TEMPERATURE DISTRIBUTION IN A TUBULAR FLAT PLATE TYPE SOFC

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ABSTRACT

We investigated the temperature distribution in a tubular flat plate (TFP) type SOFC cell by computer simulation. We adopted the control volume method for the simulation, taking into account the material balance, energy balance, and electrochemical reactions. It is shown that the temperature distribution in the TFP cell can be suppressed by a return path for the 1123 to 1273 K operation temperature range.

INTRODUCTION

Solid oxide fuel cells (SOFCs) are of great interest as economical, clean and efficient means of producing electricity in a variety of commercial and industrial applications (1). The monolithic or planar stack concepts have been studied because such designs are expected to yield high power outputs and efficiencies, as well as low fabrication costs, relative to the earlier tubular or in-series connected plate designs (1). However, the strength of planar cells is relatively low (2). Tubular cells, on the other hand, have sufficient strength, but the ohmic resistance is high due to the long current flow length (3). The tubular flat plate (TFP) cell can overcome the above problems: it has sufficient strength due to the use of a cathode substrate and low ohmic resistance due to the use of cathode ribs for current flow (4).

The temperature distribution in SOFCs has been studied by computer simulation with the aim of improving the mechanical reliability (5,6,7). It was shown that the temperature distribution of the cell is a function of the gas flow path and is largely determined by the boundary conditions on the cell (7). However, up to now, there has been no simulation of TFP cells. In this paper, we studied the temperature distribution of TFP cell for various operating temperatures.
The TFP Model for the Analysis

The TFP cell consists of a cathode substrate with gas-flow channels, a thin layer of electrolyte, an anode, and an interconnector as shown in Fig. 1. The gas flow path for oxidant gas in TFP cells was modeled as illustrated in Fig. 2. In model (a), the oxidant gas is introduced from the center gas flow channel and expelled from the outer gas flow channels. We refer to this gas flow configuration as a return path. In our analysis, we studied the influence of the return path on the temperature distribution.

The temperature distribution for the z-direction (See Fig. 2) was assumed to be negligible compared to that for the x-direction. This is because the anode of a TFP cell faces the interconnector of the neighboring cell in the stack model (8). It was also assumed that there is no mass flow in the z-direction. Thus, the temperature in a cell can be simulated to solve the two-dimensional boundary problem. We assume that the boundary conditions are largely determined by the operation temperature (referred as $T_{\text{sink}}$) due to the cell configuration of air electrode substrate. That is, the fuel inlet temperature (referred as $T_{\text{f, in}}$) is substituted for $T_{\text{sink}}$.

Equation for the Analysis

In this section, we review the equations that obey the control volume in the SOFC cell (5). The SOFC cell was divided into unit cells for the control volume method as shown in Fig. 3. The unit cells are labelled 1,2, ...,k,...K in the x-direction and 1,2, ...,1,...L in the y-direction. We assume that solid temperature and gas-phase composition and temperature are uniform for each unit cell.

It follows from Faraday’s law for local current densities that

$$J_{k,i} = 2N_{H_2}F \alpha_{i} \left( \phi_{H_2,k,i} - \phi_{H_2,k,i-1} \right),$$

and

$$J_{k,i} = 4N_{O_2}F \alpha_{i} \left( \phi_{O_2,k,i} - \phi_{O_2,k,i-1} \right).$$

Here, $J_{k,i}$ is current density, $N_i$ Z-gas molar flux, the Z-gas conversion ratio, $F$ the Faraday constant, and $a_1, a_2, b_1, b_2, d_2$ are unit cell dimensions.

As the enthalpy energy balance was adopted for the fuel and the oxidant gases with the solid cell, we derived the following three equations.

$$a_1b_2N_{H_2}(1 - \phi_{H_2,k,i-1})c_{H_2}T_{F,k,i-1} + a_1b_2N_{H_2}\phi_{H_2,k,i-1}c_{H_2}T_{F,k,i-1} + a_1b_2N_{H_2}c_{H_2}T_{F,k,i-1} \left( \frac{J_{k,i}}{2F} \right) - \frac{J_{k,i}}{2F} a_1b_2c_{H_2}T_{F,k,i-1} + 2a_1b_2c_{H_2}T_{F,k,i-1} = 0,$$

$$\left[ (a_1 - d_2)b_1N_{O_2}c_{O_2}(1 - \phi_{O_2,k,i-1}) + (a_1 - d_2)b_1N_{O_2}c_{O_2} \right] T_{F,k,i-1} - \left[ (a_1 - d_2)b_1N_{O_2}c_{O_2}(1 - \phi_{O_2,k,i}) + (a_1 - d_2)b_1N_{O_2}c_{O_2} \right] T_{F,k,i} = 0.$$
\[-\frac{J_{k,i}}{4F} + a_{a_2} c_{\rho_1}(T_{S,k,i} + 2h_{a_2}z(a_1 + b_1 - d_2)(T_{S,k,i} - T_{M,k,i}) = 0, \quad [4]\]

and
\[
\begin{align*}
& k_{\alpha} A_{S1}(T_{S,k,i+1} - T_{S,k,i}) + k_{\alpha} A_{S1}(T_{S,k,i-1} - T_{S,k,i}) \\
& + k_{\alpha} A_{S2}(T_{S,k,i+1} - T_{S,k,i}) + k_{\alpha} A_{S2}(T_{S,k,i-1} - T_{S,k,i}) \\
& \quad - 2h_{a_2}z(a_1 + b_1 - d_2)(T_{S,k,i} - T_{M,k,i}) - 2h_{a_2}z(a_1 + b_2)(T_{S,k,i} - T_{F,k,i}) \\
& + a_{a_2} \frac{J_{k,i}}{2F} c_{\rho_1}(T_{S,k,i} - T_{F,m}) + a_{a_2} \frac{J_{k,i}}{2F} c_{\rho_2}(T_{F,k,i} - T_{F,m}) \\
& \quad - a_{a_2} \frac{J_{k,i}}{2F}[c_{\rho_2}(T_{S,k,i} - T_{F,m}) + \Delta H^0] = J_{k,i}[a_{a_2} U]. \quad [5]\end{align*}
\]

Here, $c_{\rho_2}$ represents Z-gas specific heats, suffix $D$ corresponds to the diluent in fuel stream, $h_{a_2}$ is gas-solid heat transfer coefficient, $T_{S}$ is gas or solid temperature, $k_{\alpha}$ is solid thermal conductivity, and $\Delta H^0$ is standard enthalpy change of reaction. The $A_{S1}$ and $A_{S2}$ areas and are defined as
\[
A_{S1} = a_1(d_1 + d_3) + b_1d_2, \quad [6]
\]
and
\[
A_{S2} = a_2(b_1 + d_1 + d_3), \quad [7]
\]
where $d_1, d_2$ are unit cell dimensions.

The unit cell volume was derived from the open circuit voltage, the ohmic resistance and overpotential of the cell. Then, we obtained
\[
U_{k,i} = U_{k,i}^0 - (R_{i}^{\alpha} + R_{i}^{\rho})I_{k,i}, \quad [8]
\]
where $U_{k,i}$ is cell voltage, $U_{k,i}^0$ open circuit voltage, $R_{i}^{\alpha}$ the ohmic resistance of a cell, and $R_{i}^{\rho}$ the polarization part of cell resistance, assuming a linear approximation of the Butler Volmer equation, and $I_{k,i}$ the current.

As the open circuit voltage depends on the temperature and oxygen partial pressure, we obtained
\[
U_{k,i}^0 = -\frac{\Delta G_{k,i}^0(T_{S,k,i})}{2F} + \frac{RT_{S,k,i}}{2F} \ln[\sqrt{P_{O_2,k,i}} + \sqrt{1 - \phi_{O_2,k,i}(1 - \phi_{H_2,k,i})}], \quad [9]
\]
Here, $R$ is the gas constant, $P_{O_2,k,i}$ oxygen partial pressure, and $\Delta G_{k,i}^0$ the Gibbs energy change of the reaction, which is given by
\[
\Delta G_{k,i}^0 = \Delta H^0 - T_{S,k,i} \Delta S^0, \quad [10]
\]
where $\Delta S'$ is the standard entropy change of the reaction.

**Parameters for the Analysis**

Before discussing the result, we mention the approximation and parameters used for the simulation. The dominant factor of ohmic resistance is attributed to the electrolyte, then we get

$$R_{k,l}^0 = \rho_{k,l} \frac{d_1}{a_1 a_2} = \rho_o \exp\left\{ \frac{E_{act}}{RT_{i,m}} \left( 1 - \frac{T_{i,n}}{T_{S,k,l}} \right) \right\} \frac{d_1}{a_1 a_2}. \quad [11]$$

Here, $\rho_o$ is electrolyte resistivity at $T_{i,n}$ and $E_{act}$ is the activation energy for O$_2^-$ conduction in solid electrolyte. We also assumed the polarization $R^P$ has the same temperature dependence as $R^0$. The $\rho_o$ and $R^0$ values were decided considering the results for a TFP cell in (9).

Solid heat conductivity can be roughly approximated by the heat conductivity of the electrolyte. Gas transfer coefficients were taken from Ref. (5), although there was not always a fuel gas path in the TFP cell, and TFP cell dimensions were always same as those of the planar-type cell in Ref. (5).

Typical values for various parameters for the simulation are listed in Table I.

**RESULTS AND DISCUSSION**

To confirm that the resistivity value used here was appropriate, we compared the V-I curve of the simulation result with the experimental data for the cathode substrate TFP cell in (9). The dependence of ohmic resistance on the operating temperature obtained using eq. [11] is shown in Fig. 4, which coincides with the well-known experimental data (10). The electrolyte thickness was decided to be 50 $\mu$m considering the experimental data in (9). Figure 5 shows the V-I curve obtained using the same parameters in Table I and the linear approximation for the overpotential with the operation temperature $T_{\text{inlet}} = T_{i,n}$ of 1223 K and the air inlet temperature of 973 K. In (9), the cell was placed in an Al$_2$O$_3$ holder, and the holder was placed in a furnace for the experiment. Therefore, the temperatures on the cell boundary and inlet gas were the same, which is the same condition as our simulation boundary condition. These results indicate that the resistivity used here was appropriate for the simulation.

Figure 6 shows the temperature distribution in a cell with a return path (a) and without a return path (b) for the operation temperature of 1223 K and the air temperature of 973 K. Hereafter, we refer to the former a cell-R and the latter as cell-N. Here, air was used not only as an oxidant but also for cell cooling. In cell-N, the temperature near the air inlet drastically decreases compared to other parts of the cell due to low-temperature air, which leads to high thermal stress. On the other hand, such a temperature decrease at the air inlet was suppressed in cell-R because the high-temperature air compensates for the cooling effect. Figure 7 shows the maximum temperature difference for cell-N and cell-R as a function of the air inlet gas temperature at $T_{\text{inlet}} = 1273$ K. The maximum temperature difference decreases as the air inlet temperature increases since...
the cooling effect is reduced. These results indicate that a return path can suppress the temperature difference for the whole range of air inlet temperatures.

Figure 8 shows the maximum temperature difference for cell-N and cell-R as a function of the operation temperature at the air inlet temperature of 973 K. The maximum temperature difference increases as the operation temperature increases since the air becomes cold relative to the atmosphere. A return path can suppress the temperature difference for the whole range of operation temperature. This indicates that a return path can also suppress thermal stresses for a wide range of operation temperatures.

CONCLUSIONS

We investigated the temperature distribution in a TFP SOFC cell with a return path for an oxidant gas by the control volume method, taking into consideration the material balance, energy balance, and electrochemical reactions. It was demonstrated that the cooling effect resulting in thermal stress near the air inlet can be suppressed by a return path for operation temperatures ranging from 1123 to 1273 K.

REFERENCES

(1) Solid Oxide Fuel Cells VI, S. C. Singhal and M. Dokiya, Editors, The Electrochemical Society Proceedings Series, Pennington, NJ (1999).
(2) H. Yokokawa, Solid Oxide Fuel Cells VI, S. C. Singhal and M. Dokiya, Editors, p.10, The Electrochemical Society Proceedings Series, Pennington, NJ (1999).
(3) S. C. Singhal, Solid Oxide Fuel Cells VI, S. C. Singhal and M. Dokiya, Editors, p.39, The Electrochemical Society Proceedings Series, Pennington, NJ (1999).
(4) T. Matsushima, D. Ikeda, H. Kanagawa, T. Hirai and A. Komura, p.139, Fuel Cell Seminar Abstracts, Orlando, Florida, USA, November (1996).
(5) E. Erdle, J. Gross, H. G. Mueller, W. J. C. Mueller, H. J. Reusch and R. Sonnenschein, p.265, Proceedings of 2nd Int'l. Symp. on SOFCs, Commission of the European Communities (1991).
(6) H. Yakabe, T. Ogiwara, I. Yasuda and M. Hishinuma, in Solid Oxide Fuel Cells VI, S. C. Singhal and M. Dokiya, Editors, p1087, The Electrochemical Society Proceedings Series, Pennington, NJ (1999).
(7) M. Iwata, T. Hikosaka, M. Morita, T. Iwanari, K. Ito K. Onda, Y. Esaki, Y. Sasaki and S. Nagata, 132, p.273, Solid State Ionics (2000).
(8) M. Arakawa, K. Watanabe, H. Orui, K. Nozawa, Y. Tabata and T. Hirai, p.603, Fuel Cell Seminar Abstracts, Portland, Oregon, USA, Oct (2000).
(9) H. Orui, S. Nakano, K. Watanabe, M. Arakawa and T. Hirai, D3-3, p.387, The 3rd International Fuel Cell Conference Proceedings (1999).
(10) N. Q. Minh, T. Takahashi, p.86, Science and technology of ceramic fuel cells (1995).
### Table. I. Input data for SOFC operation

| Parameter                                      | Dimension       | Value   |
|------------------------------------------------|-----------------|---------|
| molar fuel flow rate                           | mol·s⁻¹·m⁻²     | 1.2     |
| molar air flow rate                            | mol·s⁻¹·m⁻²     | 40      |
| cell voltage                                   | V               | 0.7     |
| specific heat of the fuel                      | J·mol⁻¹·K⁻¹     | 31      |
| specific heat of the water vapor               | J·mol⁻¹·K⁻¹     | 44      |
| specific heat of the oxygen                    | J·mol⁻¹·K⁻¹     | 32.3    |
| specific heat of the nitrogen                  | J·mol⁻¹·K⁻¹     | 34.8    |
| heat conductivity of solid                     | J·s⁻¹·m⁻¹·K⁻¹   | 2       |
| enthalpy of reaction at 1173K                  | J·mol⁻¹         | -249000 |
| entropy of reaction at 1173K                   | J·mol⁻¹·K⁻¹     | -55.69  |
| fuel heat transfer coefficient                 | J·s⁻¹·m⁻²       | 92      |
| air heat transfer coefficient                  | J·s⁻¹·m⁻²       | 708.8   |
| resistivity of the electrolyte                 | Ω·m             | 0.175   |
| at 1173K                                       | Ω·m²            | 5·10⁻⁵  |
| resistance due to cell polarization at 1173K   |                 |         |
| activation energy                              | J·mol⁻¹         | 69444   |
| fuel channel width a₁                          | mm              | 8       |
| fuel channel height b₂                         | mm              | 5       |
| air channel width a₁-d₂                        | mm              | 5       |
| air channel height b₁                          | mm              | 3       |
| electrolyte thickness                          | mm              | 0.05    |
Fig. 1, Sketch of TFP cell.

Fig. 2, Schematic diagrams of two types of TFP cell.

Fig. 4, Electrolyte resistivity as a function of temperature.
Fig. 5, Voltage as a function of current density for cell-R at $T_{\text{sink}} = 1223$ K.

Fig. 6, Temperature distribution of solid for: (a) cell-N, (b) cell-R at $T_{\text{sink}} = 1223$ K and air inlet temp. = 973 K.
Fig. 7, Effect of inlet air temperature on maximum temperature difference in solid at $T_{\text{sink}} = 1223$ K.

Fig. 8, Effect of operation temperature on maximum temperature difference in solid at air inlet temperature of 973 K.