International Journal of ELECTROCHEMICAL SCIENCE www.electrochemsci.org

Effect of Gas Flow Configurations on the Performance of MOLB-type SOFC

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Received: 7 February 2022 / Accepted: 3 March 2022 / Published: 5 April 2022

The impact of gas flow configurations on the performance of MOLB-type SOFC was studied in this work. Three-dimensional models of MOLB-type SOFC with different gas flow configurations were developed. The distribution of temperature, hydrogen mole fraction, current density and polarizations of six gas flow configurations were discussed in detail. It's found that the temperature gradient and peak temperature of SOFC can be significantly reduced by varying the gas flow configurations, which can affect the thermal stress distribution and service life of SOFC. By changing the gas flow configurations of the SOFC, the peak temperature of the cell can be reduced by 38.9K. For counter-flow configuration, the current density distribution of SOFC is more uniform, and the average current density is greater than others. The best performance is obtained when the fuel and air flow are in contrary direction, and at the same time the gas flow direction of the upper and lower layers of cells is also opposite.

Keywords: MOLB-type SOFC, Gas flow configurations, performance, temperature distribution

1. INTRODUCTION

Solid oxide fuel cells (SOFCs) have attracted widespread attention due to their advantages of great fuel flexibility, environmental protection and high efficiency. The SOFCs can directly convert chemical energy into electrical energy[1], and the conversion process is not limited to the Carnot cycle[2]. as a result, it is unnecessary to use precious metals as the catalysts[3-6]. At present, the widely used SOFCs include: planar SOFC, tubular SOFC and (mono-block layer built) MOLB-type SOFC, etc[7-9]. Among them, tubular SOFC is not conducive to commercial development due to the high manufacturing cost and low power generation. And compared to the tubular SOFC, the planar SOFC has a simpler structure and a shorter current transmission path, but it has the disadvantage of poor sealing[10, 11]. The MOLB-type SOFC adopts the corrugated PEN design, which improves the output performance of the cell by increasing the reaction area and enhances the mechanical strength of the cell[12]. Based on the above advantages, the MOLB-type SOFC has a promising research prospect.

In comparison with experimental studies, numerical simulation has been widely used as an alternative technique to provide direct insights of the experimental results[13-15]. Lots of numerical studies on SOFC have been conducted[16-19]. There are some differences between planar SOFC and MOLB-type SOFC, several works have compared the performance of the two types of SOFCs. Yang[20]compared the distribution of temperature and species concentration along the length of planar SOFC and MOLB-type SOFC. It was found that the temperature gradient of the MOLB-type SOFC was lower than that of the planar SOFC, and increasing the air flow rate would make the temperature distribution more uniform. Ramirez[21]compared the performance of planar SOFC and MOLB-type SOFC considering methane reforming reactions. The results indicated that the trends of species concentration distribution and their current density distribution are similar. However, the MOLB-type SOFC was recommend due to the lower average temperature value. The above studies show that MOLB-type SOFC has a better performance because MOLB-type SOFC has a larger electrochemical reaction area, and thus has a better research prospect.

As a relatively novel structure, MOLB-type SOFC has attracted a lot of attention owing to its higher output performance. Hwang[22]established a three-dimensional model of MOLB-type SOFC and analyzed the distribution of hydrogen and oxygen concentration, current density distribution, etc. The results showed that the mass transfer in the contact area between electrode and connector was difficult, which caused concentration polarization and made the current density distribution uneven. Ramirez[23]discussed in detail the effects of electrolyte thickness and operational parameters on SOFC, which had a great influence on the prediction of thermodynamic irreversibility. Sciacovelli[24] investigated the angle of the flow channel of the MOLB-type SOFC. The results indicated that when the channel angle changes from 107° to 117°, the distribution of current density and species concentration of MOLB-type SOFC were more uniform, and the efficiency of the cell was enhanced. Huang[25] studied the influence of structural parameters on the performance of planar SOFC and MOLB-type SOFC. It was concluded that the structural parameters had a significant influence on two types of SOFCs. However, the study only studied electrochemical performance, and lacked the analysis of gas and temperature distribution.

Gas flow configurations have a great effect on the operation and performance of SOFC. The study of gas flow configuration of SOFC has attracted extensive attention of researchers. The thermal stress distribution of the cell varies greatly under different gas flow configurations. Fan[26]compared the distribution characteristics of thermal stress under counter-flow and co-flow. The results showed that the maximum principal stress appeared around the fuel outlet under co-flow, while the maximum principal stress of SOFC in co-flow was smaller than that in counter-flow. In addition, the maximum principal stress of SOFC in co-flow was smaller than that in counter-flow. The gas flow configurations also have a great effect on the performance of the cell. Kim[27]investigated the performance of SOFC of counter-flow, parallel flow and cross flow, and analyzed the current density distribution, temperature distribution and electrochemical performance of the cell in three gas flow configurations. The results showed that the performance under parallel flow was quite different from that under other two flow modes. In addition, for methane reforming SOFC, the output performance and the distribution of carbon deposition were obviously different under different gas flow modes. Choudhary[28]simulated the operation of SOFC under counter-flow and co-flow, considering the reforming reaction. The results showed that co-

flow configuration produced less carbon deposition, but the power density in the counter-flow was 8.23% higher than that in the co-flow. Also, the gas flow configurations have a significant effect on the distribution of temperature of the SOFC stack. Fan[29]established four planar SOFC models to investigate the influence of gas flow configurations on SOFC performance. The results showed that the gas flow configurations had significant impact on the temperature distribution of the cell. Stygar[30] compared the distribution of temperature of MOLB-type SOFC in co-flow configuration and counterflow configuration. The results showed that the distribution of temperature gradient was lower in the counter-flow configuration. The above research shows that the gas flow configuration can significantly affect the performance of the cell. The research can provide theoretical guidance for SOFC design and improving durability.

However, most studies of MOLB-type SOFC focus on single-channel models, which ignore the effects between adjacent channels and between upper and lower cells. This is especially important when SOFC stacks are designed with different flow modes. Based on the above considerations, six comprehensive multi-channel three-dimensional MOLB-type SOFC models supported by an anode were developed, which coupled heat and mass transfer, fluid flow and electrochemistry. The impact of gas flow configurations on the performance of multi-channel MOLB-type SOFC was studied and analyzed. The distribution of temperature, gas concentration, current density and polarization loss of SOFC were discussed in detail, which helps to better understand the impact of gas flow configurations on the performance of MOLB-type SOFC.

2. MATHEMATICAL MODEL

2.1 Model description

A three-dimensional MOLB-type SOFC model was established to predict the performance of cell in this paper. Fig. 1 shows the schematic diagram of calculation model, which consists of anode, cathode, electrolyte, interconnector and trapezoidal flow channels.



Figure 1 Schematic diagram of the MOLB-type SOFC (a) 3D illustration, (b) cross section of the x-y plane.

The material is Ni-YSZ for the anode, LSM-YSZ for the cathode, and YSZ for the electrolyte. Fig. 1a shows the geometric construction of the MOLB-type SOFC, and Fig. 1b shows cross section of the x-y plane of MOLB-type SOFC. The detailed geometric parameters of cell are shown in Table 1.

Table 1. Geometric	parameters	of	cell
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Parameters	Value	
Cell width (mm)	32	
Cell length (mm)	32	
Anode thickness (mm)[25]	0.5	
Electrolyte thickness (mm)[25]	0.05	
Cathode thickness (mm)[25]	0.25	
Interconnector thickness (mm)[25]	0.5	
Gas flow channel height (mm)	2.5	
Total height (mm)	8.6	

In this work, six models were considered to investigate the effect of gas flow configurations on the performance of MOLB-type SOFC, as shown in Fig. 2. The six models were identical in operating conditions except the gas flow configurations.

Model 1 shows the traditional co-flow. Model 3 reverses the flow direction between the upper and lower layers on the basis of co-flow of air and fuel. Model 2 is a traditional counter-flow. Model 4 reverses the flow direction between the upper and lower layers on the basis of counter-flow of air and fuel. Model 5 and Model 6 are cross-flow between upper and lower layer, wherein Model 5 is co-flow of air and fuel, and Model 6 is counter-flow of air and fuel.





Figure 2. The models of 6 gas flow configurations

2.2 Model assumptions

In order to simplify the model, the following assumptions are made[31]:

- 1.SOFC operating state is under steady state condition
- 2. The fluid are assumed as incompressible and ideal fluid
- 3. Each channel is assigned to the same flow
- 4. The porous media is homogeneous and isotropic

2.3 Governing equations

The model is coupled with mass and heat transfer, fluid flow and electrochemical reactions, applying the following conservation equations to describe these transfer processes.

2.3.1 Mass conservation equation

The fluid flow zone includes gas channels and porous electrodes. The mass conservation equation can be described as:

$$\nabla \cdot \left(\rho \stackrel{\rightarrow}{u} \right) = W \tag{1}$$

where *u* represents the velocity, and ρ represents the density of the gas mixture. *W* is the mass source term.

In the fluid channel, W = 0. While in the anode and cathode, since the consumption of reactants and generation of products, the mass source term W can be written as[32]:

$$W = \frac{\left(M_{\rm H_2O} - M_{\rm H_2}\right)S_a i_a}{2F}, \quad W = \frac{M_{\rm O_2}S_c i_c}{4F}$$
(2)

where *F* represents the Faraday constant, S_a and S_c are the reaction area of the anode and cathode, respectively. M_{H_2O} , M_{H_2} , M_{O_2} represent the molar mass of H_2O_2 , H_2 and O_2 , respectively. i_a represents the current density for the anode, and i_c represents the current density for the cathode.

2.3.2 Momentum conservation equation

Considering the friction term, the gas flow in electrode can be expressed by the Brinkman equation:

$$\nabla \cdot \left(\frac{\overrightarrow{\rho u u}}{\varepsilon}\right) = -\varepsilon \nabla P + \nabla \left[\mu \left(\nabla \overrightarrow{u} u + \nabla \overrightarrow{u}^{T}\right) - \frac{2}{3}\mu \nabla \overrightarrow{u}\right] - \frac{\varepsilon \mu u}{\kappa}$$
(3)

where ε and κ are porosity and permeability, respectively. μ is the dynamic viscosity of the gas mixture. And *P* represents the pressure.

2.2.3 Species Conservation Equation

Considering Knudsen diffusion, the diffusion in porous electrode can be determined by Fick's law expressed as follows:

$$\nabla \cdot \left(\rho \omega_i \vec{u} \right) = \nabla \cdot \overrightarrow{J}_i + R_i \tag{4}$$

where ω_i represents the mass fraction of species *i*. R_i represents the source term of species *i*, and the source term of H₂, H₂O and O₂ can be described as[32]:

$$R_{H_2} = -\frac{M_{H_2} S_a i_a}{2F}$$
(5)

$$R_{H_2} = \frac{M_{H_2O} S_a i_a}{2F}$$
(6)

$$R_{o_2} = \frac{M_{o_2} S_c i_c}{4F}$$
(7)

 \vec{J}_i is the diffusion flux, which can be calculated by:

$$\dot{I}_i = \rho \cdot D_{i,eff} \cdot \nabla \omega_i \tag{8}$$

where $D_{i,eff}$ represents the modified diffusion coefficient, which can be described as:

$$D_{i,eff} = \frac{\varepsilon}{\tau} \left(\frac{1}{D_{mix,i}} + \frac{1}{K_{n,i}} \right)^{-1}$$
(9)

where τ is the tortuous. $D_{mix,i}$ and $K_{n,i}$ represent the average diffusion coefficient and the Knudsen diffusion coefficient of the gas mixture, respectively, which can be described as:

$$D_{mix,i} = (1 - x_i) / \sum_{j \neq i} \frac{x_j}{D_{ij}}$$

$$K_{n,i} = \frac{2}{3} r_{pore} \sqrt{\frac{8RT}{\pi M_i}}$$
(10)
(11)

where x_i and M_i represent the molar fraction and molar mass of species *i*, respectively. r_{pore} represents the average pore radius. And D_{ij} represents the binary diffusion coefficient, which can be described as:

$$D_{ij} = \frac{3.198 \times 10^{-8} T^{1.75}}{P \left(V_i^{1/3} + V_j^{1/3} \right)^2} \left(\frac{1}{M_i} + \frac{1}{M_j} \right)^{0.5}$$
(12)

where V_i represents diffusion volume of species *i*.

2.3.4 Energy conservation equation

The SOFC will generate and transfer a large amount of heat during operation, therefore, it is essential to consider the energy transfer. The energy conservation equation can be expressed as:

$$\nabla \cdot \left(\rho C_p T \stackrel{\rightarrow}{u}\right) = \nabla \cdot \left(\lambda_{eff} \nabla T\right) + Q_h \tag{13}$$

where C_p represents the specific heat, λ_{eff} represents the effective thermal conductivity, and it can be described:

$$\lambda_{eff} = \varepsilon \lambda_g + (1 - \varepsilon) \lambda_s \tag{14}$$

where λ_s and λ_g represent the thermal conductivity of solid material and gas, respectively.

 Q_h represents the heat generation/consumption, which can be expressed as:

$$Q_h = Q_{ohm,elec} + Q_{ohm,ion} + Q_{act} + Q_{chem}$$
(15)

where Q_{ohm} and Q_{act} are irreversible heat generated by ohmic polarization and activation polarization, respectively. And Q_{chem} is the reversible heat due to entropy change of electrochemical reaction.

2.3.5 Charge conservation equation

Charge transfer involves electron transfer in the electrode and ion transfer in the electrolyte. According to Ohm's law, the charge conservation equation can be written as[33]:

$$\nabla \cdot i_{elec} = \nabla \cdot \left(-\sigma_{elec}^{eff} \nabla \phi_{elec} \right) = 0 \tag{16}$$

$$\nabla \cdot \mathbf{i}_{ion} = \nabla \cdot \left(-\sigma_{ion}^{eff} \nabla \phi_{ion} \right) = 0 \tag{17}$$

where i_{elec} represents electronic current density, and i_{ion} represents ionic current density. σ_{elec}^{eff} and σ_{ion}^{eff} are the effective electronic conductivity and the effective ionic conductivity, respectively. ϕ_{elec} and ϕ_{ion} represent the electronic potential and ionic potential, respectively.

The cell voltage has polarization loss when operating, which can be calculated by:

$$V_{\text{cell}} = E^{OCV} - \left(\eta_{\text{act}} + \eta_{\text{ohm}} + \eta_{\text{conc}}\right)$$
(18)

where η_{ohm} , η_{act} , η_{conc} represent the ohmic overpotential, activation overpotential and concentration overpotential, respectively. E^{OCV} is the equilibrium potential, which can be expressed by the Nernst equation[34].

$$E^{OCV} = E_0 - \frac{R \cdot T}{2 \cdot F} \cdot \ln\left(\frac{p_{\mathrm{H}_2\mathrm{O}}}{p_{\mathrm{H}_2}\sqrt{p_{\mathrm{O}_2}}}\right)$$
(19)

where E_0 represents the open circuit voltage.

 $\eta_{act,a}$ and $\eta_{act,c}$ represent the activation overpotential of anode and cathode, respectively, which can be written as:

$$\eta_{act,a} = (\phi_{elec} - \phi_{ion}) - E_{eq,a}$$
(20)

$$\eta_{act,c} = (\phi_{ion} - \phi_{elec}) - E_{eq,c} \tag{21}$$

where $E_{eq,a}$ represents the equilibrium potential for anode, and $E_{eq,c}$ represents the equilibrium potential for cathode.

The ohmic polarization can be calculated by:

$$\eta_{\rm ohm} = \frac{il_e}{\sigma_e} \tag{22}$$

where σ_e represents the ionic conductivity of electrolyte, l_e represents the electrolyte thickness. The concentration polarization can be expressed as:

$$\eta_{\text{conc,a}} = -\frac{RT}{2F} \ln \left(\frac{P_{H_2}}{P_{H_2}^0} \frac{P_{H_2O}^0}{P_{H_2O}} \right)$$
(23)
$$\eta_{\text{conc,c}} = -\frac{RT}{4F} \ln \left(\frac{P_{O_2}}{P_{O_2}^0} \right)$$
(24)

where P_i^0 represents the inlet pressure of species *i*.

For electrochemical reactions, i_a and i_c are the current densities as the oxidation reaction and the reduction reaction, respectively, which can be expressed as the Butler–Volmer equation[35]:

$$i_{a} = S_{V}i_{0,a} \left[\frac{C_{H_{2}}}{C_{H_{2},ref}} \exp\left(\frac{n_{e}\alpha_{a}F}{RT}\eta_{act,a}\right) - \frac{C_{H_{2}O}}{C_{H_{2}O,ref}} \exp\left(\frac{-n_{e}\beta_{a}F}{RT}\eta_{act,a}\right) \right]$$
(25)
$$i_{c} = S_{V}i_{0,c} \left[\exp\left(\frac{n_{e}\alpha_{c}F}{RT}\eta_{act,c}\right) - \frac{C_{O_{2}}}{C_{O_{2},ref}} \exp\left(\frac{-n_{e}\beta_{c}F}{RT}\eta_{act,c}\right) \right]$$
(26)

where S_V represents the activation specific area, $C_{\text{H}_2, ref}$, $C_{\text{H}_2\text{O}, ref}$ and $C_{O_2, ref}$ represent the reference concentrations of H_2 , H_2O and O_2 , respectively. α and β represent the charge transfer coefficients of the electrochemical reactions. n_e is number of electrons involved in the reactions. $i_{0,a}$ is the reference exchange current density for anode, and $i_{0,c}$ is the reference exchange current density for cathode.

$$i_{0,a} = \gamma^{A} \left(\frac{p_{H_{2}}}{p_{0}} \right) \left(\frac{p_{H_{2}O}}{p_{0}} \right) \exp \left(-\frac{E_{A}}{RT} \right)$$

$$(27)$$

$$i_{0,c} = \gamma^{C} \left(\frac{p_{0_{2}}}{p_{0}}\right)^{0.25} \exp\left(-\frac{E_{C}}{RT}\right)$$
(28)

where γ^A and γ^C represent the pre-exponential coefficients for anode and cathode, respectively. E_A represents the activation energy for anode, and E_C represents the activation energy for cathode. The operation parameters and physical parameters of materials are listed in Table 2.

Table 2. Operation parameters and physical parameters of materials

Parameters Value	
Tortuosity	3 Anode, 3 Cathode
Porosity	0.4 Anode, 0.4 Cathode
Permeability (m ²)	1.7×10 ⁻¹⁰ Anode, 1.7×10 ⁻¹⁰ Cathode
Fuel composition	$90\% H_2 + 10\% H_2O$
Air composition	$21\% O_2 + 79\% N_2$
Velocity	0.5 m/s Fuel, 3m/s Air
Transfer coefficient[36]	0.5 Anode, 0.5 Cathode
Thermal conductivity of PEN	6.23 Anode, 9.6 Cathode, 2.7
(W/m·K)[37]	Electrolyte
Specific heat capacity of PEN (J/kg·K)[37]	650 Anode, 900 Cathode, 300

	Electrolyte		
Activation energy (J/mol)[37]	1.0×10^5 Anode, 1.2×10^5 Cathode		
Electronic conductivity of anode (S/m)[38]	9.5×10^7 (-1150)		
Ionic conductivity of electrolyte(S/m)[38]	$\frac{-T}{T} \exp\left(\frac{-T}{T}\right)$		
tome conductivity of electrolyte(3/m)[38]	$3.34 \times 10^4 \exp\left(\frac{-10500}{T}\right)$		
Electronic conductivity of cathode	4.2×10^7 (-1200)		
(S/m)[38]			

2.4 Boundary conditions

In this work, six flow modes were studied. And at the channel inlet, constant inlet flow rate and constant compositions are given, both fuel and air inlet temperatures are set at 1073K, the channel outlet is set at ambient atmospheric pressure. The left and right walls are set to symmetric boundary conditions, and the left and right walls are applied as adiabatic conditions. In addition, the bottom and top surfaces of the cell are set at periodic boundary conditions. Finally, the electric ground is applied to the bottom of the anode side interconnect, and the electric potential is applied to the top surface of the cathode side interconnect.

2.5 Validation of model

To verify grid-independence, the model was simulated at the grid numbers of 182176, 364352 and 728704, respectively. When the number of grids is 364352, the maximum errors of the numerical results are 2.74% and 1.16% compared with that at the number of grids of 182176 and 728704, respectively. To ensure the accuracy and efficiency of the numerical model, the number of 364352 grids was chosen in this work. In addition, to test the validity of the model, the simulation results are compared with the experimental data given by Huang[25], and the operation conditions and material parameters are consistent with those adopted in the experiment. Fig. 3 shows that the numerical results are in good agreement with the experimental results, and the error is within 4.78%, which shows the accuracy of the results of this study.



Figure 3. Comparison of simulated results with the experimental data[25] at 1073K

3. RESULTS AND DISCUSSION



Figure 4. Temperature distribution of anode-electrolyte interface under different flow modes

It is important to study the distribution of temperature, which can effectively predict the performance and reliability of the cell. Fig. 4 shows the temperature distribution of anode-electrolyte interface under six different flow modes when the operating voltage is 0.6V. As shown in Fig. 4, the temperature under the channel of SOFC is higher than that under the rib. The gas diffusion under the rib

is difficult, the electrochemical reaction intensity is weak, as a result, the less heat is generated. In addition, it is found that the temperature distribution of the six models is significant different. The temperature of Model 1 increases gradually along the length, and reaches a maximum at the outlet, while the temperature of Model 2 increases first and then decreases along the flow direction, and the highest temperature appears in the middle of the cell. In addition, the temperature gradient and the highest temperature of Model 1 are higher than that of Model 2. This indicates that for the counter-flow configurations, the distribution of temperature is more uniform and the peak temperature is lower. The highest temperature of Model 3 also appears in the middle section of the cell. This is because the hightemperature outlet of the cell is adjacent to the low-temperature inlet of the cell in the adjacent layer of Model 3. The inlet gas absorbs part of the heat of the outlet gas, resulting in a decrease in the temperature of the cell near the outlet. By comparison, it can be found that the highest temperature of Model 5 is 13.3K lower than that of Model 1. This is because the gas flow configuration of Model 5 is the cross flow of the upper and lower layers, and the channel on one side of the upper and lower layers is cooled by the low-temperature gas in the inlet section of the other layer. It is worth noting that the temperature of Model 5 increases diagonally from the inlet to the outlet due to its two-dimensional conduction direction. And the temperature distribution trend is similar to that in the study of Kim[27]. The maximum temperature of Model 6 occurs in the center of the cell and gradually decreases to the periphery, with an improved temperature distribution uniformity compared to that of Model 5. The above results show that the flow mode can significantly affect the temperature distribution of SOFC, and the peak temperature and temperature gradient can be significantly reduced by selecting the appropriate gas flow configuration, thus reducing the thermal stress and improving the durability of the cell.





Figure 5. The distribution of hydrogen mole fraction at the anode/electrolyte interface under six gas flow configurations

Fig. 5 shows the distribution of hydrogen mole fraction at the interface of anode and electrolyte under various gas flow configurations. Due to the consumption of electrochemical reaction, hydrogen mole fraction of the six models gradually decreases along the length and the minimum value is reached at the outlet. In the direction of channel width, the hydrogen mole fraction under the channel is significantly higher than that under the rib, because the diffusion resistance of the substance under the rib is much higher than that under the channel. In addition, the fuel utilization of Model 2, Model 4 and Model 6 is higher than that of Model 1, Model 3 and Model 5. The results indicate that the fuel utilization of the counter-flow configuration is higher than that of the co-flow configuration. Model 3 consumes more hydrogen than Model 1. This is because the inlet of the cell is adjacent to the outlet of the cell in the adjacent layer due to the specific gas flow configuration of Model 3, which causes an increase of the temperature of the inlet and therefore enhances the intensity of the electrochemical reaction. In Model 5, as the cooling effect of the gas at the inlet of the adjacent layer, the reaction intensity and fuel utilization are reduced. Model 4 has the highest fuel utilization due to the counter-flow configuration and higher average temperature, so the electrochemical reaction is more intense and consumes the most hydrogen.





Figure 6. The distribution of current density at anode/electrolyte interface under six flow modes

Model number	Model 1	Model 2	Model 3	Model 4	Model 5	Model 6
Average current density (A/m ²)	7282.2	7445.7	7359.2	7466.9	7199.4	7392.5

Table 3. Average current density of anode-electrolyte interface for 6 models

The current density can reflect the intensity of electrochemical reactions, which plays a key role in the output performance. The distribution of current density at the anode/electrolyte interface under six gas flow configurations are shown in Fig.6. It can be seen that the current density at the channel is significantly higher than that at the rib, because the rib limits the diffusion of reactants and causes the difference in distribution of current density. In addition, the distribution trend of current density is consistent with the hydrogen distribution trend. The maximum current density appears in the hydrogen inlet zone, and the current density decreases along the length due to the consumption of reactants, the results indicate that the distribution of current density is positively correlated with the hydrogen concentration. By comparing Model 1 and Model 5, it can be found that the peak current density of Model 1 is higher, and the variation along the length is larger than that of Model 5. This is due to the higher temperature of Model 1, which leads to smaller ohmic polarization and activation polarization; and higher output current density. By comparing the six flow modes, it can be found that the peak value of local current density in co-flow mode is higher than that in counter-flow mode, and the distribution of current density in counter-flow mode is more uniform. The average current density at the anode/electrolyte interface under six flow modes are shown in Table 3. It is found that the average current density of Model 2, Model 4, and Model 6 is higher than that of Model 1, Model 3, and Model 5, indicating that the electrochemical reaction intensity in counter-flow is higher than that in co-flow. Among them, the average current density of Model 4 is higher than that of Model 2 and Model 6, showing the best performance.



Figure 7. Local electron current density distribution at Z=0.016m for six models

The average current density of Model 4 is 3.72% higher than that of Model 5. In addition, the output performance of Model 4 is improved, and it does not cause a large temperature increase. In summary, Model 4 is recommended for the relatively uniform distribution of current density and large average current density value.

Figure 7 shows the distribution of local electron current density in the middle section of the SOFC for six models. The arrows indicate the direction of current conduction from the anode to the cathode, after which the current is collected by the connector. Due to the different structure of Model 5 and Model 6 compared with other models, the direction of current conduction in the top connector part is also slightly different. The maximum electron current density of the six models all appears at the corner

where the cathode intersects with the connector and the current is collected. In addition, by comparing 6 models, it can be found that the minimum value and maximum value of electron current density of Model 1, Model 3 and Model 5 are significantly lower than those of Model 2, Model 4 and Model 6. The results show that the electron current density in co-flow is higher than that in counter-flow, which is consistent with Fig. 6. The maximum current density of Model 4 is 6.35% higher than that of Model 5. Through the comparison of Model 2, Model 4 and Model 6, it can be found that the local electron current density of Model 4 is the largest. This is because that the electrochemical reaction of Model 4 consumes more hydrogen, which causes the increase of temperature and the decrease of ohmic polarization. And it is consistent with the trend of electrolyte current density in Fig. 6. In conclusion, the current conduction and distribution of electron current density can be improved by changing the gas flow configuration, thus improving the performance of the cell.



Figure 8. Concentration overpotential distribution of anodes for six Models at Z=0.016mm cross section

Concentration polarization occurs in the process of reactant supply, which can reflect the resistance of gas diffusion in porous electrode. Fig. 8 shows the concentration overpotential distribution

of anode at Z=0.016mm cross section of the cell for the six models. It can be found that the maximum concentration overpotential appears under the rib, and the concentration overpotential under the rib is much larger than that under the channel.



Figure 9. Average value of activation overpotential, ohmic overpotential and concentration overpotential at the anode/electrolyte interface

This is because the gas under the channel diffuses along the thickness direction of the porous electrode, and its transmission cross section area is large and the transmission path is short. Meanwhile the gas in the porous electrode under the rib diffuses along the width direction of the electrode, which makes the gas transmission path longer and results in increased diffusion resistance and difficulty in mass transmission. In addition, due to the limitation of the rib on gas diffusion, the corner effect appears at the intersection of the channel and the rib, where the concentration overpotential is slightly higher than that under the channel. The results also indicate the importance of rib design. Also, the concentration overpotential of Model 1, Model 3 and Model 5 is higher than that of Model 2, Model 4 and Model 6, indicating that the effect of substance transport in the electrode is better in the counter-flow than in the co-flow. The above results show that the flow mode plays a key role in the mass transfer of gas, and the reasonable design of flow mode is beneficial to enhance the performance of SOFC.

Various polarization losses limit the output performance of SOFC. Therefore, quantitative analysis of SOFC is helpful to better understand the influence of various overpotential on cell performance. According to equation (20)-(24), the various polarization losses of SOFC are calculated. Fig. 9 presents the average value of activation overpotential, concentration overpotential and ohmic overpotential at the anode/electrolyte interface for six gas flow configurations. It can be seen from the figure that activation polarization is dominant among the three polarization losses and the ohmic overpotential and activation overpotential, while Model 6 has the largest activation overpotential and ohmic overpotential. This is because the activation polarization and ohmic polarization are mainly affected by temperature. With the increase of SOFC temperature, the activation energy required for the reaction decreases, and the conductivity increases, and the resistance gradually decreases. In addition,

the results show that the average concentration overpotential of Model 1, Model 3 and Model 5 is higher than that of Model 2, Model 4 and Model 6, indicating that the concentration polarization of co-flow configuration is higher than that of counter-flow configuration. And this result is consistent with that of Fan's research[29]. Concentration polarization is closely related to the concentration distribution of reactants. As Model 4 consumes more reactants, the concentration distribution of reactants in the porous electrode is not uniform, so its concentration polarization is higher than that of Model 6.

4. CONCLUSION

For the purpose of studying the effect of gas flow configuration on the performance of MOLBtype SOFC, six three-dimensional MOLB-type SOFC models are established and coupled with electrochemical reaction, mass and heat transfer, fluid flow. The effects of gas flow configuration on temperature distribution, hydrogen mole fraction distribution, current density distribution and various polarization losses of MOLB-type SOFC are discussed in detail. Conclusions are as follows:

1. Changing the gas flow configuration can reduce the peak temperature and temperature gradient of SOFC, so as to reduce the thermal stress. The maximum temperature in the six flow modes decreases from 1135.6K to 1096.7K, and the change is significant.

2. The hydrogen distribution trend is similar in the six flow modes, but the fuel utilization is higher in the counter-flow mode. By reversing the flow direction of the upper and lower layers, the average temperature and temperature gradient of the cells can be reduced to achieve higher fuel utilization.

3. SOFC with counter-flow configuration has a more uniform current density distribution and a higher average current density. Compared with Model 5, Model 4 shows a 3.72% increase in average current density and is recommended for the strongest electrochemical output performance.

4. Due to the higher temperature in co-flow mode, the activation polarization and ohmic polarization are lower than those in counter-flow. Compared with the co-flow, the concentration polarization is relatively small in the counter-flow.

ACKNOWLEDGMENTS

This work is supported by the National Natural Science Foundation of China (Grant No. 21676257).

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