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Journal of Power Sources 158 (2006) 52–59

JOURNAL OF POWER SOURCES

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Cycle analysis of planar SOFC power generation with serial connection of low and high temperature SOFCs

Takuto Araki [a,*], Takahiro Ohba [a], Shinya Takezawa [a], Kazuo Onda [a], Yoshinori Sakaki [b]

[a] *Department of Electrical and Electronic Engineering, Toyohashi University of Technology, 1-1 Hibarigaoka, Tenpaku, Toyohashi, Aichi 441-8580, Japan*

[b] *Electric Power Research and Development Center, Chubu Electric Power Co., Japan*

Received 5 July 2005; received in revised form 31 August 2005; accepted 2 September 2005

Available online 19 October 2005

Abstract

Solid oxide fuel cells (SOFCs) can be composed of solid components for stable operation, and high power generation efficiency is obtained by using high temperature exhaust heat for fuel reforming and bottoming power generation by a gas turbine. Recently, low-temperature SOFCs, which run in the temperature range of around 600 °C or above and give high power generation efficiency, have been developed. On the other hand, a power generation system with multi-staged fuel cells has been proposed by the United States DOE to obtain high efficiency. In our present study, a power generation system consisting of two-staged SOFCs with serial connection of low and high temperature SOFCs was investigated. Overpotential data for the low-temperature SOFC used in this study are based on recently published data, while data for high-temperature SOFC are based on our previous study. The numerical results show that the power generation efficiency of the two-staged SOFCs is 50.3% and the total efficiency of power generation with gas turbine is 56.1% under standard operating conditions. These efficiencies are a little higher than those by high-temperature SOFC only.

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Keywords: Two-staged serial SOFCs; Low temperature SOFC; Lanthanum gallate; High temperature SOFC; Cycle analysis

1. Introduction

Solid oxide fuel cells (SOFCs) are made entirely of solid materials for high reliability. The high temperature exhaust heat obtained simultaneously with power generation is used in fuel reforming, bottoming power generation, and the regenerative heating of fuel and air, as a result of which the total power generation efficiency of the entire cycle is high. In addition to the conventional high temperature SOFC that uses Y_2O_3 stabilized ZrO_2 as the electrolyte, a recent low temperature SOFC with a lanthanum gallate electrolyte that can be operated from about 600 °C has shown superior power generation characteristics [1], thereby expanding the operating temperature range of SOFCs. Since the power generation efficiency of a fuel cell is higher than that of a gas turbine, which is used as a bottoming power generator in the integrated SOFC-gas turbine cycle, expansion of the operating temperature range of SOFC is promising for increased system power generation efficiency. The United States Department of Energy (DOE), on the other hand, has investigated ways to achieve high power generation efficiency of 80% and has proposed a multi-staged fuel cell system with five serial stages of fuel cells in order to reduce the regenerative heat for fuel and air, and to extend the operating temperature range of fuel cells [2]. We have conducted previously cycle analyses of the combined cycle of high temperature SOFC and gas turbine, with consideration of realistic losses from overpotentials and other factors [3–4]. In the present study we propose a planar SOFC with two stages of low and high temperature SOFCs placed in series. We also speculate how much the combined cycle efficiency of two-staged SOFCs and gas turbine can actually be improved in the several hundred kW class of power generation, with investigation of the available data on overpotentials and other physical properties of low temperature SOFC [5–8].

1.1. Low and high temperature SOFCs of planar type

1.1.1. Cell configuration

Fig. 1 shows the configuration of a planar unit cell investigated in this study. The unit cell for both low and high

* Corresponding author. Tel.: +81 532 44 6728; fax: +81 532 44 6728.
E-mail address: araki@eee.tut.ac.jp (T. Araki).

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doi:10.1016/j.jpowsour.2005.09.003

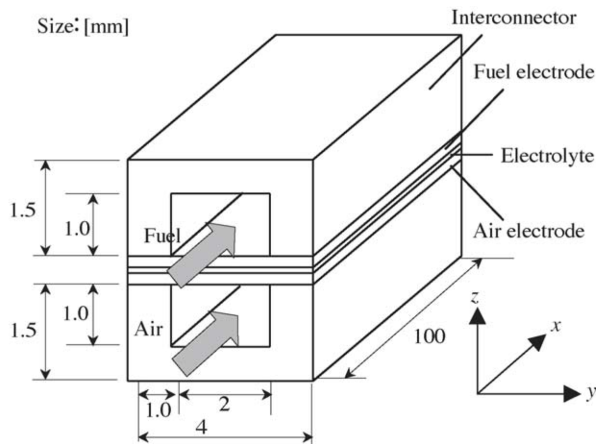

Fig. 1. Configuration of a unit cell.

temperature SOFCs is assumed to be a planar and parallel-flow type with similar sizes, as shown in Fig. 1. The materials and thickness of the electrodes and electrolyte for both low and high temperature systems are shown in Table 1. The interconnector for the low temperature system is SUS (stainless steel), and that for the high temperature system is $La_{1-x}Sr_xCrO_3$. The physical properties used for the low temperature SOFC were obtained by referring to SOFC studies [5–8] using lanthanum gallate electrolytes, and those for high temperature SOFC by referring to our previous reports [3,4]. Tables 2 and 3 show the thermal conductivity and resistivity for each element of low and high temperature SOFCs, respectively. The resistivity at temperature T_e of low and high temperature electrolytes, ρ_{e_low} (Ω m) [8] and ρ_{e_high} (Ω m) [9], is described by Eqs. (1) and (2), and the physical properties that have not been published for a low temperature system were assumed to be the same as for high temperature system.

$$\rho_{e\_low} = 0.03997 + 0.58731 \exp\left(\frac{T_e - 823.15}{86.47858}\right) \quad (1)$$

$$\rho_{e\_high} = 3.61 \times 10^{-5} \exp\left(\frac{10092}{T_e}\right) \quad (2)$$

1.1.2. Cell performance analysis

Two-dimensional conservation equations for charge, mass, and energy in both the low and high temperature systems are discretized together with an equivalent electric circuit of the fuel cell along the direction of gas flow and membrane thickness. The distribution of species concentration, current density, potential, and so on within the cell was analyzed numerically using the control volume method [3,4]. We first set operating conditions for the calculations, such as cell size, mean current density, and overall fuel and air utilization rates for both the low and high temperature systems. Then the inlet gas composition was decided for the low temperature SOFC. Next, with some mean electrolyte temperature of the low temperature cell as a parameter, calculations were started from the low temperature SOFC, and the current and temperature distributions were made to converge. The gas composition and temperature obtained at the low temperature SOFC outlet were then taken as the high temperature inlet condition, and calculations for the high temperature SOFC were carried out the same as for the low temperature SOFC. Therefore the mean temperature of high temperature SOFC was calculated from the mean temperature of low temperature SOFC and the operation conditions. Here, the activation overpotential V_{act_low} of the low temperature SOFC is given by Eq. (3), assuming a constant overpotential resistance from published data [5–8], and V_{act_high} of the high temperature SOFC by Eq. (4) from our previous reports [3–4]. Similar to V_{act_high}, V_{act_low} should be given by a temperature dependent function, but the temperature dependent V_{act_low} has not been published elsewhere.

$$V_{act\_low} = \frac{2.5 \times 10^{-5}}{w\,dx} I_e \quad (3)$$

$$i_e = i_0 \left\{ \exp\left(\frac{2FV_{act\_high}}{RT}\right) - \exp\left(\frac{-(2 \text{ or } 1)FV_{act\_high}}{RT}\right) \right\} \quad (4)$$

Here, w is cell width, dx is segmented length along flow direction, F is the Faraday constant, R is the gas constant, T_e is electrolyte temperature, I_e is current through electrolyte, i_e is current density through electrolyte, and i_0 is the exchange current density as a function of oxygen partial pressure. In our previous study [3], fuel was reformed internally in the cell to suppress the temperature rise of high temperature SOFC, but in the present study methane fuel was reformed completely at an external reformer and the reformed gas was introduced to the low temperature SOFC, since the cycle configuration would become too complex

Table 1
Compositions of electrolyte and electrode for low and high temperature SOFC

SOFC Type	Electrolyte (thickness: mm)	Fuel electrode (thickness: mm)	Air electrode (thickness: mm)	Interconnector
Low temperature	$La_{0.8}Sr_{0.2}Ga_{0.8}Mg_{0.15}Co_{0.05}O_{3-\delta}$ (200×10^{-3})	$Ni/Ce_{0.8}Sm_{0.2}O_2$ (1)	$Sm_{0.5}Sr_{0.5}CoO_3$ (1)	SUS
High temperature	YSZ (100×10^{-3})	Ni-YSZ (70×10^{-3})	$LaSrMnO_3$ (70×10^{-3})	$La_{1-x}Sr_xCrO_3$

Table 2
Physical properties of low temperature SOFC

Element	Electrolyte	Fuel electrode	Air electrode	Fuel side interconnector	Air side interconnector
Thermal conductivity ($W\,m^{-1}\,K^{-1}$)	2.7	11	2.2	16.3	16.3
Resistivity (Ω m)	Eq. (1)	1.0×10^{-5}	1.3×10^{-4}	7.4×10^{-7}	7.4×10^{-7}

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