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High Efficiency Operation Method for Solid Oxide Fuel Cell System

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The Solid Oxide Fuel Cell (SOFC) is a promising alternative as an energy utilization unit. The performance of a SOFC system strongly depends on the operating conditions. Keeping a high operating voltage and fuel utilization is a key condition for high efficiency output. However, high fuel utilization usually incurs an over-temperature risk of the SOFC stack and retards the power output and system efficiency. This study develops a systematic method with internal reforming application to stabilize the stack temperature and to analyze its effect on performance of the SOFC system installed at China Steel (CSC). With the internal reforming ratio from 0 to 0.65, the efficiency of the SOFC is promoted from 32% to 50%, and power output increases from 650W to 1kW, respectively. The highest efficiency of 52.3% can be achieved at partial load of 0.82V per cell. The internal reforming can also enhance the power output to 36W per cell higher than the original rated power of 25W. The internal reforming method is a promising solution to promote performance.

Keywords: Solid Oxide Fuel Cell (SOFC), Efficiency, Internal reforming

1. INTRODUCTION

The Solid Oxide Fuel Cell (SOFC) is an energy conversion unit that converts a gaseous fuel to electricity by electrochemical reaction. It is able to convert carbon monoxide as well as hydrogen, and the high operating temperature allows internal reforming of gaseous fuel and promotes rapid kinetics to produce high quality heat for energy conversion. The SOFC has several advantages over other types of fuel cells, and is a promising alternative as an energy utilization unit, with its advantages of high power density, high efficiency, fuel flexibility, and environmental friendly.

Since the SOFC offers a wide range of operating possibilities, identifying the influence of operational conditions on the efficiency and power density is critical for optimal operation of the SOFC. The performance of the SOFC strongly depends on the operating conditions and the inlet fuel composition(1). Operating in the region of high efficiency may result in a very low power density requiring a large cell volume to deliver the required power output, while operating at high power density can lead to low efficiency. Hence, the SOFC often has to be operated in a reasonable region compromised between efficiency and power density.

A number of publications report that the SOFC system efficiency is independent of the characteristics of membrane electrode assembly with the thermodynamic model analysis(2-5). Keeping on high operating voltage and utilization is the key condition for high efficiency output. However, high fuel utilization may result in the over-temperature problem of the SOFC stack and retards the power output and system efficiency(6). Internal reforming is a good solution for heat management in a SOFC stack(1). The main problem of internal reforming operation is to control the ratio to balance the heat between requirement for steam reforming reaction and the generation from the fuel cell section. An additional problem is carbon deposition on the anode side, which leads to the loss of fuel cell performance.

In this study, a control method of internal reaction ratio was developed, and practically applied to the SOFC system of China Steel (CSC) to check its effect on the SOFC efficiency.

2. EXPERIMENTAL METHOD

2.1 SOFC System at CSC

CSC cooperated with the Institute of Nuclear Energy Research (INER), Taiwan, to construct a prototype SOFC system comprising a Natural Gas (NG) reformer, a SOFC stack, an after-burner, a fuel heat exchanger and an air heat exchanger. The flow diagram of the system as shown in Fig.1.

In this system, the hot cathode off-gas exiting the SOFC is passed through a heat exchanger to preheat the fuel prior to inlet into the SOFC, then flow to the

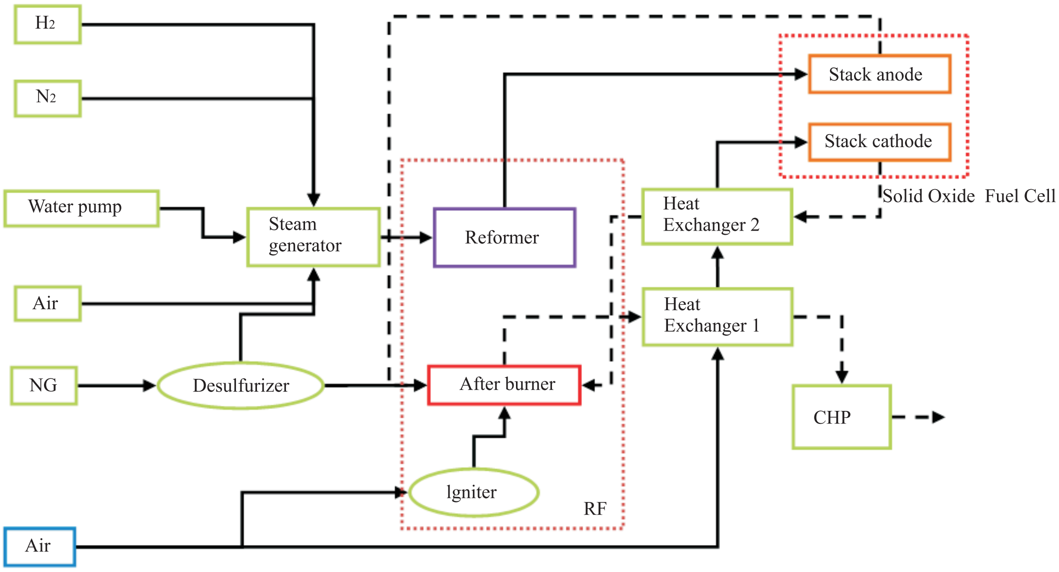

Fig.1. Flow diagram of SOFC system at CSC.

after-burner. Meanwhile, the hot anode off-gas, containing a relatively high percentage of unburned fuel, is fed directly to the after-burner and is burned with the cathode off-gas. The hot flue gas exiting the after-burner is passed through a heat exchanger to preheat the air prior to entering the SOFC, then is vented to the environment.

The SOFC stack is an assembly with 30 cells purchased from Elcogen company, Finland. The rated power per cell is around 25W(8).

2.2 Experimental simulation of reforming reaction

In order to identify the appropriate internal reforming ratio, the nature gas steam reforming reaction was simulated with Aspen Plus software to disclose the relationship between temperature and output of methane concentration. The Gibbs reactor model was selected to simulate the gas composition with different reaction temperatures from 500 to 800°C. The composition of NG was 92% methane, 4% ethane, 2% propane and 1% butane, respectively. Simulation is based on the value of 2 for steam to carbon ratio. The relative reactions set in Aspen plus were shown below:

$$CH_4 \longleftrightarrow 2H_2 + C \quad (1)$$

$$C_2H_6 \longleftrightarrow 3H_2 + 2C \quad (2)$$

$$C_3H_8 \longleftrightarrow 4H_2 + 3C \quad (3)$$

$$C_4H_{10} \longleftrightarrow 5H_2 + 4C \quad (4)$$

$$H_2O + C \longleftrightarrow H_2 + CO \quad (5)$$

$$H_2O + CO \longleftrightarrow H_2 + CO_2 \quad (6)$$

Various temperatures of reforming reaction was also experimented in the prototype SOFC system with a novel catalyst fabricated by INER, and gas composition was measured by Non-Dispersive Infrared (NDIR) sensor simultaneously.

2.3 Performance test

The performance test was operated with an external DC load. Various current loads were set here to measure the relative power output and efficiency. The definition of efficiency here is shown as Eq. (1), where η is DC efficiency, P is power, and H is Low Heating Value (LHV) of NG.

$$\eta = \frac{P}{H} \quad (7)$$

Various internal reaction ratios were also conducted to investigate the effect on the SOFC performance. The definition of internal reaction ratio is shown as Eq. (8), where σ is internal reaction ratio, M_0 is the total mole of methane, M_r is the mole output of methane after external reformer.

$$\sigma = \frac{M_r}{M_0} \quad (8)$$

3. RESULTS AND DISCUSSION

3.1 Experimental simulation of reforming reaction results

Figure 2 is the simulation results for NG steam reforming reaction. The results indicate that ethane, propane and butane can be converted completely at relative lower temperature, and no carbon formation. It implies that the value of 2 for steam to carbon ratio is an appropriate operating parameter. The claim is also proven in some literatures[9-10].

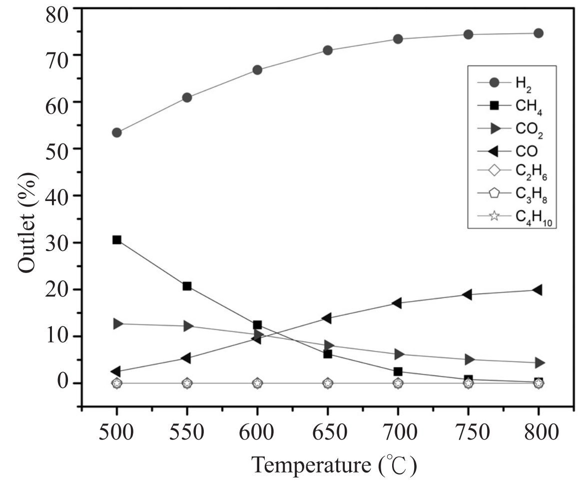

Fig.2. Simulation result of steam reforming with various reaction temperatures.

Figure 3 is the mapping for NG-steam reforming experimental results. It shows that the concentration of methane after the reforming reaction is restricted by thermodynamic equilibrium. The result of steam reforming reaction with Gibbs model simulation was close to the practical situation. The maximum methane tolerance of Elcogen's cell is 25% based on the internal reforming ratio of 0.65[8]. It implies that the operating temperature of the reformer should be higher than 550℃ to prevent coke formation on the SOFC anode. Hence, the reformer's temperature is a suitable operating parameter to control the internal reforming ratio, and should be higher than 550℃.

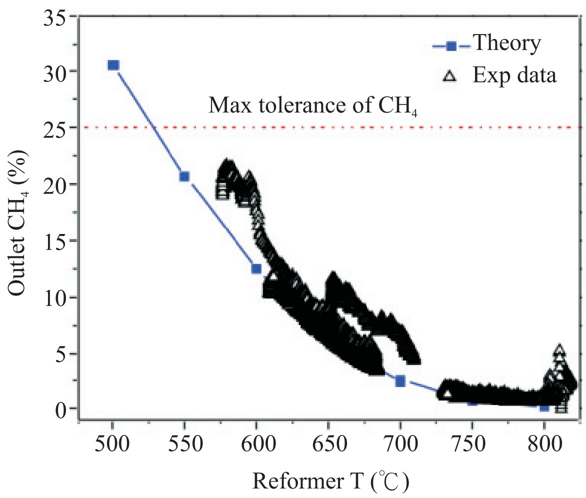

Fig.3. Comparison of simulation and experimental results.

3.2 Effect of internal reforming on the SOFC performance

Due to polarization, the SOFC stack also produces heat during electric generation. The heat should be managed very carefully to prevent thermal shock or over temperature. The quantity of heat output during electrochemical reaction was proportional to the voltage drop. The predictive equation is shown as Eq.(9), where Q_S is heat generated from stack, E is equilibrium voltage, V_{op} is operating voltage, A is current, and C is cell quantity. The value of E can be calculated by Nernst equation.

$$Q_S = (E - V_{op}) \times A \times C \quad (9)$$

The material of the SOFC anode is Ni/YSZ (Yttria-stabilized zirconia), which is a promising catalyst for NG-steam reforming. Hence, the SOFC anode conducts not only an electrochemical reaction but also a reforming reaction. The heat required can be easily calculated by the consumption of methane from the chemical reaction equilibrium. The heat requirement for a reforming reaction is 206 kJ/mol_{CH4}. Hence, the heat removal of internal reforming in the SOFC can be express below:

$$Q_i = 206M_r = 206M_0\sigma \quad (10)$$

To combine in Eq. (9) and Eq. (10), the internal reforming ratio can be found for the balance of heat, as shown in Eq. (11). Cooperating with Fig.2, the appropriate operating temperature can be obtained.

$$\sigma = \frac{(E - V_{op}) \times A \times C}{206M_o} \quad (11)$$

Table 1 is the effect of the internal reforming ratio on SOFC performance, based on the same 2kWh LHV inlet. It indicates that the power is increased from 650W to 1000W with increasing the ratio from 0 to 0.65. The fuel utilization is increased with the internal reforming ratio. The efficiency is also enhanced with the same proportion. The reformer temperature is still higher than 550^{0}C. NG-steam reforming is a highly endothermic reaction. The heat requirement of the external reformer can be reduced due to the heat contribution from the stack. Therefore, the utilization can be promoted, and so does the power and efficiency. The internal reforming reaction is an effective method of increasing the SOFC performance.

Table 1 Effect of various internal reforming ratios on performance

Power (W)	DC efficiency (%)	Internal reforming Ratio	Fuel Utilization (%)	Reformer Temperature (°C)
650	34%	0	48	850
780	42%	0.3	60	750
1000	50%	0.65	70	600

3.3 Performance test

Figures 4 and 6 are the results of performance tests with heat balance of the internal reforming method as described in section 3.2. The power is increased with the increasing external load. However, the efficiency is higher at a lower current load because of higher operating voltage. It implies that higher efficiency can be achieved under an appropriate partial load. Comparing three test results reveals that the power fluctuates slightly at a lower current load (36A). Because at a higher current load, the higher steam generating rate by electrochemical reaction retards the dispersion of fuel gas and obviously makes the concentration gradient. Consequently, concentration gradient causes the obvious fluctuation of voltage, and so does power output.

Table 2 summarizes the results of performance tests. The power output per cell can achieve 36W at the current load of 45A, and voltage can still maintain 0.8V. The performance is already higher than that of the rated power as stated by Elcogen's stack specification (25W per cell). It implies that internal reforming can enhance the power generation. The explanation is that internal reforming can reuse the steam, which is gener-

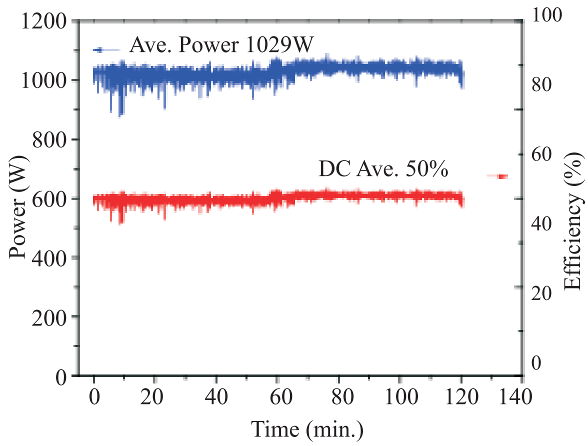

Fig.5. Stabilization test result of SOFC with 42A load.

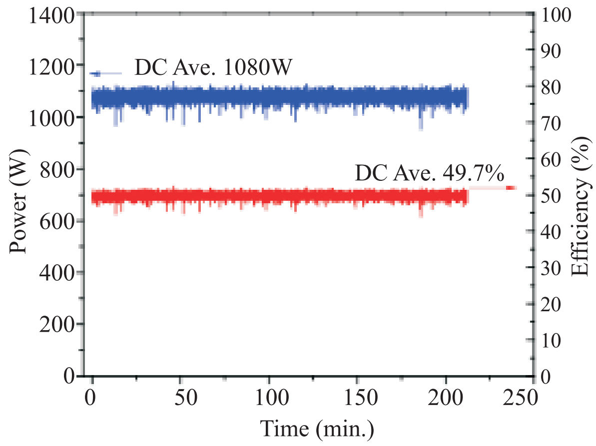

Fig.6. Stabilization test result of SOFC with 45A load.

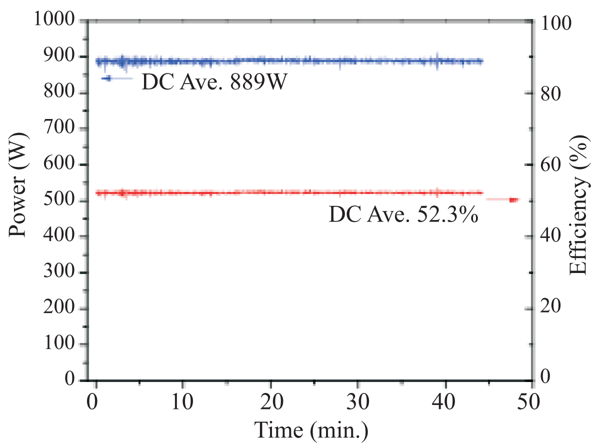

Fig.4. Stabilization test result of SOFC with 36A load.

Table 2 A list of performance test results

Current Load (A)	Power (W)	DC efficiency (%)	Power per cell (W)	Voltage per cell (V)
36	889	52.3	29.6	0.82
42	1029	50	34	0.81
45	1080	49.7	36	0.8

ated by electrochemical reaction from the anode, partially reducing the steam pressure, and that is helpful for increasing voltage and power output. It can be concluded that using the internal reaction method is an effective way to increase fuel utilization and obtain a higher power and efficiency through the balance of heat.

4. CONCLUSIONS

1. Internal reforming ratio can be controlled by the operating temperature of external reformer.
2. According to the simulation results, the value of 2 for steam to carbon ratio can prevent coke formation. And ethane, propane and butane can be converted completely.
3. The fuel utilization increases with increasing the internal reforming ratio, so does efficiency. The efficiency of CSC's SOFC was promoted from 32% to 50%, and power increases from 650W to 1 kW, respectively.
4. The power is increased with increasing external load. However, the high efficiency of the SOFC can be achieved under an appropriate partial load.
5. The internal reforming can enhance the power output to 36W per cell higher than the original rated power of 25W.

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