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Performance Analysis of SOFC/MGT Hybrid System

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Key Words : Solid Oxide Fuel Cell (SOFC), Micro Gas Turbine (MGT), SOFC/MGT hybrid cycle, Electric efficiency, Cell area

Abstract

A performance analysis of a SOFC/MGT hybrid system has been carried out for concept design. Thermodynamic models for each component being able to describe electrochemical characteristics and heat and material balance are proposed. Estimated is the power capacity of a SOFC suitable for the hybrid operation with a 5kW class MGT. Effects of current density and operating pressure are also investigated. Electric efficiency showed weak dependence on operating pressure and current density. It is desirable that the SOFC operates at high current density in manufacturing cost's point of view though operating with high current density slightly decreases the electric efficiency and specific power.

1. INTRODUCTION

Distributed energy supply system or more specifically the distributed electricity supply system will become very important in the near future. Electricity is the form of energy supporting our modern life, but construction both of large-scale electricity supply system and electricity distribution network is expensive. Loss of electricity in the distribution network is zero with the distributed energy supply system. There are many districts in the world where are located remote from any power station. At such electrically isolated districts, ample amount of electricity cannot be supplied or there is no means to supply electricity at all. Therefore, development and introduction of distributed electricity supply systems for small community or for a private house is eagerly desired in such districts.

Recently, the integration of a fuel cell with a micro gas turbine (MGT) is emerging as a potentially attractive way to generate electricity and heat with high efficiency and very low emission in the distributed power generation fields. This synergic combination attributes to the progress in micro gas turbine technologies and the maturing of the modular fuel cell. In particular, solid oxide fuel cell (SOFC) can be thought of as an appropriate heat source for a MGT, since it operates at high temperature of about 850°C to produce high temperature exhaust gas. In practice, a 220kW SOFC/MGT hybrid power system was installed and has been operated for site testing at the University of California, Irvine in early 2000(1, 2).

Theoretical investigations have been actively carried out to predict the operating characteristics of SOFC itself and the overall performance of its hybrid system over the last two decades. Operating characteristics of the SOFC have been generally evaluated by 2D(3) or 3D(4) simulation. These models are, however, too complicated and time-consuming in calculation to be appropriate to a system performance analysis. Therefore, robust but reliable 1D models for SOFC have been introduced in performance analysis of a SOFC/MGT hybrid system(5-8).

In this study, a concept design of SOFC/MGT hybrid system is carried out through the performance analysis. Thermodynamic models for each component being able to describe electrochemical characteristics and heat and material balance are proposed. The model is verified compared with the estimated performance data by the manufacturer. Estimated is the power capacity level of SOFC suitable to combine with a 5kW class MGT for the distributed power generation. Effects of current density and operating pressure are also investigated.

2. SYSTEM CONFIGURATIONS

The SOFC/MGT hybrid system proposed in this study is shown in Fig. 1. The MGT considered in this study is of 5kW power capacity level and has a radial type compressor and turbine. Through the preliminary concept design(9), the turbine inlet temperature (TIT) and pressure ratio (PRc) has been decided to be 1000°C and 2.9, respectively. The SOFC is an internal reforming type one

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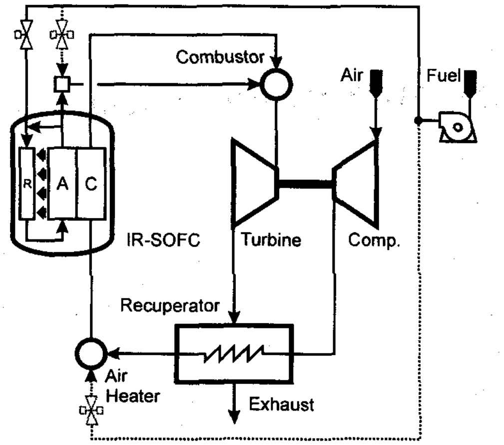

Fig. 1 Schematic of a pressurized SOFC/MGT hybrid system

(IR-SOFC), which is basically of the same configuration as that of Siemens-Westinghouse. The IR-SOFC can be divided into two zones, which are the reformer and cell stack as shown in Fig. 1. The fuel is pressurized and fed to the ejector as the working gas to induce an anode gas recycle. The anode exhaust gas recycle provides an internal steam supply for the reforming reaction. Heat required in the endothermic reforming process is also provided by the cooling of the cell stack where the exothermic cell reaction occurs as shown in Fig. 1. The unreacted fuel in the SOFC is burnt completely in the combustor. The waste heat of turbine exhaust gas is recovered by heating the cathode inlet air in the recuperator.

Combustion with the additional new fuel and air heating which are represented by dotted lines in Fig.1 are conducted only during startup operation. Only the steady state operation at the design point is taken into account in this study.

3. ANALYSIS METHOD

Thermodynamic properties of working fluid (air, fuel, combustion gas and etc.) such as enthalpy, entropy and Gibbs free energy are evaluated in the composition level, which are also functions of temperatures and pressures(10).

Power produced by the MGT can be determined at given TIT, PRc and isentropic efficiencies of a turbine and compressor, 73% and 74% at the design point, respectively.

The IR-SOFC adopted in the system introduces the indirect internal reforming method that the almost reforming process is completed before the cell stack reaction. In the cell stack, the electrochemically active region consists of the tri-layer represented by the cathode, electrolyte and anode. The following chemical reactions are assumed to be relevant for an SOFC operated with an air and methane.

Reforming $$CH_4 + H_2O \leftrightarrow CO + 3H_2 \qquad (1)$$

Shift $$CO + H_2O \leftrightarrow CO_2 + H_2 \qquad (2)$$

Electrochemical $$H_2 + \frac{1}{2}O_2 \leftrightarrow H_2O \qquad (3)$$

In this study, it is assumed that the reforming and shift reaction are completed in the reformer and there is no CO produced due to the perfect CO-CO$_2$ conversion by the shift reaction. All of these reactions in the IR-SOFC are taken into account in the overall heat and material balances.

The flow rate of recycled anode gas can be determined with given steam/carbon ratio (S/C=3) and fuel utilization factor (U_f = 85%). Cell operating voltage (V) at given current density (J) can be evaluated based on the cell open circuit potential, i.e. ideal Nernst potential given in eq. (4).

$$E_N = -\frac{\Delta G}{2F} \qquad (4)$$

$$\Delta G = G(T_c, p_{H_2O}) - G(T_c, p_{H_2}) - \frac{1}{2}G(T_c, p_{O_2}) \qquad (5)$$

G indicates molar Gibbs free energy. F denotes Faraday constant and T_c and p are cell operating temperature and partial pressure of each layer. The Nernst potential is reduced to the cell operating voltage due to ohmic resistance of the cell layers and polarization of electrodes as following.

$$V = E_N - E_p - J(\rho_a L_a + \rho_e L_e + \rho_c L_c) \qquad (6)$$

Resistivity (ρ) of each layer is a function of cell operating temperature and L is the thickness of each layer. Resistivity of each layer is given by the following equations(7).

Anode $$\rho_a = 0.00298 e^{(-1392/T_c)} \qquad (7)$$

Cathode $$\rho_c = 0.008114 e^{(600/T_c)} \qquad (8)$$

Electrolyte $$\rho_e = 0.00294 e^{(10350/T_c)} \qquad (9)$$

The voltage reduction due to polarization (E_p) is obtained using Butler-Volmer equation(11) given as follows.

Table 1 Predicted performance summary

	Siemens-Westinghouse	This Study
Current density, mA/cm^2	320	320*
Cell voltage, V	0.610	0.596
Pressure ratio	2.9	2.9*
Compressor air inlet, kg/s	0.5897	0.5339
TIT, °C	840	840*
SOFC DC power, kWe	187	190
SOFC AC power, kWe	176	181
GT AC power, kWe	47	42
Net AC Power, kWe	220	220*
Efficiency (net AC/LHV), %	57	61
Cell area required, m^2	96†	100

* : given value, † : real data, not predicted

$$E_p = \left(V_a \frac{\ln(J_c / J_0)}{\ln(1 + J_c / J_0)} \right) \ln(1 + J / J_0) \qquad (10)$$

$$J_0 = 10^{(-7520/T_c + 4.51)}, \quad V_a = 0.074(T_c / 1273) \qquad (11)$$

where J_0 (A/cm^2) is exchange current density and J_c (A/cm^2) is assumed to be 0.4A/cm^2 up to 1500K. Using these equations, the cell operating voltage can be determined from the current density and cell operating temperature.

When the fuel-feeding rate and current density are given, the required active cell stack area (A) can be determined. From these values, the power produced in the SOFC can be obtained as follows.

$$\dot{W}_{FC} = VJA \qquad (12)$$

The cell operating temperature, which is assumed to be the same value at the SOFC exit, is determined so that the following energy balance may be satisfied.

$$\sum_R \dot{n}_i \bar{h}_i = \sum_P \dot{n}_i \bar{h}_i + \dot{W}_{FC} \qquad (13)$$

where R and P refer to the reactants and products, respectively. $\dot{n}_i$ represents molar flow rate of each composition in the reactants or products.

For 1kg/s compressor inlet airflow, the fuel-feeding rate is obtained iteratively so that TIT may be the target value (1000°C in this study) with given cell current density. TIT is determined as an adiabatic flame temperature in the combustor where the unreacted fuel (H_2) is burnt. The required compressor inlet airflow for the desired MGT or the whole power can be determined with the specific power obtained by the above calculation.

4. RESULTS AND DISCUSSION

To validate the proposed model, performance of 220kW class SOFC/MGT power system has been predicted and compared with the data predicted by the Siemens-Westinghouse(1). The overall predicted data are in good agreement with the corresponding data as shown in Table 1. In particular, it is known that the required cell area has been predicted reasonably compared with real data.

A concept design has been carried out to estimate an appropriate power capacity, in other words, the current density of the SOFC for 5kW class MGT. Since the system operating temperature and pressure are assumed to be the same, the Nernst potentials at each current density are almost the same. The cell voltage, therefore, is reducing with increasing current density. Increasing the current density, the voltage reduction remains to be small so that the SOFC has larger power density at higher current density as shown in Fig. 2. Because the SOFC power has almost the same at each current densities under a fixed TIT, question would be which is better way to introduce the small cell area with high power density or the large cell area with low power density in designing the SOFC.

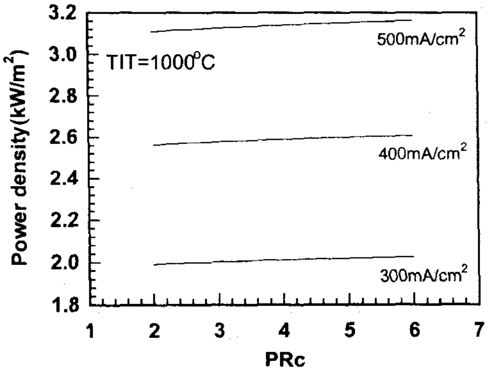

Fig. 2 Power densities at various current densities

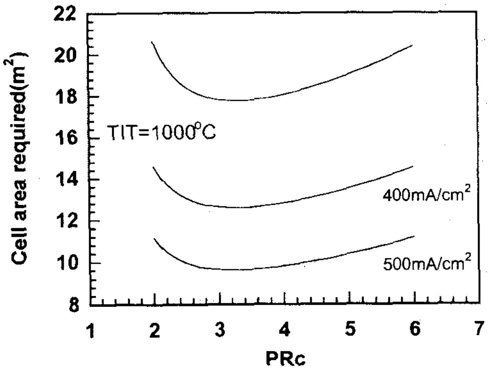

Fig. 3 Cell area required for 5kW MGT

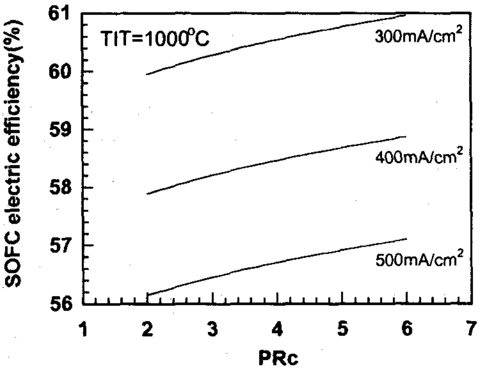

Fig. 4 SOFC electric efficiency

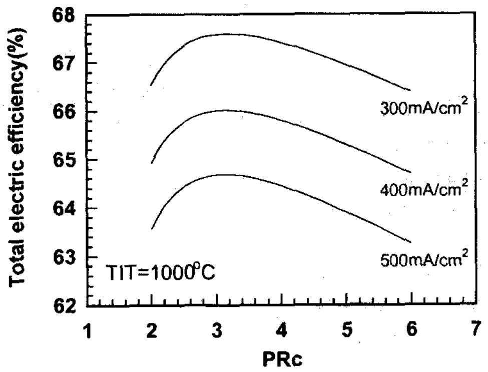

Fig. 5 Total electric efficiency of SOFC/MGT system

Required cell areas at each current density are shown in Fig. 3. About two times larger cell area is required at 300mA/cm^2 current density than at 500mA/cm^2, while difference of electric efficiencies between them is about 4%, as shown in Fig. 4 and Fig.5. From these results, operation at higher current density or operation with smaller area is, therefore, preferred to in view of manufacturing cost though operating with high current density slightly decreases both the electric efficiency and specific power. Fig. 6 shows the SOFC power capacity level required for 5kW MGT at various current densities. At 500mA/cm^2, it can be known that the SOFC produces the electric power at about 85% of total electric power. Compared with conventional power cycles such as simple and regenerative gas turbine, the SOFC/MGT hybrid system produces electric power efficiently as shown in Fig. 7.

5. CONCLUSIONS

Simulation model for performance analysis of SOFC/MGT hybrid cycle has been developed and a concept design has been carried out to estimate the power capacity level of SOFC to be combined with a 5kW class MGT. Electric efficiency shows weak dependence on operating pressure and current density. It is desirable to operate SOFC at high current density in manufacturing cost's point of view.

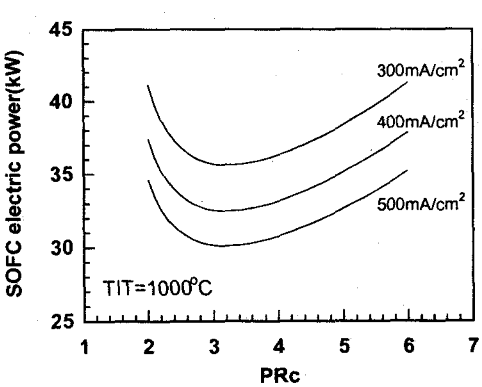

Fig. 6 SOFC electric power

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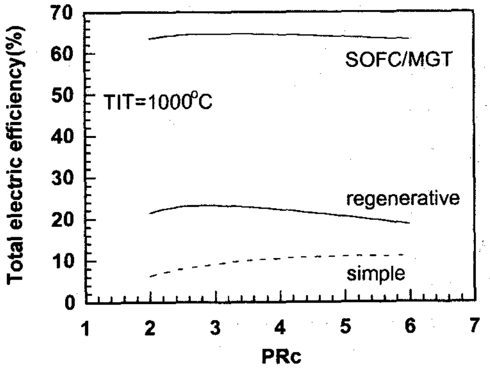

Fig. 7 Electric efficiency of SOFC/MGT hybrid system compared with those of other cycles

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