

Simulating Analysis of Combined Power System with Solid Oxide Fuel Cell and Gas Turbine

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Abstract: A combined power system with solid oxide fuel cell(SOFC) and gas turbine(GT) which is fed by natural gas is presented in this paper. The simulating model of the system is used to analyze the performance of the power system. Effects of operating pressure and current density of SOFC on system performance are studied. It is found that increasing the operating pressure will increase SOFC power generation and improve the system efficiency in some range; on the other hand, the increase in current density of SOFC will decrease the power generation of SOFC stack and total system. Results show that the combined power system which is composed of SOFC and GT can achieve a power generation efficiency of more than 65%(LHV) and an energy utilization of more than 85%.

Keywords: Solid Oxide Fuel Cell ; Gas Turbine ; combined power system ; simulating model ; power generation efficiency

NOMENCLATURE

Q_{dw}^y	Lower heat value of application basis [kW]	Δh_f^o	Standard enthalpy [kJ/kmol]
K_{pr}	Equilibrium constant of reforming reactions	η_{IR}	Ohm overpotential [V]
R	Gas constant [8.3144J/mol · K]	Q_f	Heat enthalpy of fuel [kW]
X_{H_2}	Sum of H_2 in cell reactions [kmol/h]	Q_{bu}	Losses of incomplete combustion [kW]
n_e	Electron numbers shifted in oxyhydrogen reactions [$n_e = 2$]	N_p	Sum of combustion product [kW]
ΔG^0	Standard Gibbs function variation in oxyhydrogen reactions	Q_{fr}	Sum of reclaimed waste heat [kW]
F	Faraday constant [$F = 96487C/mol$]	w_{ic}	Interconnector width [cm]
$h_{m,T}$	Molar enthalpy at T [kJ/kmol]	σ_{ic}	Interconnector resistivity [Ω cm]
$h_{m,298}$	Molar enthalpy at 298K [kJ/kmol]	d_{ic}	Interconnector thickness [cm]
Q_a	Heat enthalpy of air [kW]	η_e	System electricity generation efficiency [%]
Q_{san}	Heat losses [kW]	P_0	Standard pressure [1 bar]
C_p	Specific heat capacity at constant pressure [kJ/kmol · K]	N	Molar rate of flow [kmol/h]
W_{sofc}	Power generation of SOFC [kW]	E_{re}	Ideal reversible voltage [V]
W_{comp}	Power consumption of compressor [kW]	E	Cell voltage of SOFC [V]
W_{GT}	Power generation of GT [kW]	n	Number of cells
P	Pressure [bar]	h	Total enthalpy [kJ/kmol]
K_{pr}	Equilibrium constant of reforming reactions	η_a	Overpotential at anode [V]
T	Temperature [K]	η_c	Overpotential at cathode [V]
i	Cell current density [mA/cm ²]	σ_e	Electrolyte resistivity [Ω cm]
A	Cell unit dimensions [cm ²]	d_e	Electrolyte thickness [cm]
		σ_c	Cathode resistivity [Ω cm]
		d_c	Cathode thickness [cm]
		σ_a	Anode resistivity [Ω cm]

d_a Anode thickness [cm]

 l Cell diameter [cm]

1. INTRODUCTION

Fuel cell is a device that converts chemical energy into electricity directly from the reaction of fuel and oxidant. It can achieve higher electricity generation efficiency than that obtained from conventional heat engine and it is also an environmental benign method of electric power production which work at the temperature as high as 800-1000°C[1], so it has the advantage of high temperature waste heat recovery and could be used to combined cycle with traditional gas turbine and steam turbine. The SOFC sets of 25 kW investigated by American Westinghouse Company have been experimented for a long time demonstration, a demonstration equipment of 100kW located in Holland has conducted in 1997 and a generating device of 250kW-7MW has been in the plan. Thus provide the precious experience for putting up and conducting the same pattern power station.

At present, the research on SOFC focused on the material and preparation of the battery, while the research referring to the advantage of SOFC and exaltation of the utilization rate. A system with external pre-reforming and anode gas recirculation for the internal supply of steam is investigated by Jens Palsson et al., and the conclusion that the pressure ratio has a large impact on the characteristics and performance of the system has been obtained[2]. Doc. Wang Xun established a new SOFC power generation system with chemical looping combustor, whose fuel is hydrogen, and made a research on evaluation and optimization of the system[3].

In this study, a combined power system with GT and internal pre-reforming SOFC was thermodynamically analyzed, and a simulating model was established to evaluate the influence of the performance parameters, including pressure of SOFC, current density, etc. on the performance of system.

2. SYSTEM DESCRIPTION

A combined power system with GT and SOFC which was fed by natural gas and air was investigated in this study. The reference SOFC/GT system making good use of the hot exhaust by gas turbine, where the methane transferred into hydrogen by internal pre-reforming was developed according to Fig.1. The fuel and air which were compressed to increase the pressure and heated by the exhaust gas of GT, were sent to the anode and the cathode of SOFC respectively. The fuel was blended with steam before entering the anode to be easier to reform in the SOFC. In the anode chamber, reforming and shift reactions of methane and water-gas happened to create hydrogen. Oxygen contained in the air which was deoxidized in the air side/interface of electrolyte, flowed to the fuel side due to the concentration difference of the oxygen between the air side and the fuel side. In the fuel side, the electrochemical reaction of oxygen ions and hydrogen took place to create water and released the electrons which flowed to the

air side through external circuit forming a loop and producing electric energy. The anode gas effusing from the anode including methane, hydrogen and carbon monoxide was burned completely in back combustion chamber together with cathode off-gas to increase the gas temperature. The burned gases which were expanded in GT, were utilized for the compressor discharge as well as generating electricity as the addition to the electric energy generated by SOFC constituting the total system power generation. Besides heating the fuel, air and water to a certain temperature, the exhaust gas of the GT provided an external hot water or steam supply to employ waste heat and increase the energy utilization efficiency.

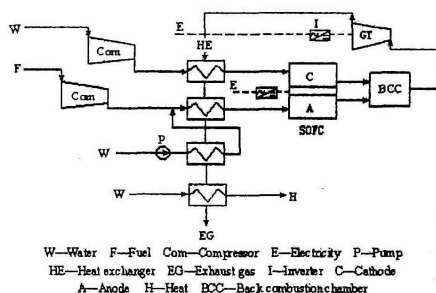


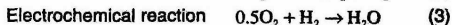
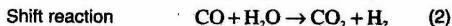
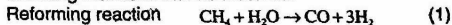
Figure 1: Flowsheet of SOFC-GT system

3. SIMULATING MODEL

3.1 System simulating

a. Internal reforming model

The reforming reaction of methane occurs to generate hydrogen and carbon monoxide, and the shift reaction of carbon monoxide continues with water-gas to get hydrogen as an addition at anode of SOFC, which is regarded as the reaction mechanism for the internal reforming of SOFC stack. The following reactions can be involved:



The equilibrium constant, which shows the quantity relations of various masses in the equilibrium state, is the significant foundation to calculate the equilibrium components for a certain chemistry reaction. The compositions of the anode gas and the cathode gas are determined by the components of inlet gas, molar rate of flow and the reactivity temperature as a result of dependence of the equilibrium constant on the reactivity temperature.

$$K_{pr} = \frac{P_{\text{CO}} P_{\text{H}_2}^3}{P_{\text{H}_2\text{O}} P_{\text{CH}_4} P_0^2} = \frac{N_{\text{CO}} N_{\text{H}_2}^3}{N_{\text{H}_2\text{O}} N_{\text{CH}_4} N^2} \left(\frac{P}{P_0} \right)^2 \quad (4)$$

$$K_{ps} = \frac{P_{\text{CO}_2} P_{\text{H}_2}}{P_{\text{CO}} P_{\text{H}_2\text{O}}} = \frac{N_{\text{CO}_2} N_{\text{H}_2}}{N_{\text{CO}} N_{\text{H}_2\text{O}}} \quad (5)$$

b. Current density

The cell current density can be estimated as follows:

$$i = \frac{X_{H_2} n_e F}{nA} \quad (6)$$

c. Cell voltage

The ideal reversible voltage of SOFC, given by Nernst equation[1], isn't the terminal voltage of SOFC which is calculated by eliminating various irreversible losses involving the overpotential at anode and cathode (η_a, η_c) and the Ohm overpotential (η_{IR}) due to the resistance of the electrolyte, electrodes and interconnector[4]:

$$E_{re} = E^0 + \Delta E = -\frac{\Delta G^0}{2F} + \frac{RT}{2F} \ln \frac{P_{H_2} P_{O_2}^{0.5}}{P_{H_2O}} \\ = -\frac{\Delta G_{H_2O}^0 - \Delta G_{H_2}^0 - \frac{1}{2} \Delta G_{O_2}^0}{2F} + \frac{RT}{2F} \ln \frac{P_{H_2} P_{O_2}^{0.5}}{P_{H_2O}} \quad (7)$$

Based on experimental results to be reported elsewhere[4], the anode overpotential is assumed to independent of current density and has a constant value of 150mV at 1073K, 50mV at 1273K. Whereas the cathode overpotential is obtained as follows:

$$\eta_c = 0.07i^3 - 0.077i^2 + 0.04i - 0.00003 \quad (8)$$

The Ohm overpotential (η_{IR}) due to the resistance of electrolyte, electrodes and interconnector is represented as follows:

$$\eta_{IR} = i\sigma_e d_e + i\pi\sigma_{ic} \frac{d_{ic}}{w_{ic}} + \frac{i\pi^2 l^2}{8} \left(\frac{\sigma_c}{d_c} + \frac{\sigma_a}{d_a} \right) \quad (9)$$

Therefore, the terminal voltage of SOFC is calculated using:

$$E = E_{re} - \eta_{IR} - \eta_a - \eta_c \quad (10)$$

d. Power output of SOFC

The power generation of SOFC can be described as:

$$W_{SOFC} = inAE \quad (11)$$

e. Energy equilibrium

The operating temperature of SOFC is obtained by the first law of thermodynamics. When the sums of the change of heat energy and enthalpy are estimated, the influenced chemistry energy should be involved due to the chemical reaction occurred in the SOFC. In another hand, an accordant standard should be adopted in the energy analysis on account of the appearance of various compounds in the same reaction formula during the reacting process. In this paper, the SOFC is treated as a syntheses, and the chemical standard state (pressure 1bar, temperature 25°C) is utilized as the calculation basis to describe the energy equilibrium equation (heat loss can be neglected):

$$\sum_{in} N_i h_i = \sum_{out} N_i h_i + W_{SOFC} \quad (12)$$

$$h = \Delta h_f^0 + h_{m,T} - h_{m,298} \quad (13)$$

Suppose that the working temperature of SOFC is equal to the cell outlet gas temperature. The current

density and cell voltage related to operating temperature must be calculated in advance of the operating temperature obtained from the energy equation, resulting in the choice of iterative calculation to compute the operating temperature of SOFC.

3.2 Back combustion chamber

Combustion temperature is the important operating parameter of combustion arrangements, whose value is impacted by fuel performance, fuel component, reactive degree of combustion and mechanism of combustion arrangements, and can be ascertained by the heat equilibrium. On the basis of the principle of energy equilibrium, the total energy sent to the back combustion chamber equals to the consumed energy:

$$Q_{dw}^y + Q_a + Q_f = N_p c_p T_p + Q_{sun} + Q_{bu} \quad (14)$$

η_c is defined as a back combustion chamber

efficiency, that is $Q_{dw}^y - Q_{bu} = \eta_c Q_{dw}^y$, where only the combustion temperature T_p is unknown, the temperature of combustion output is evaluated by iterative calculation consequently.

3.3 System efficiency

Exception of the losses, some of the energy entering the system transfers to the power generation of SOFC and GT, and some waste heat is reclaimed.

An index η_e which is the ratio of total efficient power generation by SOFC and GT (exclude the power generation supplied to the compressor) to total energy input (calculate on lower heat value on application basis of the fuel) is defined as total power generation efficiency:

$$\eta_e = \frac{W_{SOFC} + W_{GT} - W_{comp}}{Q_{dw}^y} \quad (15)$$

An index η_{total} which is the ratio of the sum of total efficient power generation and reclaimed waste heat to the total energy input is defined as total energy utilization efficiency:

$$\eta_{total} = \frac{W_{SOFC} + W_{GT} - W_{comp} + Q_{fr}}{Q_{dw}^y} \quad (16)$$

4. EVALUATION AND ANALYSIS

4.1 Evaluation case

In this paper, the fuel was natural gas whose molar component are 96% CH₄, 1% CO₂ and 3% N₂, molar rate of flow was 17.9kmol/h. The air was composed of 21% O₂ and 79% N₂, whose molar rate of flow was 250kmol/h. The computation was made for the temperature of 25°C, the pressure of 1 bar when the fuel, air and water flowing into the system, and other system parameters were showed in Table I:

Table 1: System input parameters

Input parameters	Value
Fuel utilization efficiency	82%
Fuel inlet temperature	773 K
Number of cells	5000 个
Anode thickness	0.01 cm
Electrolyte thickness	0.015 cm
Interconnector width	0.3 cm
Air inlet temperature	963 K
Unit dimensions	250 cm ²
Pressure drop in cells	5 %
Cathode thickness	0.15 cm
Interconnector thickness	0.015 cm
Cell diameter	1.8 cm
Mass losses in every unit	1%
Compressor adiabatic efficiency	83%
Pressure drop in heat exchangers	2%
Back combustion chamber efficiency	99%
Heat losses in back combustion chamber	2%
Inverter efficiency	96.5%
Exhaust gas temperature	383 K
Compress ratio of compressor	8
GT pressure ratio	5
Steam/Carbon ratio	2.5
Mechanical efficiency	98%
Heat losses in heat exchangers	3%
Pressure drop in back combustion chamber	5%
GT adiabatic efficiency	86%

In this paper, Visual Basic was used to give the thermodynamic estimation of the system. After being input the initial parameters, the modules of compressor, SOFC, back combustion chamber and GT etc. were transferred to evaluate the performance of each working point, resulting in the performance indexes including current density, cell voltage, power generation of SOFC and system power generation efficiency, energy utilization efficiency (showed in Table 2).

Table 2: System performance indexes

System Performance Index	Value
Compressor work consumption of fuel side	45.96 kW
Current density of SOFC	226.36 mA/cm ²
Operating temperature of SOFC	1152.94 K
Back combustion chamber temperature	1466.1 K
Sum of reclaimed waste heat	870.92 kW
Total electricity generation efficiency	65.18%
Ohm overpotential	0.3483 V
Compressor work consumption of air side	595.95 kW
Cell voltage of SOFC	0.7325 V
Electricity generation of SOFC	2000.12 kW
Electricity generation of GT	1139.27 kW
Total electricity generation	2497.84 kW

Total energy utilization efficiency	87.91%
Total cellove rpotential	0.4642 V

In this study: current density of SOFC was 226.36 mA/cm², cell voltage was 0.7325V, power generation was 2000.12kW, which presented 80.07% of the total power generation. The system power generation efficiency was 65.18% and the system energy utilization efficiency was up to 87.19% if waste heat reclaimed was taken into account, whereas the power generation efficiency of the traditional power generation technique only arrived approximately 40%[5]. The conclusion was illustrated consequently, that is the combined power system with solid oxide fuel cell and traditional technique is an effective way to improve the energy utilization efficiency.

4.2 Current density of SOFC

Keeping other parameters constant, the influence of current density varying by the various number of cells on system generation efficiency and cell voltage is shown in Fig.2 and Fig.3 respectively. When the current density increases, the overpotential at cathode and Ohm overpotential, operating temperature of SOFC and power generation by GT will increase, which is less than the decrease of power generation by SOFC. As a conclusion, the total system electrical efficiency represents a descendent tendency with the increase of current density.

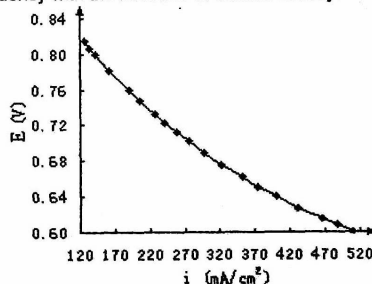


Figure 2: Effect of current density on cell voltage

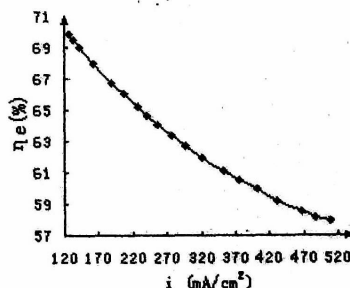


Figure 3: Effect of current density on power generation efficiency

4.3 Operating pressure

The operating pressure of the SOFC rises from 3.65bar to 16.42bar with the various compress ratio of compressor, which leads to the increasing electric power consumed by compressor as well as the increasing amount of hydrogen generated by reforming and shift reactions which makes the hydrogen attending the cell reaction increase accordingly. Fig.4 shows the power generation of SOFC rises due to the increase of operating pressure. The system power generation efficiency improves at the beginning on account of the enhanced pressure ratio of GT and the rising power generation owing to the augment of operating pressure. However, the increment of power generation by SOFC and GT is less than that of electricity consumption by compressor, which reduces the overall system power generation efficiency shown in Fig.5. Therefore, the system operating pressure should be opted appropriately, or else an opposite consequence would occur in stead of improving the system power generation efficiency.

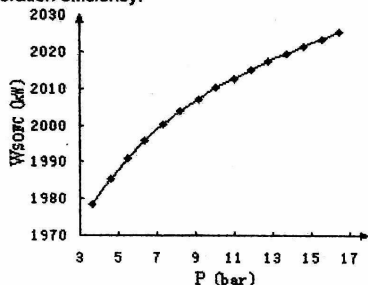


Figure 4: Effect of pressure on SOFC power generation

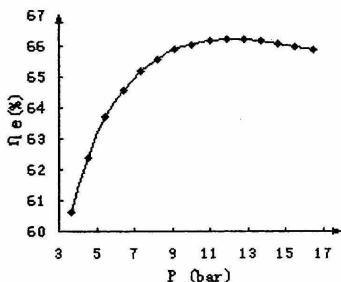


Figure 5: Effect of pressure on power generation efficiency

4.4 Steam/Carbon(S/C) ratio

The methane is blended with steam whose minimal S/C ratio reaches 2.0[6] preventing methane from pyrolysis which produces solid carbon deposition in the cell and debases the cell performance. Fig.6 and Fig.7 shows the effect of S/C ratio varying from 2.0 to 5.0 on power generation of SOFC and system power generation efficiency. Note

that the cell power generation decreases corresponding to the fall of cell voltage in respect that the water pressure in the cell increases in virtue of the improvement of S/C ratio. The overall system electric efficiency remains the rising tendency although the power generation of the SOFC decreases since the amount of mass expanded in the GT augments owing to the increase of the steam.

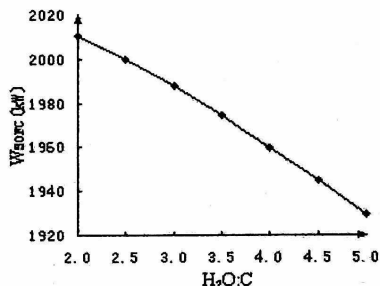


Figure 6: Effect of steam/carbon ratio on SOFC power generation

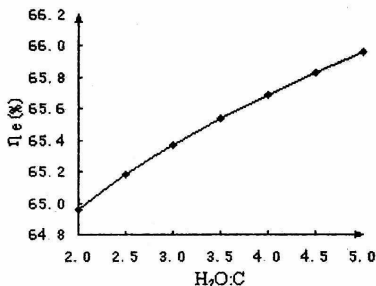


Figure 7: Effect of steam/carbon ratio on power generation efficiency

5. CONCLUSION

A combined power system with solid oxide fuel cell and gas turbine of 2MW was studied in this paper, the simulating model was advanced, and the system performance was analyzed. The conclusions obtained as follows:

(1) The operating temperature of SOFC fed by the natural gas and the air at cathode approximately was 1152K, the power generation was 2000.12kW for the cell operating pressure of 7.3bar, the fuel inlet temperature of 77K, the air inlet temperature of 963K and the fuel utilization efficiency of 82%. The total system power generation and power generation efficiency achieved 2497.84kW and 65.18% respectively so that the overall system energy utilization efficiency approached to 88% on condition that the combined power system was formed with the

cell and a GT whose pressure ratio was 5, indicating the advantages of the system.

(2) The fact that the actual cell voltage was much lower than the reversible cell voltage due to the existence of overpotential went against the augment of cell power generation. In this system, the total overpotential was 0.4642V of which the Ohm overpotential represented 75% as the value was 0.3483V. Accordingly, the cell material performance was attached importance to reduce the Ohm overpotential bringing on the fall of the cell overpotential and the increase of the efficiency.

(3) The system power generation efficiency was raised on account of the augment of cell power generation owing to the decrease of current density, for which some extra cells should be added resulting in the raise of the investment.

(4) After improving the cell operating pressure, the cell power generation was advanced. However, if the value exceeded some range, the total power generation efficiency declined in virtue of the excess augment of the electricity consumed by compressor leading to the reasonable choice of the value.

(5) In order to avoid the pyrogenation of the methane contained in the natural gas which had disadvantageous influence on the cell performance, some proportional steam should be added into the fuel before entering the cell. The power generation of SOFC and the system were raised with the amount of the steam increased, whereas the dimensions of heat exchanger increased correspondingly as well as the system exhaust gas. Therefore, the S/C ratio can't be increased blindly.

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