Simulation Study of SOFC/GT Combined Cycle System with Turbine Exhaust Recycled to Heat Fuel Cell Air Intake

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Abstract. For the low-temperature SOFC/GT combined cycle system used to recover the SOFC cathode intake air by using turbine exhaust gas circulation, a simulation model of the combined cycle system was established based on the lumped parameter model of SOFC, turbine, compressor and preheater. Some experimental data have verified the validity of the zero-dimensional model of SOFC. The system simulation results show that the air intake pressure caused by the air recirculation does not completely depend on the outlet pressure of the compressor. When the outlet pressure of the compressor is between 0.2MPa and 0.5MPa, the intake pressure of the SOFC will decrease to varying degrees, and it depends on the proportion of the exhaust gas recirculation. The compression ratio is not related to the output power and efficiency of the SOFC. Increase in compression ratio will reduce the output of the turbine, resulting in a reduction in the overall efficiency of the system.

1. Introduction

The energy conversion efficiency of fuel cells is not limited by Carnot cycle, and has the advantages of low pollution and high energy utilization rate. Among them, SOFC has high power density, strong fuel adaptability, high solid electrolyte stability, and wide range of power and power generation. It can realize the advantages of cogeneration and so on [1]. The research shows that the hot start time of low temperature metal-supported SOFC is also shortened to within 10 minutes [2], which greatly broadens the application field of SOFC. The application of SOFC in ship power field is receiving more and more attention [3]. The high-temperature exhaust gas of the gas turbine (containing a large amount of oxygen) acts as the intake of the SOFC, and the high-temperature exhaust of the SOFC is used to preheat the outlet of the compressor, which has the characteristics of simple system coupling, easy control, and can improve the power of the gas turbine.

The model plays an important role in diagnosing solid oxide fuel cell (SOFC) system [4]. The zero-dimensional (0-D) model based on physical assumptions is usually employed for system performance analysis [5-7]. The input variables are directly converted into output variables without considering the changes in the internal space of the SOFC. Generally, only electrochemical models are considered, and they are mostly used for energy analysis of SOFC in power generation systems. Bove et al. [8] established a zero-dimensional model that ignores concentration polarization. The main research is to calculate the SOFC voltage by using three different gas compositions, namely the intake gas composition, the outlet gas composition, and the average between the two. The results show that the average simulation results are the best. The current research on the performance of the SOFC / GT
combined cycle is mainly focused on high-temperature fuel cells, and less research on medium-temperature and low-temperature fuel cells.

2. Combined cycle system configuration and simulation models

2.1. System configuration
The system using turbine exhaust as SOFC intake is shown as figure 1. The main idea of this configuration is to use the SOFC's exhaust gas to recirculate to preheat the intake air, avoiding the use of heat exchanger. The working pressure of the SOFC is determined by the compression ratio of the compressor and the pressure of the recirculated exhaust gas. It is not possible to directly control the working pressure of the SOFC. This configuration is suitable for low-temperature SOFC / GT cycles with low preheating requirements.

![Figure 1. System configuration](image)

2.2. Simulation models and parameters
The main system components of SOFC / GT are SOFC, preheater, compressor and turbine. Regardless of the flow loss of the gas transmission pipeline, a lumped parameter method was used to establish a simulation model for the four components.

2.2.1. Low temperature SOFC model and validation. The data used in this low-temperature SOFC model will refer to the experimental data of a metal-supported SOFC [9] from Ceres Power Company as shown in table 1. The base thickness of the SOFC is about 200mm-300 mm.
Table 1. Model parameters of low-temperature SOFC

| Parameter                             | value         | unit       |
|---------------------------------------|---------------|------------|
| Cathode exchange current pre-factor $K_C$ | $7.0 \times 10^{11}$ | Sm$^{-2}$ |
| Anode exchange current pre-factor $K_A$  | $3.2 \times 10^{13}$ | Sm$^{-1}$ bar$^{-0.5}$ |
| Activation energy of anode reaction $E_{AA}$ | $1.309 \times 10^{5}$ | Jmol$^{-1}$ |
| Activation energy of cathodic reaction $E_{AC}$ | $1.294 \times 10^{5}$ | Jmol$^{-1}$ |
| FC working temperature $T$            | 873           | K         |
| Anode conductivity $\rho_{\text{anode}}$ | $8.0 \times 10^{4}$ | Sm$^{-1}$ |
| Anode conductivity $\rho_{\text{cathode}}$ | $8.4 \times 10^{3}$ | Sm$^{-1}$ |
| Pre-conductivity factor $K_i$          | $2.706 \times 10^{6}$ | SKm$^{-2}$ |
| Anode effective diffusion coefficient $D_{\text{eff, anode}}$ | $1.495 \times 10^{-6}$ | m$^2$s$^{-1}$ |
| Contact resistance $R_{\text{cont}}$   | $8.46 \times 10^{-6}$ | $\Omega$m$^2$ |
| Anode thickness $\tau_{\text{anode}}$  | 15            | $\mu$m    |
| Cathode thickness $\tau_{\text{cathode}}$ | 5             | $\mu$m    |
| Base thickness $\tau_{\text{substrate}}$ | 300           | $\mu$m    |
| Matrix hole spacing $\tau_{\text{holepitch}}$ | 125           | $\mu$m    |
| Electrolyte thickness $\tau_{\text{el}}$ | 15            | $\mu$m    |

The electrochemical model used in the paper is the same as that in [10].

\[ V_{\text{cell}} = V_0 - V_{\text{act}} - V_{\text{conc}} - V_{\text{ohm}} \] (1)

Where, $V_{\text{cell}}$ is the voltage, $V_0$ is the ideal reversible voltage, $V_{\text{act}}, V_{\text{conc}}, V_{\text{ohm}}$ are the activation polarization, concentration polarization and ohmic polarization of SOFC respectively.

The electrochemical reaction inside SOFC needs to satisfy the energy conservation equation as following,

\[ W_{\text{SOFC}} = \sum m_i h_i - \sum m_o h_o \] (2)

where, $W_{\text{SOFC}}$ is the output electric power of the SOFC, $m_i, m_o$ is the mass of each substance in and out of the SOFC, and $h_i, h_o$ is the specific enthalpy value corresponding to the substance in and out of the SOFC.

The material reaction inside the SOFC meets the material conservation equation

\[ \sum m_i = \sum m_o \] (3)

Output power of SOFC stack:

\[ W_{\text{SOFC}} = jV_{\text{cell}}NA \] (4)

where, $j$ is the output current density, $V_{\text{cell}}$ is the output voltage of the SOFC, $N$ is the number of SOFC cells in the stack, and $A$ is the effective reaction area of the SOFC cells.

The power generation efficiency of SOFC is defined as the ratio of the net power generation energy of the solid oxide fuel cell stack to the fuel reaction energy input to the cell stack:

\[ \eta_{\text{SOFC}} = \frac{W_{\text{SOFC}}}{m_{H_2}LHV_{H_2}} \] (5)

where, $m_{H_2}$ is the pure hydrogen mass flow rate participating in the reaction, $LHV_{H_2}$ is the low calorific value of hydrogen combustion.
The low-temperature SOFC experimental data [5] at three operating temperatures (600 °C, 570 °C, 550 °C) are compared with the polarization curves obtained from the model simulation, as shown in figure 2, and the results match well.

Figure 2. simulation polarization curves of low temperature SOFC

2.2.2. Preheater model Energy conservation equation inside the preheater:

\[ Q_{hex} = (h_{h1} - h_{h2})q_{hm} = (h_{l1} - h_{l2})q_{lm} \]  

(6)

Where, \( Q_{hex} \) is the heat exchange power of the preheater, \( q_{hm} \) is the working fluid flow of the cold end and hot end of the preheater; \( h_{h1}, h_{h2} \) is the average specific enthalpy value of the inflow and outflow of the working fluid at the hot end of the preheater; \( h_{l1}, h_{l2} \) is average specific enthalpy of mass inflow and outflow.

The performance index of the preheater is the heat transfer efficiency:

\[ \eta = \frac{Q_{hex}}{h_{h1}q_{hm} - h_{l1}q_{lm}} \]  

(7)

2.2.3. Turbine model Ignoring the potential energy and kinetic energy, the output power of the turbine is simplified as the change in the inlet enthalpy and outlet enthalpy.

\[ \eta_T = \frac{h_2 - h_2}{h_1} \]  

(8)

Where, \( h_{2a} \) and \( h_{2s} \) are the specific enthalpy values of the exit state of the actual turbine process and the isentropic process, respectively, and \( h_1 \) is the specific enthalpy value of the inlet.

Turbine output power calculation expression:

\[ W_T = q_m(h_1 - h_{2a}) \]  

(9)

Where, \( q_m \) is the mass flow of working fluid flowing through the turbine.

2.2.4. Compressor model Similar to the isentropic efficiency of the turbine, the calculation expression of the isentropic efficiency of the compressor:

\[ \eta_C = \frac{h_{2s} - h_1}{h_{2a} - h_1} \]  

(10)

\( h_{2a} \) and \( h_{2s} \) are the specific enthalpy of the working fluid at the outlet state of the actual and ideal isentropic processes of the compressor, respectively, and \( h_1 \) is the specific enthalpy of the inlet.

Calculation expression of compressor power consumption:
Where, $q_m$ is the working fluid flow through the compressor.

2.2.5 Cycle performance index

Output Power:

$$W_{sys} = W_{SOFC} + W_{th} - W_{cp}$$  \hspace{1cm} (12)$$

System efficiency:

$$\eta_{sys} = \frac{W_{sys}}{m_{fuel} n_{H_2} LHV_{H_2}}$$  \hspace{1cm} (13)$$

Where, $LHV_{H_2}$ is the output power of the turbine, $W_{th}$ is the power consumption of the compressor, $W_{cp}$ is the flow rate of the fuel, $m_{fuel}$ is the mass fraction of hydrogen in the fuel, $n_{H_2}$ is the low heating value of hydrogen.

3. Simulation results and discussion

The SOFC/GT combined cycle system output power and efficiency curve using turbine exhaust gas as fuel cell intake is shown in Figure 3 and Figure 4 for the gas turbine and SOFC fuel flow as the abscissa. When the flow rate exceeds 4g/s, as the pressure ratio increases, the output power increases significantly, and the efficiency curve also reflects a similar trend as the highest efficiency appears at about flow rate of 2.6g/s.

![Figure 3. Power-fuel flow characteristic curve](image1)

![Figure 4. Efficiency-fuel flow characteristic curve](image2)

Since the working pressure has little effect on the performance of low temperature SOFC, the change of compression ratio has little effect on the system power, and the impact on efficiency is not more than 1%, and the highest efficiency is 41.95%, as shown in Figure 5. The system efficiency at the air pressure of 0.3MPa is generally higher, while the efficiency is very small compared to that at other pressures. When the pressure ratio is different, the change trend of current density with the increase of flow is similar to the shape of a willow leaf. The curve at a pressure ratio of 0.3MPa is basically located at the center line of the willow leaf, and the more the pressure ratio deviates from 0.3MPa, the farther the curve is from the center line of the willow leaf.
4. Conclusion
1) The use of the high-temperature exhaust gas of the gas turbine as the intake of the SOFC has the characteristics of simple structure and high operational reliability, and is suitable for use in the ship power system.

2). The design parameters of SOFC/GT combined cycle system using turbine exhaust gas as fuel cell intake are recommended: operation pressure of fuel cell is about 0.2MPa-0.3MPa, fuel utilization is 0.8-0.85, current density is around 3000 A/m², and system efficiency is around 46%.

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