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Estimation of heat generation rate in solid oxide fuel cell module from single cell performance and module performance based on impedance analysis

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ABSTRACT

Heat generation rate in SOFC module was estimated under various thermal self-sustained conditions. SOFC module and system was designed to evaluate power generation property and temperature of module. Single cell was also evaluated the performance and electrode overpotential by impedance analysis under the similar condition to module power generation state. We estimated the heat generation rate with enthalpy calculation based on the actual module performance, and also with entropy calculation based on the impedance analysis of single cell. It was found that the heat generation rate calculated by enthalpy is approximately corresponded with that calculated by entropy. There still contains small error between heat generation rate calculated by enthalpy and that calculated by entropy. It was considered that these errors are originated from distribution in stack temperature and reforming gas temperature in the module. According to impedance analysis, it was found that the ohmic resistance is varied under operating condition and related with the current distribution which is calculated with the current path length in the cell. It was suggested that power generation state of module is affected by the current path length in the cell (in another word, distribution of power density) and distribution of overpotential; these phenomena is dominated by gas composition and thermal self-sustainable temperature.

1. Introduction

Solid oxide fuel cells (SOFCs) are mainly used oxide ion conductor for electrolyte and mainly consisted of ceramics. Since high oxide ion conductivity is achieved at high temperature, SOFC generally operates at high temperatures like 1273 K. Therefore, SOFCs realizes an internal reforming reaction at the anode, and it provides a high energy conversion efficiency since it is not necessary to supply additional fuel for reforming [1,2]. Recently, field test of a combined heat and power generation (CHP) system using SOFCs for a residential application is started and now SOFCs CHP system is

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closing to a commercialization like the case of polymer electrolyte fuel cells (PEFCs) system in Japan [3–5]. However, there are several requirements for residential CHP system using SOFCs. That is, a higher energy conversion efficiency than that of the current thermal power generation system and long service life (longer than 10 years for residential application). SOFC have to follow the change by electric demands in the house continuously and so, in order to achieve a high efficiency, high energy conversion efficiency is also requested under partial load condition. In addition, it is difficult for SOFCs to operate in daily start and stop (DSS) mode [6] because its high operating temperature requires large energy as well as long period for starting up. Therefore, long service life at least 10 years is requested for SOFC system. In order to achieve a high energy conversion efficiency, high thermal efficiency is requested from SOFC system for keeping the operating temperature by using small amount of fuel. For these requirements, we designed SOFC module and adopt lower operating temperature of system by using $LaGaO_3$ based oxide which shows much higher oxide ion conductivity than that of Y_2O_3 stabilized ZrO_2, the most popularly used electrolyte [7–11]. Since power size of the currently developing SOFC CHP system is 1 kW class, input heat energy is small and so small heat loss is strongly requested for thermal self sustaining state [12,13]. In the previous study, SOFC module consisting of micro tubular cells which use $LaGaO_3$ electrolyte film was developed and power generation as well as thermal self-sustainable property of the developed module was also studied [14]. It became evident that the SOFC module can not keep the operating temperature when a heat generation amount from stack placed inside the SOFC module is small under partial load condition. Generating heat value from stack changes depending on module output power and so the stack temperature is strongly related with the fuel utilization in a constant current power generating mode. SOFC module can be thermally self-sustained in a limited temperature range because of the limited fuel and air utilization from requested heat value. Thus, it is important to estimate the heat generation rate from stack and inlet heat energy to the module for achieving higher efficiency of SOFC module. Since fuel reformer and stack is placed at high temperature part inside of SOFC module, it is difficult for measuring practical reforming gas composition and flow rate.

Heat generation in the cell is mainly classified into reaction enthalpy and Joule heat which is assigned to the internal resistance of the cell. Internal resistance of the cell consists of electrical resistance and electrode overpotential. Impedance spectroscopy is based on a frequency response of the cell against applied ac signals and gives the information of resistance and capacitance element in the cell, and so electrical resistance and overpotential of electrode can be estimated with impedance measurement. Nakajima et al reported temperature distribution of SOFC cell by using impedance spectroscopy [15]. Heat generation rate could be estimated separately from anode and cathode overpotentials measured by impedance analysis. Although the heat generation rate of single cell was estimated, numbers of detail study on correlation between module and single cell performance by using impedance analysis are very limited up to now.

In this study, we estimated the heat generation rate in module by comparing enthalpy calculation based on the real module performance and single cell performance. Furthermore, we study the power generation property of SOFC module by impedance analysis of single cell. When heat value can be separated each overpotential heat loss under thermal self-sustained state, it emerged the origin of overpotential heat loss in the SOFC module. It is expected that energy conversion efficiency could be further improved with decreasing overpotential under partial load condition.

2. Heat generation rate calculation

2.1. Method for heat generation rate estimation

Fig. 1 shows typical I–V characteristics of SOFC power generation and details of energy balance. Enthalpy ΔH can be divided into Gibbs free energy ΔG and entropy TΔS terms. Output power is obtained by multiplying current density I by terminal voltage V which is subtracted overpotential η from open circuit voltage $E_{OCV.}$ Heat generation rate is sum of overpotential and entropy energy, and so heat generation rate could be calculated from the following two methods. One is subtracting power from enthalpy as follows [16].

$$Q_1 = \Delta H - P \quad (1)$$

where ΔH and P are enthalpy and power. Another is a sum of entropy heat and overpotential multiplied by current density as shown in the following equation [17].

$$Q_2 = \eta I + T\Delta S \quad (2)$$

where η, I, T, ΔS are overpotential, current density, temperature, entropy, respectively. Q_1 should be equal to Q_2 theoretically. In this study, heat generation rate in module was estimated by Eq. (1) and that for single cell was Eq. (2). For estimation of heat generation rate, reformate gas enthalpy

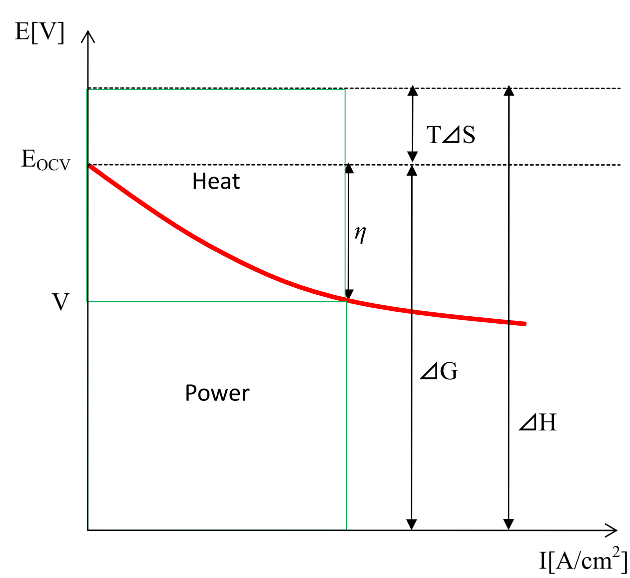

Fig. 1 – Energy balance in I–V characteristics of general SOFC.