Performance Analysis of SOFC/GT Combined Cycle System with Preheater Arranged after the Turbine

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Abstract. For the SOFC/GT combined cycle system where the preheater is arranged behind the turbine, the thermodynamic model is used to describe the compressor, turbine, and preheater, and the zero-dimensional model is used to describe the fuel cell. The performances of the low-temperature fuel cell combined cycle system and the medium-temperature fuel cell combined cycle system are studied. The results show that the medium-temperature fuel cell system has higher power and efficiency, because the efficiency of SOFC is higher than that of gas turbines under most operating conditions. Increasing, power and efficiency tend to decrease. The increase of fuel utilization rate leads to an increase in the overall efficiency of the system. The higher the fuel utilization rate, the more obviously the cycle efficiency is affected by the SOFC, and the faster the decline with the increase of fuel. When the fuel consumption is high and the current density of the SOFC is high, low cell fuel utilization is beneficial to cycle efficiency.

1. Introduction

Solid oxide fuel cells (SOFCs) have high energy utilization rates, are environmentally friendly, have no pollution, and have high stability [1-3]. In particular, they have the advantage of wide applicability of fuels, and they are receiving increasing attention in the field of marine equipment [3]. How to improve the total energy utilization rate through the combined cycle of SOFC and gas turbine (GT) is the forefront and hot spot of current research [4-6]. Based on the SOFC zero-dimensional model, a SOFC turbine combined cycle simulation platform is established in this paper. For the SOFC/GT combined cycle system configuration scheme in which the preheater is arranged after the turbine, the influence of cycle parameters on system performance is analyzed.

2. Combined cycle system configuration and simulation models

2.1. System configuration

In the SOFC / GT cycle, high-temperature exhaust gas is used to preheat the intake air to meet the energy conservation inside the fuel cell. The hot end of the preheater will usually choose high temperature and low pressure exhaust gas after turbine expansion. Schematic composition diagram shown in Figure 1.
The change of SOFC/GT cycle performance caused by different working pressure and output current density is analyzed. In the SOFC/GT combined cycle system where the preheater is arranged behind the turbine, the operating pressure of the SOFC depends on the outlet pressure of the compressor and the pressure loss of the preheater. The operating pressure of the SOFC is controlled by adjusting the compression ratio.

3. Calculation results and analysis

3.1. Performance of medium temperature SOFC combined cycle system
For medium-temperature SOFC, the output current density ranges from 2000A/m² to 22000A/m², and the SOFC fuel utilization rate is maintained at 0.85. The cycle steady state operating point is calculated by changing the compressor compression ratio and controlling the SOFC output current density. The cycle output Power and efficiency are shown in Figure 2 and Figure 3.

![Figure 2. Current density-power characteristic curve under different working pressure](image-url)
Figure 3. Current density-efficiency characteristic curves under different working pressures

It can be seen from Figure 2 and Figure 3 that the efficiency and power curve of the SOFC / GT cycle is similar to that of the medium-temperature SOFC. As the working pressure increases, the increase gradually decreases, and the circulating current density corresponding to 0.4-0.8MPa. The efficiency characteristic curves almost coincide. The reason for the similar rules may be that the efficiency of SOFC is higher than that of gas turbines, and the fuel utilization rate of SOFC is high, and the power allocation tends to SOFC, and the system change law is similar to that of SOFC.

The working pressure of 0.3MPa was selected to study the change of SOFC / GT cycle performance caused by different SOFC fuel utilization and current density. The curves of output power and efficiency of medium-temperature SOFC / GT as a function of fuel flow are shown in Figure 4 and Figure 5.

Figure 4. Fuel flow-power characteristic curve under different fuel utilization rates
Figure 5. Fuel flow-efficiency characteristic curve under different fuel utilization rates

As shown in Figure 4, the change law of cycle power is similar to the change law of SOFC power. Under the same fuel flow, the higher the SOFC fuel utilization, the power distribution ratio tends to SOFC, and the higher the total output power. This should be related to the high efficiency of SOFC. However, near the limit of the current density, that is, the rightmost end of each curve, there will be a decline in power. At this time, the Fuel Cell efficiency is lower than the output efficiency of the gas turbine. As shown in Figure 5, the increase in fuel utilization leads to an increase in the overall efficiency of the system because the efficiency of SOFC is higher than that of gas turbines under most operating conditions. Consistent with the reaction law in Figure 4, the higher the fuel utilization rate, the more obviously the cycle efficiency is affected by the Fuel Cell, and the faster it decreases with the increase of fuel. When the fuel consumption is high and the current density of the SOFC is high, low cell fuel utilization is beneficial to cycle efficiency.

3.2. Performance of low-temperature SOFC combined cycle system

For low-temperature SOFC, the SOFC / GT cycle output power and efficiency are shown in Figure 6 and Figure 7. It is also assumed that the SOFC fuel utilization rate is 0.85. Because the output current density is too low will cause the leakage current to be too high, so the range of the current density is selected from 1500A/m²-6000A/m². As can be seen from Figure 6 and Figure 7, the effect of current density on the power and efficiency of the system is similar to that on the SOFC body. However, the working pressure has a small effect on the power of the low-temperature SOFC/GT cycle configuration. Only the outlet pressure is 0.2-0.3MPa, and the difference is not higher than 10kW; 0.3MPa-0.5MPa has no effect on the system output. The reason may be that the working pressure has little effect on the performance of the low-temperature SOFC. At a fuel utilization rate of 0.85, the cycle performance is not sensitive to the Fuel Cell pressure.

It can be seen from Figure 7 that the effect of the outlet pressure on the efficiency of the low-temperature SOFC/GT cycle is more complicated. In the interval of 0.2MPa-0.4MPa, the efficiency increases with the increase of the outlet pressure, but at 0.5MPa, the efficiency decline occurs. The reason may be Fuel cell efficiency improvement is not obvious. The low-temperature SOFC/GT cycle is not suitable for higher working pressures. As shown in the figure, the working pressure of 0.5MPa is not suitable for nearly half of the working conditions (current density). In fact, the steady-state working of higher working pressure cannot be solved. Situation point. The reason is that the efficiency curve of the low-temperature SOFC is an approximately convex parabola. If the current density is too high or too low, the Fuel Cell efficiency will decrease. When the electrical efficiency is too low, the
chemical energy of the reaction inside the SOFC exotherms too much, and the energy in the cycle is not conserved. The ideal working pressure is 0.3MPa, the efficiency is not low, and the range of steady-state operating conditions is wide.

![Figure 6. Current density-power characteristic curves under different working pressures](image)

Figure 6. Current density-power characteristic curves under different working pressures

![Figure 7. Low-temperature fuel cell system Current density-efficiency characteristic curves](image)

Figure 7. Low-temperature fuel cell system Current density-efficiency characteristic curves

The curves of output power and efficiency of low-temperature SOFC / GT as a function of fuel flow are shown in Figure 8 and Figure 9. The law is similar to the medium temperature SOFC / GT cycle for the same reason. The difference is that the curve of the low-temperature SOFC / GT cycle has no intersection point, because the efficiency of the low-temperature SOFC is relatively lower than that of the medium-temperature SOFC when the current is large.
Figure 8. Fuel flow-power characteristic curve of low temperature fuel cell system

Figure 9. Fuel flow-efficiency characteristic curve of low temperature fuel cell system

4. Conclusion
In the SOFC/GT combined cycle system with preheater arranged after the turbine, the characteristics of the fuel cell play a decisive role in the efficiency and output power of the system. From the perspective of efficiency and power density, medium temperature SOFC have advantages. However, the metal-supported low-temperature SOFC has a start-up time of less than 10 minutes, which makes it an irreparable advantage of medium-temperature SOFC in mobile applications. In summary, the recommended design parameters for maintaining high efficiency in the low-temperature SOFC/GT cycle are as follows: the fuel cell operating pressure is 0.4MPa, the fuel utilization rate is 0.8-0.85, the current density is around 3000, and the system efficiency can reach 51%. The efficiency of medium temperature SOFC can reach the highest at the minimum allowable range of current density; but the small current density leads to low power density of SOFC, so the medium temperature SOFC/GT cycle needs to consider the balance between power and efficiency. The recommended operating parameters of the medium temperature SOFC/GT cycle are: working pressure is 0.4MPa-0.6MPa, fuel utilization rate is 0.8-0.85, current density is 2, and maximum efficiency is around 75%.
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References
[1] Hakim K, Faris A J, Aldo R and Audrius B 2018 Improving the Performance of Gas Turbine Power Plant by Modified Axial Turbine. International Journal of Mechanical and Mechatronics Engineering 12(6) 690-6
[2] Singhal S C and Kendall K 2013 High-temperature solid oxide fuel cells: fundamentals, design and applications Elsevier
[3] Leah R T, Bone A, Hammer E, S Ahmet and Selby M 2017 Development Progress on the Ceres Power Steel Cell Technology Platform: Further Progress Towards Commercialization ECS Transactions 78(1) 87-95
[4] Yousri M. A. Welaya, M. Mosleh and Nader R. A 2013 Thermodynamic analysis of a combined gas turbine power plant with a solid oxide fuel cell for marine applications International Journal of Naval Architecture and Ocean Engineering 5(4) 529-45
[5] Leah R T, Brandon N P and Aguiar P 2005 Modelling of cells, stacks and systems based around metal-supported planar IT-SOFC cells with CGO electrolytes operating at 500-600°C Journal of Power Sources 145(2) 336-52
[6] Cengel Y A and Boles M A 2014 Thermodynamics: an engineering approach New York: McGraw-Hill Education