Performance Enhancement of Solid Oxide Fuel Cells Using Metal-Foam Flow Distributors

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Abstract: A three-dimensional numerical model of solid oxide fuel cell (SOFC) with straight channel is established to investigate the effect of using metal foam as flow distributor on the performance of the fuel cell. The existence of metal foam in both of the flow channels effects on the velocity field of gases, and results in more fuels penetration into the electrodes up to the catalyst layers of the cell. This enhances the rate of chemical reaction, the species distribution, the current density, and the cell efficiency. It is deduced that the average current density rises by 26% upon adopting metal foam when compared to the case of smooth channels. This study proposes a new SOFC channel that can be utilized for operation processes.

Keywords: solid oxide fuel cell; metal foam; velocity field; species distribution; current density; CFD simulation.

1 Introduction

Fuel cells are regarded as a promising energy source for the future, and solid oxide fuel cell (SOFC) is a significant alternative clean power generator that can be used in vehicles, portables, and stationary applications. SOFC produces zero to low emissions, performs at high temperatures, provokes high efficiency and can use hydrogen or hydrocarbons as the fuel [1-3]. Therefore, efficient methods should be considered for the development of SOFC.
Several research suggested improving flow field designs to enhance current and flow distribution uniformity. To mitigate the limitations inherent to conventional flow-channel configurations in fuel cells, a viable approach is to replace these channels with a porous transport medium, such as metallic foam. Metallic foam exhibits high porosity, tunable permeability, and low density, characteristics that render it an effective medium for uniform reactant distribution [4]. Numerous experimental and numerical investigations concerning the use of metallic foams have been reported in the literature. Metal-foam-based flow fields have been extensively implemented in PEMFC systems, and comprehensive studies have demonstrated that their use can significantly enhance overall cell performance [5,6]. Afshari et al. [7] reported that employing metal foam as a flow-field structure yields a more uniform temperature distribution, and that increasing the foam porosity further improves cell performance. Zhan et al. [8] numerically modeled an SOFC in which the cathode flow field was substituted with metal foam, resulting in a 13.74% increase in output power relative to a conventional channel configuration. This improvement was attributed to more homogeneous distributions of oxygen concentration, electron transport, and temperature throughout the cell. Numerous mathematical models have been adopted to forecast the behavior of cells under various conditions, a rare modeling studies that describe the flow channel design of SOFC systems have been published in the literature. This work aims to study the impact of applying metal foam as flow distributor in the flow channels of SOFC on the output current density.

2 Numerical model

2.1 Geometry description

Three-dimensional steady model for a single planar SOFC is developed based on the finite element method using the CFD commercial software COMSOL Multiphysics (version 5.3a) to solve fully coupled transport- reaction model.
Figure 1 presents 3D SOFC single cell schematically.

Table 1: Geometry size of the single cell SOFC [9]

	Hight- y *(m)*	Depth-x *(m)*	Length-z *(m)*
Gaz channel	50×10^{-5}	20×10^{-4}	10×10^{-2}
Interconnector ribs		50×10^{-5}	
Interconnector	65×10^{-5}	30×10^{-4}	
support anode layer	40×10^{-5}		
active anode layer	15×10^{-6}		
Electrolyte	10×10^{-6}		
active cathode layer	20×10^{-6}		
support cathode layer	50×10^{-6}		

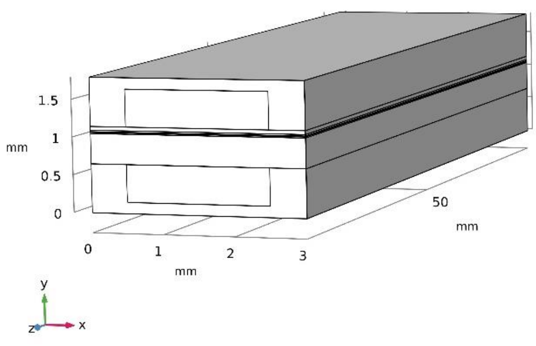


Figure. 1. Schematic of a single cell SOFC geometry

2.2 Mathematical model and major assumption

Heat transfer, mass transfer, and electrochemical reactions are the primary processes involved in the internal reaction of SOFCs. All gases obey ideal gas law own to ambient pressure and high working temperature, heat transfer due to radiation is negligible, and a steady state operation is applied [9,10].

The electrochemical reaction takes place at triple phase boundary (TPB) of the electrode. Electro-migration is transmitted from the TPB to the bulk phase. The reaction expressions of the cathode and anode TPB are shown in (1) and (2):

$$O_2 + 2e^- \rightarrow 2O^{2-} \quad (1)$$

$$H_2 + O^{2-} - 2e^- \rightarrow H_2O \quad (2)$$

The charge transfer is produced by the electrode reaction, and the electrode potential and electrolyte potential regulate the migration of electrons and oxygen ions. Equations (3) and (4) display the electron current density.

$$\nabla . i_{ion} = \nabla . (-\sigma_{ion}^{eff} \nabla \varphi_{ion}) = Q_{ion} \quad (3)$$

$$\nabla . i_{elec} = \nabla . \left(-\sigma_{elec}^{eff} \nabla \varphi_{elec}\right) = Q_{elec} \quad (4)$$

The velocity fields distribution and pressure distribution of the model electrode are used for calculation through the free and porous medium flow fields. The flow of gas within the flow channel adopts the continuous Navier-Stokes momentum conservation equation.

$$\rho u . \nabla u = -\nabla p + \nabla \left[\mu \left(\nabla u + (\nabla u)^T\right) - \frac{2}{3} \mu (\nabla . u) I \right] + F \quad (5)$$

In the battery model, due to the mass transfer caused by convection and diffusion, the concentration distribution of each participating reactant is solved by the concentrated substance diffusion fields. The governing equation is as follows:

$$\nabla(\rho . u . \omega_i) + \nabla J_i = M n_i r_i \quad (6)$$

$$\rho (u . \nabla) \omega_i = (\rho . \omega_i \sum_{k=1}^{n} D_{i,j}^{eff} . \nabla x_j + \left(x_j - \omega_j\right) \frac{\nabla p}{p} . u) + S_i \quad (7)$$

$$D_{i,j}^{eff} = \varepsilon D_{i,j} \quad (8)$$

The electrode reaction kinetics of SOFC are given in the Butler-Volmer equation, which is applicable to both the cathode and anode of the fuel cell. The expression is shown in (9): [11]

$$i = i_0 \left\{ \frac{C_{Rc}}{C_{Rc}^0} \exp\left(\frac{\beta n F \eta_{act}}{RT}\right) - \frac{C_{Ox}}{C_{Ox}^0} \exp\left(\frac{-(1-\beta) n F \eta_{act}}{RT}\right) \right\} \quad (9)$$

when SOFC works, it is accompanied by three polarization phenomena, namely activation polarization, concentration polarization and ohmic polarization. Voltage loss and power loss are caused by three polarization processes.

For resolving the governing equations, boundary conditions are imposed at particular locations in the SOFC [9,10]

3 RESULTS AND DISCUSSION

3.1 Model validation

By calculating the overall SOFC using the current model, it is possible to observe the potential of this research to manage the overall cell performance. We use the current model to solve a SOFC in its entirety, as mentioned in the section above.

The voltage-current density curve derived from the modeling is presented alongside the experimental data in Figure 2. The simulation results of the polarization curve present an acceptable accuracy with experimental data obtained from references [9,11]. A small difference is achieved between numerical and experimental results, this is most likely due to hypotheses and errors correlated with the SOFC model.

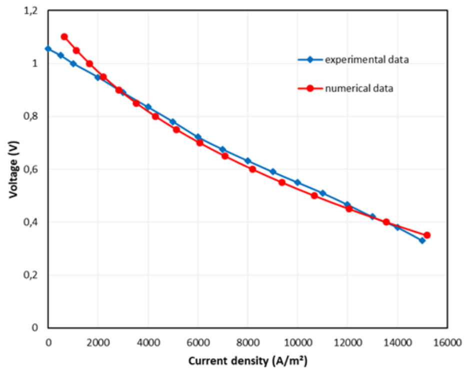


Figure 2. . Polarization curve: Comparison between experimental and predicted results [11]

3.2 Case study:

In the present study, the impacts of use of metal foam as flow distributor on fuel cell efficiency are investigated. Two cases are explored, as indicated in Figure 3.

Case (a): a SOFC unit with two conventional straight channels, as described in Figure 3.a.

Case (b): Utilization of a nickel metallic foam with 90 % porosity as flow distributor in the SOFC unit (Figure 3.b).

Case (a) Case (b)

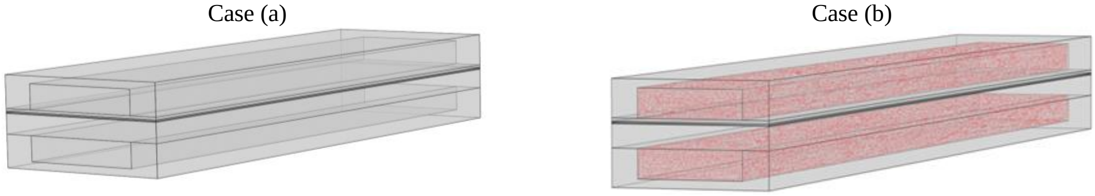


Figure 3: Schematic of the SOFC for the 2 different flow field cases: (a) conventional SOFC model (base case); (b) novel SOFC model with metal foam.

3.2 Velocity distribution

Figures 4 presents the velocity field in the SOFC for the two cases. As we can see in the case (a), the speed is greater in the center of the channels. Once the fuels hit the cell wall, the fluid loses momentum and their speed minimizes. The velocity in the anode and cathode are also very low own to the low permeation in these areas.

Compared to the base configuration (Case a), incorporating metal foam as a flow distributor (Case b) yields a markedly more uniform velocity distribution within the cell channel, with the anodic and cathodic regions exhibiting nearly identical velocity magnitudes. In addition to promoting a more uniform velocity distribution, the use of metal foam facilitates smoother flow transport and increases the velocity in the cathode flow channel from 1.98 m/s to 2.59 m/s, thereby significantly enhancing gas mass transfer within the electrode diffusion layers.

Therefore, the mass flow rate of hydrogen and oxygen in the diffusion, support and active layers is increased and the chemical reaction is enhanced

Case (a) Case (b)

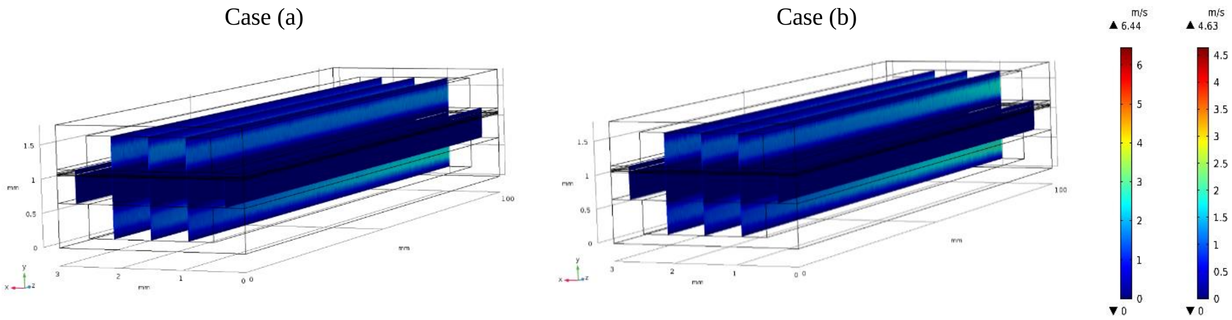
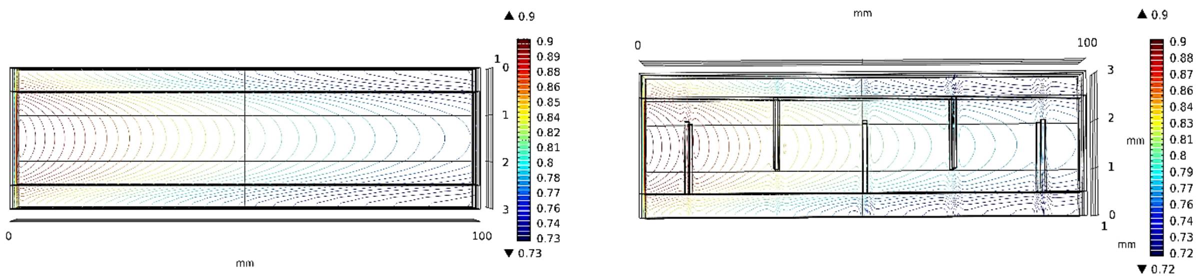


Figure 4: Parallel slice plot in a 3D model for the velocity distributions in the SOFC

3.3 Mass fraction distribution:



Case (a) Case (b)

Figure 5: Cross section of the molar fraction streamline distribution at the hydrogen flow channel for y=1 mm

Figure 5 presents the distribution of the hydrogen molar fraction nearby the anode reaction layer. In general, it is evident that the maximum mass fraction is recorded at the fuel inlet and that it decreases along the fuel channel direction, due to the hydrogen consumption by electrochemical reaction.

It is evident that employing metal foam results in increased hydrogen consumption, attributed to both the more uniform distribution and the higher pressure drop, which enables the reactant gas to access the entire anode (Case b).

3.4 Current density distribution:

The distribution of current density at the anode–electrolyte interface is shown in Figures 6 and 7, with a consistent color scale maintained for comparison. Overall, the current density profiles are broadly similar for both cases. As illustrated, the electronic current density is highest near the anode inlet, where fuel concentration is maximal, and gradually decreases along the primary flow direction as hydrogen and oxygen are consumed and water and electrons are generated toward the outlet. In the direction perpendicular to the main flow, the maximum current density occurs near the channel/interconnect interfaces, where the electron transfer path is shortest. Additionally, hydrogen concentration diminishes along the cell, reaching its minimum at the outlet, which corresponds to the lowest current densities.

As depicted in Figure 7, in (case b) the current density distribution is considerably more intense and uniform a using metal foam due to the significant reactants transfer volume, and *Imax* boosts by 26.4 %.

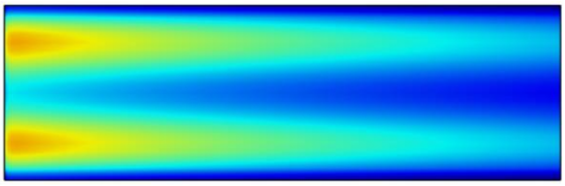


Fig.6 Distribution of current density at the IAE for conventional channel flow (A/m²)

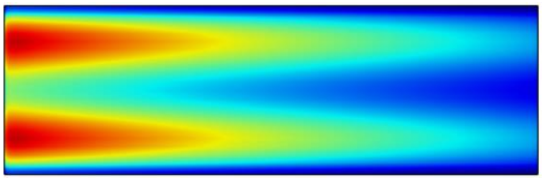
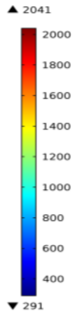


Fig.7 Distribution of current density at the IAE for channel flow with alternated baffles (A/m²)



4 CONCLUSION

A single planar solid oxide fuel cell channel including the transport equations of momentum, species, heat, electron and ion, was evolved based on the finite element method (FEM) and using computational fluid dynamics (CFD).

The using of metal foam as flow distributor is investigated to pursue its effects on the SOFC performance. The distribution of the velocity of gases in the flow channels of fuel cell is analyzed.

The study of the current density profiles for the two models revealed that using metal foam in the channel flow has an important impact on the SOFC efficiency.

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