Performance analysis of SOFC-MGT new bottom cyclic structure

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Abstract. A new type of SOFC-MGT bottom cycle structure is proposed, and its performance is researched and analyzed based on Matlab/Simulink software and experimental tests. The research results show that the higher the initial temperature of the fuel, the worse the reforming efficiency. With the continuous increase of the initial fuel temperature, the reformed product CO can increase by up to 1.1%, CO2 can be reduced by up to 2.8%, H2 can be reduced by up to 0.3%, and the remaining water vapor is up to 0.6%. The overall power of the SOFC-MGT system is the SOFC power 2.1 times the power, which is 3.25 times the power of MGT.

1. Introduction
The fuel cell and micro gas turbine bottom cycle system (SOFC-MGT) has the advantages of high efficiency, low pollution, low noise, and diverse fuel types. It has solved the energy crisis and environmental problems well, and is currently recognized as one of the most promising power generation methods. As the next generation distributed generation device, it has unparalleled advantages in traditional power plants[1].

As a next-generation distributed power generation device, it has an incomparable advantage over traditional power plants: the power exchange system, not the power distribution system[2,3].

With the construction of South China Sea islands and reefs in full swing, an environment-friendly and resource-saving power generation device is urgently needed. As a new type of distributed power generation device, the solid oxide fuel cell and micro gas turbine bottom cycle system can solve the problems of energy shortage and ecological fragility on islands and reefs[4].

At the same time, for the local power grid of islands and reefs, it has the characteristics of large load power change and weak anti-interference ability. The distributed power generation device makes up for the shortcoming of regional local power grid and has high reliability.

In terms of circulation methods, Zhan H Y[5] et al analysed the effect of different connection methods of SOFC stacks on system performance. Zhu Runkai[6] et al analysed the effect of high back pressure (1.7 kg/cm²) case on the performance of SOFC-MGT system. The results of the study showed that a special water treatment system is required for efficient operation of SOFC-MGT hybrid power generation system under high back pressure conditions. Lv Xiaojing[7] et al analysed the effect of water vapour content on system performance by building a simulation model of the IT-SOFC-MGT top cycle.

Saisirirat[8] 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. You[9] et al introduced a micro-multi-generation power generation system consisting of SOFC and MGT, etc. By
establishing a mathematical model, they analysed the effects of fuel utilization, air-fuel ratio and other parameters on the performance of the micro Stirrer [10] proposed a safety mechanism for steady-state operation based on a SWPC demonstration of a SOFC-GT hybrid system configuration. Iw [11] et al proposed a safety zone for a medium-temperature SOFC-GT hybrid system fed by biomass gas.

Based on the previous studies, this paper proposes a novel SOFC-MGT bottom cycle structure, investigates and analyses its performance, and expands the combined SOFC-MGT cycle approach.

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 new bottom cycle proposed in this paper works on the following principle: the air is compressed by a compressor and then passes through a heat exchanger into a turbine to do the work. The high temperature air from the turbine passes directly into the cathode of the SOFC and then the exhaust gas from the cathode and anode reactions of the fuel cell enters the catalytic combustion chamber and the resulting high temperature gas is heat exchanged with the air coming from the compressor. The advantages of this design are: on the one hand it maximises the use of the turbine exhaust gas, on the other hand it allows a higher temperature to enter the SOFC air electrode without damaging the cell due to temperature differences, and it also saves on heat exchanger equipment. The new SOFC-MGT bottom cycle structure is shown in Fig. 1.

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 [12].

\[
\begin{align*}
CH_4 + H_2O & \leftrightarrow CO + 3H_2 \quad (1) \\
CO + H_2O & \leftrightarrow CO_2 + H_2 \quad (2)
\end{align*}
\]

From the equation for conservation of mass we get [6]:

\[
\frac{PV_{re}}{RT_1} \frac{dx_{\text{pre}}}{dt} = Q_{\text{pre}} - Q_{\text{pre}} + \bar{R}_{\text{pre}} \quad (i \in [CH_4, CO, CO_2, H_2, H_2O])
\]

\[
\bar{R}_{\text{pre}} = [-r_{r1}, r_{r1} - r_{e2}, r_{e2}, 3r_{r1} + r_{e2}, r_{e2} - r_{r1}, -r_{e2}] \quad (4)
\]

In the above equation, \( P \) is the average pressure inside the pre-reformer, \( V_{re} \) is the volume of the pre-reformer, \( T_1 \) is the average temperature of the pre-reformer, \( R \) is the universal gas constant...
\( (8.314 \text{ J} \cdot \text{mol}^{-1} \cdot \text{K}^{-1}) \), \( x_{2,i} \) is the molar mass fraction of the exit gas, \( Q_{\text{in},i} \) is the molar flow rate of the inlet gas, \( Q_{\text{out},i} \) is the molar flow rate of the exit gas, \( R_{\text{re},i} \) is the molar flow rate consumed by the reforming and water-gas replacement reactions of gas \( i \) in the pre-reformer, \( r_{\text{re},i} \) represents the reforming reaction rate of methane, \( r_{\text{rep}} \) 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 \([13]\) respectively:

\[
K_r = \exp\left( A_r T_r^4 + B_r T_r^3 + C_r T_r^2 + D_r T_r + E_r \right)
\]

\[
K_s = \exp\left( A_s T_s^4 + B_s T_s^3 + C_s T_s^2 + D_s T_s + E_s \right)
\]

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

### 2.3. Anode model

The hydrogen produced by methane in the pre-reformer reaches the anode and reacts with the oxygen ions transmitted from the cathode to produce water and generate electrons that are transported to the external circuit. The reaction equation is as follows:

\[
H_2 + O^{2-} \rightarrow H_2O + 2e^-
\]

At this point the anode channel is a mixture of methane, hydrogen, water, carbon monoxide and carbon dioxide. According to the mass conservation equation there is the following equation:

\[
\frac{P_{\text{an},i}}{RT_{\text{cell}}} \frac{dV_{\text{an},i}}{dt} = Q_{\text{an},i} - Q_{\text{at},i} + R_i \left( i \in \{CH_4, CO, CO_2, H_2, H_2O\} \right)
\]

\[
R_i = [-r_{\text{re},i} - r_{\text{rep}}; r_2; 3r_1 + r_2 - r_3; -r_3 - r_2 + r_1]
\]

In the above equation, \( P_{\text{an}} \) is the anode outlet gas pressure, \( T_{\text{cell}} \) is the stack temperature, \( aV \) is the anode volume, \( x_{\text{an},i} \) the molar fraction of the anode exit gas \( i \), \( Q_{\text{an},i} \) is the molar flow rate of the anode exit gas \( i \), \( r_1 \) is the reforming reaction rate, \( r_2 \) is the water-gas replacement reaction rate, \( r_{\text{an}} \) is the electrochemical reaction rate.

### 2.4. Electrochemical model

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

\[
v_{\text{f,c}} = E - \eta_{\text{ohmic}} - \eta_{\text{conc}} - \eta_{\text{act,a}} - \eta_{\text{act,c}}
\]

In the above equations, \( E \) is the stack ideal reversible voltage, \( \eta_{\text{ohmic}} \) is the ohmic polarization, \( \eta_{\text{conc}} \) is the concentration difference polarization, \( \eta_{\text{act,a}} \) is the anodic activation polarization, \( \eta_{\text{act,c}} \) is the cathodic activation polarisation. According to the Nernst equation, the ideal reversible voltage of the stack is expressed as \([14]\):

\[
E = E^0 + \frac{RT_{\text{cell}}}{2F} \ln\left( \frac{p_{\text{an},H_2}}{p_{\text{at},H_2O}} \right)
\]

\[
E^0 = 1.2723 - 2.7645 \times 10^{-4} T_{\text{cell}}
\]

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

### 2.5. Temperature model

According to the above assumptions, neglecting the heat exchange between the reactor and the outside world, the conservation of energy equation yields \([15]\):
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, $Q_{a3}$ is the molar flow rate of the cathode inlet gas, $Q_{b4}$ is the molar flow rate of the cathode outlet gas, $\overline{h}_{6,i}$ is the enthalpy of the anode inlet gas, $\overline{h}_{7,i}$ is the enthalpy of the anode outlet gas, $Q$ is the heat of reformation, $Q_2$ is the heat of water-gas replacement reaction, $Q_3$ is the heat of electrochemical reaction.

2.6. Miniature gas turbine model

The micro gas turbine system consists of a centrifugal compressor, catalytic combustion chamber, heat exchanger and turbine. Based on the existing micro gas turbine, the mathematical model of each module is constructed using the joint module method [16].

2.6.1. Pressurised gas turbine model

The operating characteristics of a compressor can be expressed in terms of four parameters $\pi$, $\overline{G}$, $\pi$ and $\eta$.

According to the conservation of mass, the flow rate at the outlet of the compressor can be obtained as:

$$G_1 = G_2$$

(14)

In the above equation, $G_1$, $G_2$ are the actual inlet and outlet flow rates of the compressor.

The equivalent flow rate $\overline{G}_1$ is:

$$\overline{G}_1 = G_1 \frac{p_0 \sqrt{T_1}}{P_1 \sqrt{T_0}}$$

(15)

The equivalent speed $\overline{\pi}_c$ is:

$$\overline{\pi}_c = n_c \frac{\sqrt{T_0}}{\sqrt{T_1}}$$

(16)

In the above equation, $T_1$ is the compressor inlet temperature, $p_1$ is the compressor inlet pressure, $n_c$ is the actual speed, $p_0 = 1.01325 \times 10^5 \ Pa$, $T_0 = 298K$.

Compressor pressure ratio $\pi$ is:

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

(17)

The compressor efficiency $\eta_c$ is:

$$\eta_c = f_2\left(G_1 \frac{p_0 \sqrt{T_1}}{p_1 \sqrt{T_0}}, n_c \frac{\sqrt{T_0}}{\sqrt{T_1}}\right)$$

(18)

The power consumed by the compressor can be expressed as:

$$\eta_c = \epsilon_a \tau \left(\pi^\alpha - 1\right) / \eta$$

(19)

$$m_a = (\lambda_a - 1) / \lambda_a$$

(20)

The compressor outlet temperature can be expressed as:
2.6.2. Turbine model

The micro gas turbine uses a centrifugal turbine, which has the advantages of simple structure, large enthalpy drop in a single stage and wide operating range [17].

The turbine expansion ratio is:

\[ \varepsilon_r = f_3 \left( \frac{G_s \sqrt{T_9}}{p_h}, \frac{n_s}{\sqrt{T_9}} \right) \]  

(22)

The turbine efficiency characteristics can be expressed as:

\[ \eta_r = f_4 \left( \frac{G_s \sqrt{T_9}}{p_h}, \frac{n_s}{\sqrt{T_9}} \right) \]  

(23)

In the above equation, \( G_s \) is turbine inlet flow, \( p_h \) is turbine inlet pressure, \( T_9 \) is turbine inlet temperature, \( \eta_r \) is turbine speed.

The work done by the turbine is:

\[ \Delta W = \frac{T_3 - T_1}{\varepsilon_r \eta_r} \]  

(24)

In the above equations, \( T_3 \) is the turbine inlet temperature, \( \eta_r \) is the turbine efficiency, \( \varepsilon_r \) is the turbine expansion ratio.

2.6.3. Heat exchanger models

The main methods for calculating heat exchangers are the "average heat transfer temperature difference method" and the "ε-NTU method", and the "average heat transfer temperature difference method" is generally used for current calculations. In the average temperature difference method the outlet temperature \( T_{out} \) not only affects the heat transfer coefficient \( K \), but also the average temperature \( \Delta T \), \( \Delta T \) is a strong function of the outlet temperature \( T_{out} \) [18].

The counter-current mean temperature difference can be expressed as:

\[ \Delta T = \frac{T_8 - T_9}{\ln \left( \frac{T_{10} - T_2}{T_{10} - T_9} \right)} \]  

(25)

In the above equations, \( T_2 \) is the inlet temperature on the air side of the heat exchanger, \( T_9 \) is the outlet temperature on the air side of the heat exchanger, \( T_8 \) is the inlet temperature on the exhaust side of the heat exchanger, \( T_{10} \) is the inlet temperature on the exhaust side of the heat exchanger.

\[ P = \frac{T_8 - T_9}{T_9 - T_2} \]  

(26)

\[ R = \frac{T_8 - T_{10}}{T_8 - T_9} \]  

(27)

In order to calculate the accuracy of the model, a temperature correction factor \( \psi \) is introduced. The corrected heat transfer temperature difference is [5]:

\[ \Delta T' = \psi \Delta T \]  

(28)

The heat exchange between the compressed air from the compressor and the exhaust gas from the catalytic combustion chamber is:

\[ \Phi' = K_A \Delta T' \]  

(29)

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.

![Solid oxide fuel cell experiment system](image)

The stack consists of 30 fuel cell panels with a single size of 14cm x 14cm and a maximum power of 50 W. The system uses methane as fuel and has a current of 43 A, a voltage of 23.5V and a power of 1010.5 W at rated operating conditions.

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

| Parameters                  | Unit       | Numerical values |
|-----------------------------|------------|------------------|
| Fuel import composition $x_i$ | —          | 100%CH$_4$       |
| Fuel inlet flow $Q_i$       | mol·s$^{-1}$ | $2.75 \times 10^{-3}$ |
| Air import composition $x_j$ | —          | 79% N$_2$ + 21% O$_2$ |
| Air inlet flow             | —          | $2.37 \times 10^{-2}$ |
| Fuel inlet pressure $P_i$   | P$_a$      | $1.013 \times 10^5$ |
| Air inlet pressure $P_j$    | P$_a$      | $1.013 \times 10^5$ |
| Fuel inlet temperature $T_i$| K          | 298              |
| Air inlet temperature $T_j$ | K          | 298              |
| SOFC input current $i$      | A          | 43               |
| Reactor pressure loss $\sigma_r$ | —      | 2%               |
| Heat capacity of the reactor $C_r$ | J·K$^{-1}$ | 471             |
| Combustion chamber pressure loss $\sigma_s$ | —      | 3%               |
| Combustion chamber efficiency $\eta_s$ | —      | 98%              |
| Number of batteries N       | —          | 30               |
| Compressor pressure ratio $\varepsilon$ | —      | 3.8              |

Through simulation and experimental testing, the volt-ampere characteristic curve of SOFC is shown in Fig.3:
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%. When the output current is greater than 50A, the power of the reactor remains the same, but the output current of the reactor is too high, resulting in a significant drop in output voltage.

By analysing the effect of the initial fuel temperature on the reforming reaction, the relationship between the water vapour and the CO, CO₂ and H₂ produced by the reforming reaction with the initial fuel temperature is shown in Fig.4.
As can be seen from the graph, as the initial temperature of the fuel increases, the reforming produces progressively more CO, less CO₂, less H₂ and more water vapour remaining. This is because the water-gas replacement reaction (equation (2)) in the methane reforming process is an exothermic reaction. The higher the initial temperature of the methane, the more violent the inverse reaction in the water-gas replacement reaction, thus consuming less water vapour, producing less H₂ and CO₂ and gradually accumulating more CO, the longer the time, the more serious the damage to the reactor.

The power relationship between the various components of the SOFC-MGT system is obtained through simulation analysis and is shown in the figure below.

As can be seen from Fig.5, the total power of the SOFC-MGT system is much greater than that of the SOFC and turbine, indicating that the combined power generation of the solid oxide fuel cell and the micro gas turbine is more advantageous than the two doing work alone, and also illustrating the feasibility of the new bottom cycle structure of the SOFC-MGT proposed in this paper.

It can also be seen from Fig.5 that as the stack discharge current increases, the output power of the stack first increases and then decreases, this is because as the discharge current gradually increases, the stack voltage will gradually become smaller, and when the discharge current exceeds the rated current of the stack, the stack voltage will drop sharply, at the same time, as the stack discharge current increases, the output power of the turbine is gradually becoming smaller, this is because, as shown in Fig.6, as the stack current increases, the inlet temperature of the turbine becomes progressively smaller.

4. Conclusion
In this paper, the following conclusions are obtained through simulation and experimental testing.

- The new bottom cycle structure of SOFC-MGT proposed in this paper is feasible.
- The higher the initial temperature of the fuel, the worse the reforming efficiency. As the initial temperature of the fuel continues to increase, the reforming products increase by up to 1.1% for CO, decrease by up to 2.8% for CO₂, decrease by up to 0.3% for H₂ and leave up to 0.6% for water vapour. The initial temperature of the fuel should not be too high as the increased CO can cause carbon poisoning and carbon build-up in the reactor.
- The overall power of the SOFC-MGT system is at most 2.1 times the power of the SOFC and 3.25 times the power of the MGT, demonstrating the necessity and feasibility of combined SOFC and MGT work.

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