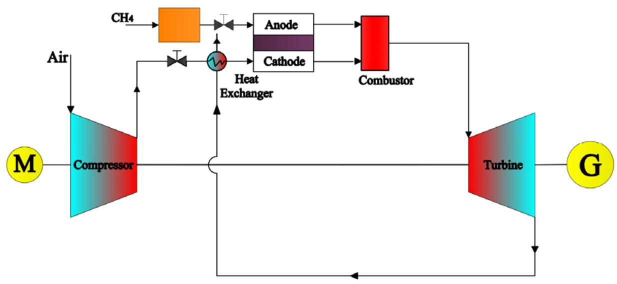

Fig.1 SOFC-MGT topping hybrid cycle

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2.2. Pre-reformer model

In the pre-reformer, which mainly consists of the reforming reaction of methane and the water-gas replacement reaction, the chemical reaction equations are as follows[8].

$$CH_4 + H_2O \leftrightarrow CO + 3H_2 \tag{1}$$

$$CO + H_2O \leftrightarrow CO_2 + H_2 \tag{2}$$

From the equation for conservation of mass we get[5]:

$$\frac{P_1 V_{re}}{RT_1}\frac{dx_{6,i}}{dt} = Q_{n5,i} - Q_{n6,i} + \overline{R}_{re,i}$$

$$(i \in [CH_4, CO, CO_2, H_2, H_2O]) \tag{3}$$

$$\overline{R}_{re} = [-r_{re1}, r_{re1} - r_{re2}, r_{re2}, 3r_{re1} + r_{re2}, -r_{re1} - r_{re2}] \tag{4}$$

In the above equation, P_1 is the average pressure inside the pre-reformer, V_{re} is the volume of the pre-reformer, T_5 is the average temperature of the pre-reformer, R is the universal gas constant ($8.314 J \cdot mol^{-1} \cdot K^{-1}$), $x_{2,i}$ is the molar mass fraction of the exit gas, $Q_{n1,i}$ is the molar flow rate of the inlet gas, $Q_{n2,i}$ is the molar flow rate of the exit gas, $\overline{R}_{re,i}$ is the molar flow rate consumed by the reforming and water-gas replacement reactions of gas i in the pre-reformer, r_{re1} represents the reforming reaction rate of methane, r_{re2} represents the replacement reaction rate of carbon monoxide.

Assuming that both the reforming and water-gas replacement reactions have reached equilibrium, the equilibrium constants can be expressed as [9] respectively:

$$K_r = \exp\left(A_1 T_5^4 + B_1 T_5^3 + C_1 T_5^2 + D_1 T_5^1 + E_1 \right) \tag{5}$$

$$K_s = \exp\left(A_2 T_5^4 + B_2 T_5^3 + C_2 T_5^2 + D_2 T_5^1 + E_2 \right) \tag{6}$$

In the above equations, K_r and K_s are the equilibrium constants for the reforming and water-gas replacement reactions respectively.

2.3. Electrochemical model

The actual voltage of a fuel cell monolith can be represented by the following equation.

$$v_{fc} = E - \eta_{ohmic} - \eta_{conc} - \eta_{act,a} - \eta_{act,c} \tag{7}$$

In the above equations, E is the stack ideal reversible voltage, η_{ohmic} is the ohmic polarization, η_{conc} is the concentration difference polarization, $\eta_{act,a}$ is the anodic activation polarization, $\eta_{act,c}$ is the cathodic activation polarization. According to the Nernst equation, the ideal reversible voltage of the stack is expressed as[10]:

$$E = E^0 + \frac{RT_{cell}}{2F}\ln\left(\frac{p_{4,H_2} p_{5,O_2}^{0.5}}{p_{4,H_2O}}\right) \tag{8}$$

$$E^0 = 1.2723 - 2.7645 \times 10^{-4} T_{cell} \tag{9}$$

In the above equations, E^0 is the standard electric potential, p_{4,H_2} is the pressure of the hydrogen at the anode outlet, p_{4,H_2O} is the pressure of the water at the anode outlet, p_{5,O_2} is the pressure of the oxygen at the cathode inlet, T_{cell} is the temperature of the stack.

2.4. Temperature model

According to the above assumptions, neglecting the heat exchange between the reactor and the outside world, the conservation of energy equation yields [11]:

$$\begin{aligned} C_{cell}\frac{dT_{cell}}{dt} = {} & Q_{n3} \cdot \sum_j (X_{3,j} \cdot \overline{h}_{3,j}) + Q_{n6} \cdot \sum_i (X_{6,i} \cdot \overline{h}_{6,i}) - Q_{n4} \cdot \sum_j (X_{4,j} \cdot \overline{h}_{4,j}) \\ & - Q_{n7} \cdot \sum_i (X_{7,i} \cdot \overline{h}_{7,i}) - P_{cell} + \sum_k Q_k \end{aligned} \tag{10}$$

In the above equations, $i \in [CH_4, CO, CO_2, H_2, H_2O]$, $j \in [N_2, O_2]$, $k = 1,2,3$, C_{cell} is the heat capacity of the reactor gas, $\overline{h}_{3,j}$ is the enthalpy of the SOFC cathode inlet gas j, $\overline{h}_{4,j}$ is the enthalpy of the cathode outlet gas, Q_{n3} is the molar flow rate of the cathode inlet gas, Q_{n4} is the molar flow rate of the cathode outlet gas, $\overline{h}_{6,i}$ is the enthalpy of the anode inlet gas, $\overline{h}_{7,i}$ 为 is the enthalpy of the anode outlet gas, Q_1 is the heat of reformation, Q_2 is the heat of water-gas replacement reaction, Q_3 is the heat of electrochemical reaction.

2.5. Pressurised gas turbine model

Compressor pressure ratio π is:

$$\pi = f_1\left(G_1 \frac{p_0 \sqrt{T_1}}{p_1 \sqrt{T_0}}, n_c \frac{\sqrt{T_0}}{\sqrt{T_1}}\right) \tag{11}$$

The compressor outlet temperature can be expressed as:

$$T_2 = T_1 [1 + (\pi^{m_a} - 1)/\eta] \tag{12}$$

2.6. Turbine model

The micro gas turbine uses a centripetal turbine, which has the advantages of simple structure, large enthalpy drop in a single stage and wide operating range[12].

The turbine expansion ratio is:

$$\varepsilon_T = f_3\left(\frac{G_9\sqrt{T_9}}{p_9}, \frac{n_T}{\sqrt{T_9}}\right) \tag{13}$$

The turbine efficiency characteristics can be expressed as:

$$\eta_T = f_4\left(\frac{G_9\sqrt{T_9}}{p_9}, \frac{n_T}{\sqrt{T_9}}\right) \tag{14}$$

In the above equation, G_9 is turbine inlet flow, p_9 is turbine inlet pressure, T_9 is turbine inlet temperature, η_T is turbine speed.

So far, the mathematical model of the SOFC-MGT combined cycle system has been established, and the simulation model of the new SOFC-MGT bottom cycle system has been obtained through Matlab/Simulink simulation.

3 Performance analysis

The laboratory has an existing 1kW solid oxide fuel cell experimental system, as shown in Fig.2.

Fig.2 Solid oxide fuel cell experiment system

The set-up parameters for the SOFC-MGT hybrid power generation system model are shown in Table 1:

Tab.1 Initial conditions of SOFC-MGT system operation

Parameters	Unit	Numerical values
Fuel import composition $x_{1,i}$	—	100% CH_4
Fuel inlet flow Q_{n1}	$mol \cdot s^{-1}$	2.75×10^{-3}
Air import composition $x_{5,i}$	—	$79\% N_2 + 21\% O_2$
Air inlet flow	$mol \cdot s^{-1}$	2.37×10^{-2}
Fuel inlet pressure P_1	P_a	1.013×10^5
Air inlet pressure P_5	P_a	1.013×10^5
Fuel inlet temperature T_1	K	298
Air inlet temperature T_5	K	298
SOFC input current i	A	43
Reactor pressure loss σ_{st}	—	2%
Heat capacity of the reactor C_s	$J \cdot K^{-1}$	471
Combustion chamber pressure loss σ_b	—	3%
Combustion chamber efficiency η_b	—	98%
Number of batteries N	—	30
Compressor pressure ratio ε	—	3.8

Through simulation and experimental testing, the volt-ampere characteristic curve of SOFC is shown in Fig.3:

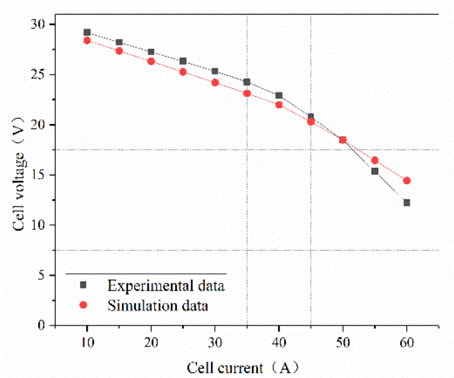

Fig.3 Volt-ampere characteristic curve of SOFC

As can be seen from the figure, the simulation model built in this paper is in good agreement with the experimental test data. When the output current is less than the rated output current of 43A, the maximum error between the simulation model and the experimental test data is 4.7%.

Through simulation, the volt-ampere characteristic curve and fuel cell power characteristic curve of the fuel cell under different methane flow rates are obtained, as shown in Figs 4 and 5:

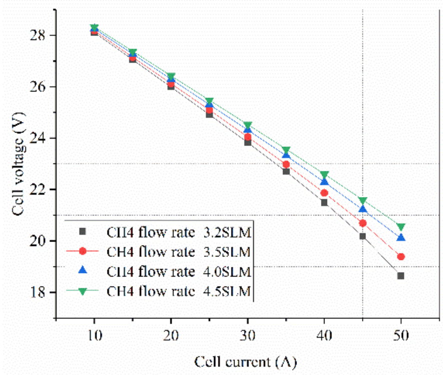

Fig.4 V-I characteristic cure of SOFC

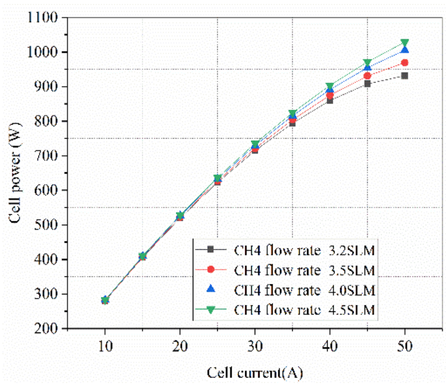

Fig.5 Power characteristic cure of SOFC

It can be seen from Fig.4 and Fig.5 that with the increase of methane flow, the output voltage and power of SOFC have increased. The larger the output current of SOFC, the increase of methane flow will greatly improve the output performance of the stack. However, the increase of methane flow will increase the internal pressure of the stack, which puts forward higher requirements on the sealing performance of the stack.

The system power characteristic curve of the SOFC-MGT top-level cycle is shown in Fig.6 under different methane flow rates obtained through simulation.

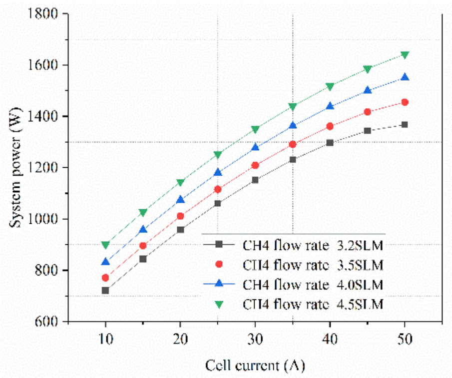

Fig.6 System power characteristic cure of SOFC-MGT

It can be seen from Fig.6 that with the increase of methane flow, the power of the SOFC-MGT system has increased. At the same time, the larger the output current of the stack, the greater the impact of the increase of methane flow on the output performance of the SOFC-MGT system.

The system efficiency characteristic curve of the SOFC-MGT top-level cycle is shown in Fig.7 under different methane flow rates obtained through simulation.

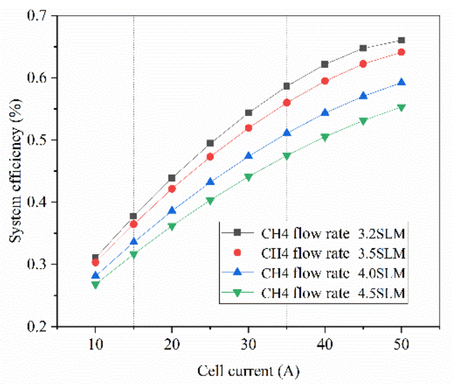

Fig.7 Efficiency characteristic cure of SOFC-MGT

It can be seen from Fig 7 that as the methane flow rate increases, the efficiency of the system gradually decreases. The greater the methane flow rate, the lower the efficiency of the system. This is because with the increase of methane flow, the maximum power of the stack gradually increases, and the maximum discharge current corresponding to the stack gradually increases, which makes the losses of the stack gradually increase, resulting in a gradual decrease in the efficiency of the system.

4 Conclusions

Through the simulation analysis of the SOFC-MGT combined cycle structure designed in this paper, the following conclusions are obtained:

• The SOFC-MGT simulation model established in this paper is correct, and the SOFC-MGT top-level combined cycle structure is feasible.

• As the methane flow rate increases, the output performance of the SOFC gradually increases. The larger the methane flow rate, the better the output performance.

• The greater the output current of the stack, the more obvious the effect of the increase in methane flow on the performance of the stack.

• With the increase of methane flow, the output performance of the SOFC-MGT system gradually increases, but the efficiency of the SOFC-MGT system gradually decreases.

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