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A numerical study on anode thickness and channel diameter of anode-supported flat-tube solid oxide fuel cells

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ABSTRACT

Fuel cells convert the chemical energy present in fuel (e.g., hydrogen) into electrical energy with high efficiency, low pollution and low noise. Of the various types of fuel cells, the solid oxide fuel cell (SOFC) was developed specifically for power plants and residual power systems. SOFCs are classified into three categories based on their shape: planar, cylindrical and flat-tube. The flat-tube SOFC (FT-SOFC) exhibits the advantages of ease in sealing, low stack volume and low current-collecting resistance. However, due to its weak strength, the FT-SOFC may get deformed or break during the manufacturing process. To improve the cell strength, the cell support must be thickened. However, as the support thickness is increased, the electrons must travel a longer distance, which leads to an increase in the electrical resistance. In another method, the hydrogen channel diameter can be reduced for the strong strength. But, it may lead to a corresponding decrease in the hydrogen mass transfer rate. In this manuscript, we study the performance of several FT-SOFC designs and suggest the better design. The numerical analysis for the FT-SOFC incorporates several physical phenomena such as gas flow, heat transfer and electrochemical reactions. The governing equations (i.e., mass, momentum, energy and species balance equations) are calculated for heat and mass transfer. The open circuit voltage, activation polarization, ohmic polarization and contact resistance are simulated simultaneously. The experimental results are compared with the numerical data for the purposes of code validation. The current density and temperature distribution are then investigated on the SOFC surface. The average current density decreases by 14.6% if the hydrogen channel diameter is narrowed by 50%, and by 10.2% if the support thickness is increased by 50%. Based on these results, we present a design for a stack of FT-SOFCs.

1. Introduction

The environmental pollution caused by fossil fuel use has become an important issue; thus, interest in renewable energy has increased. Of the various forms of renewable energy, we have chosen to concentrate on fuel cells, which convert the chemical energy of a fuel (e.g., hydrogen) into electrical energy with high efficiency, low pollution and low noise [1]. Solid oxide fuel cells (SOFCs) are composed of ceramic compartments and operate at high temperatures. They do not require an expensive noble metal catalyst, can use hydrocarbon fuel instead of hydrogen and can utilize the waste heat by adding a bottoming cycle [2].

SOFCs can be classified into three types based on their shapes: planar, cylindrical and flat-tube. The planar SOFC exhibits the advantages of low electronic resistance and ease of stacking, but it is difficult to seal the gap between the ceramic cell and the metal interconnect [3]. Although the cylindrical SOFC can easily overcome the sealing problem [4], it is difficult to stack the cells of the cylindrical SOFC, and it also exhibits high electronic resistance. The flat-tube SOFC (FT-SOFC) exhibits several merits of the planar and cylindrical SOFCs. As a result, the FT-SOFC has been manufactured considerably in Japan and Korea. Kim et al. [5] have described a process to fabricate the FT-SOFC using the extrusion process, and Ivanov et al. [6] have developed the technology to fabricate FT-SOFCs using a magnetic pulse. For the commercialization of SOFCs, the cell must be fabricated as a stack. Koi et al. [7] have successfully fabricated a stack of FT-SOFCs.

The mass transfer rate, current density and temperature distribution of the FT-SOFC are closely linked to its shape, i.e., the performance of the SOFC is strongly dependent on its shape. To design the FT-SOFC, the correlation between its performance and shape must be evaluated, and the temperature and the species

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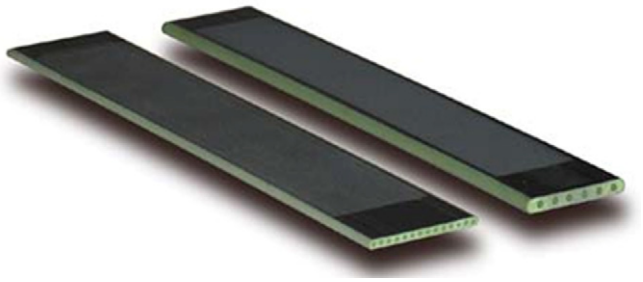

Fig. 1. An FT-SOFC single cell made by Kyocera [11].

concentration inside the SOFC must be measured. However, these factors are difficult to measure because the SOFC is an airtight box; therefore, substantial time and expense are required for this type of experiment. These challenges can be overcome through the use of numerical simulation. Lu et al. [8] have developed a three-dimensional simulation model of the FT-SOFC, and Suzuki et al. [9] have investigated polarization models for the FT-SOFC. The simulation model to predict the performance has been studied by Haberman et al. [10]. These models, focused on the simulation of the FT-SOFC, have been used in this manuscript to study the effect of the SOFC shape on its performance. The ratio of the anode support thickness to the channel diameter is considered an important design parameter. A decrease in the anode support thickness leads to an increase in the mass transfer rate of hydrogen as shown in Fig. 1 [11]. At the same time, the ohmic polarization may decrease due to the shortening of the electron path. However, the thin support may weaken the mechanical strength of the cell, leading to deforming or breaking of the cell during fabrication, stacking or operation. Therefore, in this manuscript, we have studied the effects of the support thickness and the channel diameter on the performance of the FT-SOFC.

2. Governing equations

The temperature distribution and the species concentrations in the SOFC change according to the flow in the channel and the electrochemical reaction. Therefore, the heat transfer reaction, the mass transfer reaction and the electrochemical reaction are analyzed simultaneously to develop a reliable simulation model. The governing equations are used to calculate the heat and mass

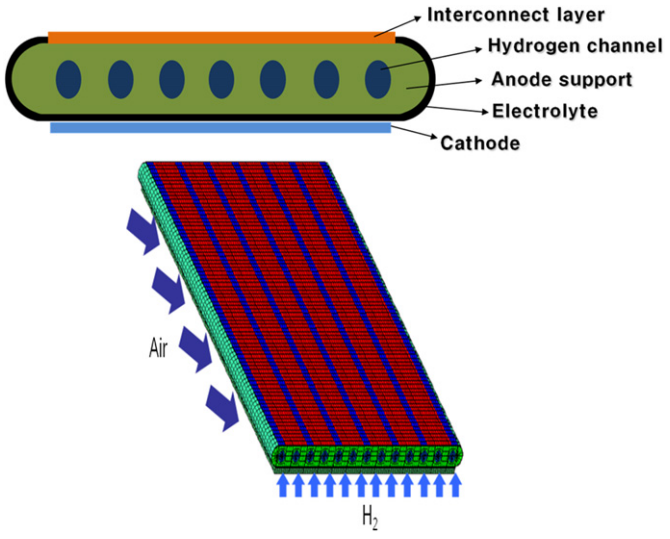

Fig. 2. The computational domain for the FT-SOFC single cell.

Table 1
Operating parameters.

	Anode	Cathode
Inlet temperature	700 °C	700 °C
Furnate temeprature	700 °C	700 °C
Inlet gas concentration	H_2	Air
Inlet flow rate	500 sccm	750 sccm
Operating voltage	0.7 V	
Active area	37.5 cm^2	

transfer occurring inside the SOFCs. The mass, momentum, energy and species balance equations are shown in Eqs. (1)–(4). The commercial software STAR-CD is used to obtain the solutions for these governing equations. Moreover, the source terms reflecting the electrochemical reaction are added to the governing equations using an in-house code. The exact electrochemical reaction models are explained in the next chapter.

The continuity equation:

$$\frac{\partial}{\partial x_i}(\rho u_i) = 0, \tag{1}$$

where ρ is the density and u_j is the superficial velocity of the gas species.

The momentum balance equation:

$$\frac{\partial}{\partial x_j}(\rho u_j u_i - \tau_{ij}) = -\frac{\partial P}{\partial x_i} + S_i, \tag{2}$$

where τ_{ij} is the stress tensor component, P is the pressure in the system and S_i is the momentum source.

The energy balance equation:

$$\frac{\partial}{\partial x_j}\left(\rho h u_j + F_{h,j}\right) = u_j\frac{\partial P}{\partial x_j} + \tau_{ij}\frac{\partial u_i}{\partial x_j} + S_e, \tag{3}$$

where h is the enthalpy of the gas species, $F_{h,j}$ is the diffusional energy flux in direction j and S_e is the energy source.

The species balance equation:

$$\frac{\partial}{\partial x_j}\left(\rho_{uj} Y_m + F_{m,j}\right) = S_s, \tag{4}$$

where Y_m is the mass fraction of species m, $F_{m,j}$ is the diffusional flux of species m in direction j and S_S is the rate of the production or consumption of the mass fraction.

When the fluid passes through electrodes with a porous medium, the gas pressure decreases due to the mass transfer resistance. The calculation of the flow in the porous electrode must be exact and precise because an SOFC's performance may change with the pressure. The pressure drop is reflected by the Ergun equation, as described in Eq. (5) [12], where the porosity of the electrode is assumed to be 0.3.

$$\frac{\partial P}{\partial_{xj}} = -\frac{150\mu(1-\chi)^2 u}{\chi^3 D_P^2 \varphi_P^2} - \frac{1.75\rho(1-\chi)u^2}{\chi^3 D_P \varphi_P}, \tag{5}$$

where μ is the dynamic viscosity, χ is the volume porosity, D_p is the particle diameter, and Φ_p is the particle shape factor.

Table 2
Boundary conditions.

Gas channel Inlet	$T = T_{in}$	$C = C_{in}$
Gas channel outlet	$\partial T/\partial x = 0$	$\partial C/\partial x = 0$
Wall	$\partial T/\partial x = 0$	$\partial C/\partial x = 0$