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Anode gas recirculation for improving the performance and cost of a 5-kW solid oxide fuel cell system

Ryohei Torii [a], Yuya Tachikawa [b, **], Kazunari Sasaki [a, b], Kohei Ito [a, b, *]

[a] Faculty of Engineering, Kyushu University, 744 Motooka, Nishi-ku, Fukuoka 819-0395, Japan
[b] Center for Co-Evolutional Social Systems, Kyushu University, 744 Motooka, Nishi-ku, Fukuoka 819-0395, Japan

HIGHLIGHTS

- Anode gas recirculation rate affects to the electrical and heat output of SOFC.
- It is possible to keep thermally self-sustained operation with the recirculation.
- The risk of carbon deposition due to the recirculation is also evaluated.
- The system operation cost can be reduced by increasing the recirculation ratio.
- The reducible cost by the recirculation and co-generation is quantified.

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ABSTRACT

Solid oxide fuel cells (SOFCs) have the potential to efficiently convert chemical energy into electricity and heat and are expected to be implemented in stationary combined heat and power (CHP) systems. This paper presents the heat balance analysis for a 5-kW medium-sized integrated SOFC system and the evaluation of the effect of anode gas recirculation on the system performance. The risk of carbon deposition on an SOFC anode due to anode gas recirculation is also assessed using the C–H–O diagram obtained from thermodynamic equilibrium calculations. These results suggest that a higher recirculation ratio increases net fuel utilization and improves the electrical efficiency of the SOFC system. Furthermore, cost simulation of the SOFC system and comparison with the cost of electricity supply by a power grid indicates that the capital cost is sufficiently low to popularize the SOFC system in terms of the total cost over one decade.

1. Introduction

Fuel cells constitute a promising next-generation energy conversion technology for controlling CO_2 emission through highly efficient power generation. Solid oxide fuel cells (SOFCs) operate at high temperature and achieve high power generation efficiency without requiring expensive catalysts, such as platinum. This enables the construction of highly efficient and inexpensive power generation systems. Among these SOFC systems, the 1-kW class has been commercialized for residential purposes in Japan, and studies for MW class SOFC systems are in progress. The economic potential of these systems has also attracted attention [1–5]. Some economic studies have evaluated these systems using exergy analysis, a highly useful method for assessing the thermodynamic potential of a system theoretically. Several previous works have investigated the potential of SOFC systems using exergy analysis [1,2], whereas others have focused on the actual material cost of the system [3,4]. However, few studies have focused on the capital cost needed to popularize SOFC systems [5], and none have utilized economic analysis to estimate the acceptable upper limit of their costs and compare a power supply from an SOFC system with an on-demand supply from a power grid. This study bridges this gap by conducting such an analysis to evaluate the economic potential of SOFC systems. Alternatives to co-generation supply-based small-capacity systems which focused in this study are being examined for

* Corresponding author. Faculty of Engineering, Kyushu University, 744 Motooka, Nishi-ku, Fukuoka 819-0395, Japan.
** Corresponding author.
E-mail addresses: ryohei.torii.fcsl@gmail.com (R. Torii), tachikawa.yuya.657@m.kyushu-u.ac.jp (Y. Tachikawa), sasaki@mech.kyushu-u.ac.jp (K. Sasaki), kohei@mech.kyushu-u.ac.jp (K. Ito).

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supplying electrical energy from medium-capacity SOFC systems for mid-sized applications, such as small shops, which at present receive power from the power grid [6]. Anode gas recirculation (AGR) [7–11], associated gas circulation ejectors [12], and blowers [9,13] have been developed to increase the electrical power output in laboratories within and outside of Japan, such as WestingHouse. To examine system performance and economy for popularizing medium-capacity SOFCs, this study clarified the impact of the operating conditions, such as the recirculation ratio of AGR and the current density load of the SOFCs, on the system performance. The effect of the differences in performance on the system installation and operation costs was also analyzed.

The most common configuration of fuel cell systems consists of a module of stacked cells and other modules, such as the reformer and burner. The stacked cells, which form the so-called SOFC stack, are the power-generating elements of the fuel cell system [14]. When AGR is not utilized, the exhaust gas generally contains 15–25% residual fuel, which is sent to the burner from the SOFC anode outlet. When AGR is implemented, the exhaust gas is returned to the reformer installed at the stack inlet and recycled, increasing the net fuel utilization (Uf_N) for the power generation of the entire system including the stack. In addition, the water vapor and carbon dioxide in the exhaust can be used for reforming while maintaining the fuel utilization of the cell stack (Uf_C). The recycled fuel sent to the reformer is supplied to the stack, where it is used to generate electricity, causing Uf_N to become higher than Uf_C. Thus, AGR decreases the exhaust heat due to off-gas combustion and increases the electrical output of the system. However, AGR also changes the gas composition, creating a risk of carbon deposition inside the reformer and stack. Moreover, dramatic reduction of the heat generation would prevent thermally self-sustained operation. Therefore, the influence of recirculation must be quantitatively evaluated while taking these problems into account.

In this study, the heat and mass balance was calculated using system analysis by modeling the processes for each module, namely, the SOFC stack, reformer, burner, regenerative heat exchanger, heat recovery unit, and blower. The power generation characteristics for a 5-kW SOFC system were calculated, and the impact of the recirculation ratio on the performance of the system with AGR was evaluated. Finally, the impact of the performance improvement by AGR on cost reduction was evaluated by comparing the cost with that of the electricity supply from the power grid.

2. Analysis model

The process flow diagram of the SOFC system used in this study is depicted in Fig. 1. The system consists of an SOFC stack (SOFC), reformer (REF), burner (BUR), regenerative heat exchanger (RHEX), heat recovery unit (HR), evaporator (EVA), and blower (BLO). Other units, such as the DC/AC conversion inverter, are not considered in this study despite being present in the actual system.

In the present system, city gas was used as the fuel gas and air as the oxidant. Water was added to the system for reforming and heat recovery, and electricity and heat were output. The composition of "City Gas 13A," which is commonly used in Japan, is as follows: 90.95% methane, 5.62% ethane, and 3.3% propane [15]. The process analysis software AspenPlus ver. 8.4 was used to analyze the model [16]. In this approach, the energy conversion was calculated based on the mass and energy conservation within each element. The heat and mass transfer between the elements, the heat exchanged within the system, and the electricity output are indicated by arrows in Fig. 1.

The fixed operating conditions are listed in Table 1. In this study, the SOFC current density and anode gas recirculation ratio were the independent variables. The SOFCs was operated at different current density loadings of 0.2, 0.3, and 0.5 [A cm^{-2}], and the recirculation ratio was set at 0, 10, 20, 30, or 40 [%]. The main parameters that were varied to achieve the conditions in Table 1 and the changes in the independent variables are listed in Table 2. The SOFC system described in Table 1 generally operates at ambient pressure. Moreover, the SOFC stack is assumed to operate at 800 °C and $Uf_C =$ 80%. The carbon deposition, electrical efficiency, and total efficiency of the system are evaluated for each current density loading.

The simulation assumes that the flow rate of the anode gas fed into the SOFC is constant during operation. For example, when the recycled anode off-gas increases in response to an increase in the AGR ratio, the water supply is reduced to keep the flow rate constant. In this study, an AGR ratio of up to 40% was considered because the gas recirculated exceeds the volume of supplied water when the AGR ratio exceeds this value.

The electrical efficiency of the SOFC system increases when loading current density decreases because the overvoltage also decreases. The electrical efficiency of the AGR-performed SOFC system is expected to increase because Uf_N increases with increasing recirculation ratio. Some of the waste heat is recycled to heat the reformer, which converts the heat to chemical energy via an endothermic reforming reaction. Meanwhile, an SOFC module with an output of 120 V was constructed by stacking 1 cm-thick unit cells and cell separators [17]. The reformer was arranged around the stack, and the SOFC unit was covered with heat-insulating material; thus, the heat radiating out of the system was considered negligible.

2.1. Power-generation characteristics of a single cell

The operating voltage on the single SOFC cell depends on the loading current density, composition, temperature, and pressure of the supplied gas. A zero-dimensional model was used to determine the output voltage on all cells based on the calculated Nernst potential and overvoltage [14,18]. The gas composition was calculated from the average value of the gas composition at the inlet and outlet of the SOFC stack. The symbols used in the following formula are defined in the glossary at the end of this manuscript. The output voltage of the single cell E is calculated as follows:

$$E = E_0 - E_{act} - E_{ohm} - E_{conc} \quad (1)$$

where E_{act}, E_{ohm}, and E_{conc} are the activation, ohmic, and concentration overvoltages, respectively. Meanwhile, the Nernst potential E_0, which is primarily determined by the operating temperature T and gas partial pressures of each species (P_{H2}, P_{O2}, and P_{H2O}), is given by the Nernst equation,

$$E_0 = -\Delta G/2F + (RT/2F)ln\left(\frac{P_{H_2}}{P_{H_{2.ref}}} * \frac{\left(\frac{P_{O_2}}{P_{O_{2.ref}}}\right)^{0.5}}{\left(\frac{P_{H_2O}}{P_{H_2O.ref}}\right)}\right) \quad (2)$$

The ohmic overvoltage E_{ohm}, which reflects the electrical resistance of the oxygen ions in the SOFC electrolyte, is expressed as

$$E_{ohm} = iR_{elec} \quad (3)$$

where the electrical resistance R_{elec} of the electrolyte is considered to be 1.0 Ω cm^2 [19]. Moreover, the activation overvoltage E_{act} is given by the Butler–Volmer equation,