Effects of changes in Solid Oxide Fuel Cell Electrode Thickness on Ohmic and Concentration Polarizations

Shichuan Su^a, Qiang Zhang^a, Xiang Gao^a, Vijay Periasamy^b, and Wei Kong^{a, *}

^a School of Energy and Power Engineering, Jiangsu University of Science and Technology, 212003, Zhenjiang, Jiangsu, China

^b Department of Chemical Engineering, Curtin University, WA 6845, Australia

Corresponding author, E-mail addresses: wkong@just.edu.cn

Abstract: In order to address the shortcomings of the solid oxide fuel cell (SOFC) associated with the thin electrode, the anode-cathode-supported SOFC (ACSC) is proposed in this study. In the ACSC, the electrolyte is thin, while both the anode and cathode have enough thickness to act as self-supporting layers. The mathematical models of both the anode-supported SOFC (ASC) and ACSC are established, which capture the intricate interdependency among the charge and gas transport, and the electrochemical reactions. The validity of the mathematical model is preliminarily verified by the good agreement between the numerical and experimental I - V curves of the ASC button cell. For the same base case parameters and operating conditions, the average current density of ASC is 6388 A m⁻², only 83% of the ACSC, 7713 A m⁻². The advantages of ACSC mainly stem from two aspects: i) the increased oxygen concentration under the solid rib covered zone, which extends the reaction active zone; ii) the increased cross section of the electric current transport path, which greatly decreases the cathode ohmic polarization. The performance comparison between the ACSC and ASC are examined by systematically varying the cathode electric conductivity, porosity, tortuosity factor and the output voltage. The results indicated that the advantage of ACSC over ASC is always obvious although the performance of ACSC varies with different parameters.

Key words: Solid oxide fuel cell; Support design; Cathode thickness; Electric current collection; Oxygen transport; Numerical simulation

1. Introduction

The fuel cell, which is an eco-friendly and highly efficient power generation device, has become the research hotspot recently [1-5]. Compared with the other type of fuel cells, the solid oxide fuel cell (SOFC) has many significant advantages such as the all solid-state structure, fuel flexibility and the non-dependence on expensive catalysts. Thus, in recent years, SOFC have received much more attention [6-9].

Traditionally, a typical planar solid oxide fuel cell (SOFC) consists of the electrolyte, anode and cathode layers; and the thickest layer is the support layer to satisfy the mechanical requirement. Up to now, the SOFC can be divided into four types based on the different support designs: a) the electrolyte-supported SOFC (indicated as ESC); b) the cathode-supported SOFC (CSC); c) the anode-supported SOFC (ASC); and d) the metal-supported SOFC (MSC) [10-13]. In the past decades, ESC with a typical electrolyte thickness around 150-300 μm was widely adopted. To reduce the large ohmic potential loss caused by the thick electrolyte, the ESCs were usually operated at a high temperature region 800~1000 $^{\circ}\text{C}$ [14]. However, high operation temperature requires strict material compatibility constraints, high manufacturing costs, shorting of the lifetime and challenging operational complexity. After that, the CSC, ASC and MSC with the thin electrolytes (i.e., 10-30 μm) were designed to work around the intermediate and low temperature zone, which significantly reduce the ohmic polarizations [15, 16].

As the open circuit voltage of a single cell is only around 1 V, many single cells are assembled into a stack through interconnectors in the form of series, parallel or series-parallel connection to meet the high potential output demands [17-20]. Many grooves are milled on the interconnector to act as the gas channels to supply the reactant gases and

exhaust the products. The remaining part of the interconnectors are the ribs which maintain contact with the electrodes to collect the produced current [21]. The electric current and gases transport paths in the typical support designs are illustrated in **Fig. 1a** and **b**, respectively. Firstly, the typical widths of the channel and rib are about several millimeters [22, 23]. Thus, the transport paths of the electric current (or gas) in the x direction (parallel to the electrode surface) is greatly longer than its transport path in the y direction (normal to the electrode surface). Secondly, in the conventional CSC, ASC or MSC structure, the electrode other than the support layer is very thin, only about 50 μm . It means that the cross-sectional areas of the x direction transport paths for both the electric charges and gases in this thinner electrode are extremely small. These two factors can tremendously increase the transport resistance of the gases (or electric current) in x direction; and cause large concentration loss (or ohmic loss). Taking the ASC with a thick support anode layer as an example, the thin cathode will seriously hinder the oxygen diffusion to those three phase boundaries (TPBs) under the solid rib. A 0.46 mm wide oxygen depletion region in the cathode of ASC was reported by Liu et al., which consists of almost 23% of the TPBs [24]. Our previous study also revealed that in the anode of CSC, the hydrogen concentration under the rib is only around one third of that under the channel covered zone [25]. Jeon et al. reported a comprehensive microscale model and investigated the electronic potential loss in the cathode. In their study, the cathode consists of a 20 μm function layer and a 50 μm current collection layer, and the rib width is 2 mm. With this configuration, they found that electronic potential in the cathode primarily varies in rib width direction due to large in-plane ohmic loss caused by thin cathode, which is about 60 mV; another interesting found is that the electronic current mainly flows in cathode current layer [26]. Geisler et al.

examined the effect of rib on the ASC performance. An oxidant starvation zone was found under the rib cover zone due to the very thin cathode, which implied a dramatic slowdown in the performance. Similarly, the produced electric current density under the rib dropped from 1.6 A cm^{-2} to almost zero [18].

To overcome the shortcomings that are caused by the very thin electrode in the ASC, CSC and MSC, the anode-cathode-supported SOFC (ACSC) is proposed in this study, as illustrated in **Fig. 1c** and **d**. In the ACSC, the electrolyte is thin, while both the anode and cathode have enough thickness to act as self-supporting layers. Here, it is interesting to compare the ACSC with the NASA's bi-electrode supported SOFC (BSC) [27-29]. In order to meet the high specific power density and low weight in aerial application, the BSC incorporated gas channels into the electrodes rather than the interconnector, so the interconnector is only a thin ceramic film. In this manner, the interconnector will no longer be responsible for the distribution of gases, and only be here to separate the fuel and air. However, the ACSC configuration proposed here is totally different from NASA's architecture, simply because the ACSC keeps the original appearances and functions of interconnector and electrodes. By manipulating the electrode thickness, it overcomes the shortcomings associated with thin electrode. In this way, we create a relatively easy to implement and novel approach to this issue.

Considering that the ASC has been more widely studied than the CSC and MSC, the performances between ASC and ACSC under different conditions are calculated and compared to illustrate the advantages of the ACSC.

2. Theoretical method

2.1 Physical model

Fig. 2 depicts the cross section of a repeat cell unit in a typical planar SOFC stack, which is an anode-electrolyte-cathode single cell sandwiched between two interconnectors. Generally, the electrodes are layered, e.g., the cathode consists of cathode function layer (CFL) and cathode current collection layer (CCCL), the former provides more reaction place and the latter is responsible for the gas and charge transfer. However, based on two facts, CFL can be degraded into a boundary condition at the interface of cathode and electrolyte. First, CFL is generally thinner than CCCL and the actual electrochemical reaction depth is even shallower [18], second the CCCL thickness is the main factor that influence the gas and charge transfer, as paper [30] revealed, more electronic current flows through CCCL. So, the cathodes appear in **Fig. 1** and **Fig. 2** are actually the CCCL, which is the main concern while addressing the “high ohmic losses and oxygen starvation” in cathode. So here the function layers in cathode and anode will be treated as boundary conditions at the cathode-electrolyte and anode-electrolyte interfaces. Considering the symmetry, only half of a repeat unit is chosen as the computational domain (indicated with the blue line frame). The width of this computational domain is noted as d_{pitch} ; it's the sum of one half of the rib width d_{rib} and one half of the channel width d_{channel} . The height of the computational domain is the total thickness of the cathode, electrolyte and anode.

2.2 Charge transport

Excluding distributed charge transfer, electronic and ionic electric current densities are governed by the charge continuity equations and Ohm's law, which can be described as follows:

$$\nabla i_{\text{el}} = \nabla(-\sigma_{\text{el}}^{\text{eff}} \nabla \varphi_{\text{el}}) = 0, \quad (1)$$

$$\nabla i_{\text{io}} = \nabla(-\sigma_{\text{io}}^{\text{eff}} \nabla \varphi_{\text{io}}) = 0, \quad (2)$$

where i_{el} and i_{io} are the electronic and ionic electric current densities, respectively, φ_{el} and φ_{io} denote the local electronic and ionic potentials.

$\sigma_{\text{el}}^{\text{eff}}$ and $\sigma_{\text{io}}^{\text{eff}}$ are the effective electronic and ionic conductivities, respectively. They can be evaluated as the function of the electrode microstructure as:

$$\sigma_{\text{el}}^{\text{eff}} = \sigma_{\text{el}}^0 [(1 - \varepsilon) \phi_{\text{el}} p_{\text{el}}]^B, \quad (3)$$

$$\sigma_{\text{io}}^{\text{eff}} = \sigma_{\text{io}}^0 [(1 - \varepsilon) \phi_{\text{io}} p_{\text{io}}]^B, \quad (4)$$

where σ_{el}^0 and σ_{io}^0 are the intrinsic electronic and ionic conductivities of the dense materials, respectively. ε is the porosity, and ϕ_{el} and ϕ_{io} are the volume fractions of the electronic and ionic conductors, respectively. p_{el} (or p_{io}) is the probability of the electronic (or ionic) conductor particles to belong to the percolated clusters. B is the Bruggeman factor used to include the effect of tortuous conduction paths, which is set as 3.5 [31]. What noteworthy is that Bruggeman effective medium theory is valid when the media was composed of isotropic particles, usually spheres and cylinders, so, it cannot capture the anisotropy in some complex non-ideal structures [32]. But usually SOFC electrode is represented by random sphere packing system, so Bruggeman effective medium theory can be applied to it with careful verification, like in paper [31].

The intrinsic electric conductivities of dense Ni, LSM and YSZ materials are greatly dependent on T [30]:

$$\sigma_{\text{Ni}}^0 = 3.27 \times 10^6 - 1065.3T, \quad (5)$$

$$\sigma_{\text{LSM}}^0 = \frac{4.2 \times 10^7}{T} \exp\left(-\frac{Q_{\text{LSM}}}{T}\right), \quad (6)$$

$$\sigma_{\text{YSZ}}^0 = 3.34 \times 10^4 \exp\left(-\frac{Q_{\text{YSZ}}}{T}\right), \quad (7)$$

in which $Q_{\text{LSM}}=1150$ eV and $Q_{\text{YSZ}}=10300$ eV.

2.3 Mass transport

The dusty gas model is adopted to model the mass transport in the porous electrode structure [33, 34];

$$\frac{N_i}{D_{iK}^{\text{eff}}} + \sum_{j=1}^n \frac{x_j N_i - x_i N_j}{D_{ij}^{\text{eff}}} = -\frac{1}{RT} \left(p \nabla x_i + x_i \nabla p + x_i \nabla p \frac{kp}{D_{iK}^{\text{eff}} \mu} \right), \quad (8)$$

where N_i and $x_i = c_i / c_{\text{tot}}$ are the molar flux and molar fraction of species i , respectively; c_i is the molar concentration of species i , $c_{\text{tot}} = \sum (c_1: c_n)$, R is the universal gas constant, p is the total gas pressure, k is the permeability coefficient and μ is the viscosity coefficient.

D_{iK}^{eff} is the effective Knudsen diffusion coefficients of species i ; and D_{ij}^{eff} is the effective binary diffusion coefficient. They can be evaluated by the equations [35-37]:

$$D_{ij}^{\text{eff}} = \frac{\varepsilon}{\tau} \frac{3.198 \times 10^{-8} T^{1.75}}{p (\nu_i^{1/3} + \nu_j^{1/3})^2} \left(\frac{1}{M_i} + \frac{1}{M_j} \right)^{0.5}, \quad (9)$$

$$D_{iK}^{\text{eff}} = \frac{\varepsilon}{\tau} \frac{2}{3} r_g \sqrt{\frac{8RT}{\pi M_i}}, \quad (10)$$

$$r_g = \frac{2}{3} \frac{\varepsilon}{1 - \varepsilon} \frac{1}{\phi_{\text{el}} / r_{\text{el}} + \phi_{\text{io}} / r_{\text{io}}}, \quad (11)$$

where τ is the tortuosity factor, ν_i and M_i are the diffusion volume and molecular mass of species i , respectively, r_g is the pore radii, r_{el} (or r_{io}) is the average radius of the electronic (or ionic) conductor.

2.4 Boundary conditions

As described above, the mass transport and charge transport equations are taken into account in this model. Appropriate boundary conditions are required to solve these coupled

partial differential equations. **Table 1** gives the boundary conditions for both the electron and ion conduction equations. Due to the oxidation of the steel rib, the effect of the contact resistance at the rib-electrode interface is considered. The electric current densities that pass through both the rib-anode interface $i_{\text{rib} \rightarrow \text{An}}$ and the rib-cathode interface $i_{\text{Ca} \rightarrow \text{rib}}$ can be related to the contact resistances as:

$$i_{\text{rib} \rightarrow \text{An}} = \frac{\varphi_{\text{e,rib/An}} - \varphi_{\text{e,An/rib}}}{ASR_{\text{contact}}}, \quad (12)$$

$$i_{\text{Ca} \rightarrow \text{rib}} = \frac{\varphi_{\text{e,Ca/rib}} - \varphi_{\text{e,rib/Ca}}}{ASR_{\text{contact}}}, \quad (13)$$

where ASR_{contact} is the contact resistance at the rib-electrode interface. For the rib-anode interface, $\varphi_{\text{e,rib/An}}$ and $\varphi_{\text{e,An/rib}}$ are the electric potentials at the rib and anode side, respectively; and the definitions are analogous for $\varphi_{\text{e,Ca/rib}}$ and $\varphi_{\text{e,rib/Ca}}$ at the rib-cathode interface.

In **Table 1**, $i_{\text{trans}}^{\text{an}}$ and $i_{\text{trans}}^{\text{ca}}$ are the transfer electronic and ionic electric current densities in anode and cathode sides, respectively, which can be calculated by Butler-Volmer equations indicated below. In order to derive the apparent dependences on partial pressure, some assumptions are made [38]: for hydrogen oxidation, five reaction steps are counted in the anode TPB, which involve six surface species and two gas-phase species, and the rate-limiting reaction is: $\text{H}(\text{Ni}) + \text{OH}^-(\text{YSZ}) \rightarrow \text{Ni} + \text{H}_2\text{O}(\text{YSZ}) + \text{e}^-(\text{Ni})$. For oxygen reduction, two reaction steps are considered: an adsorption-desorption step and a charge-transfer step, and the latter is assumed to be rate-limiting.

$$i_{\text{trans}}^{\text{an}} = i_{\text{ref}}^{\text{an}} \exp\left(-\frac{E_{\text{H}_2}}{R} \left(\frac{1}{T} - \frac{1}{T_{\text{ref}}}\right)\right) \left(\frac{p_{\text{H}_2}^{\text{TPB}} p_{\text{H}_2\text{O}}^{\text{TPB}}}{p_{\text{H}_2}^0 p_{\text{H}_2\text{O}}^0}\right) \left[\exp\left(\frac{2\alpha_{\text{f}}^{\text{an}} F}{RT} \eta_{\text{act}}^{\text{an}}\right) - \exp\left(-\frac{2\beta_{\text{r}}^{\text{an}} F}{RT} \eta_{\text{act}}^{\text{an}}\right)\right], \quad (14)$$

$$i_{\text{trans}}^{\text{ca}} = i_{\text{ref}}^{\text{ca}} \exp\left(-\frac{E_{\text{O}_2}}{R}\left(\frac{1}{T} - \frac{1}{T_{\text{ref}}}\right)\right)\left(\frac{p_{\text{O}_2}^{\text{TPB}}}{p_{\text{O}_2}^0}\right)^{0.25} \left[\exp\left(\frac{2\alpha_f^{\text{ca}} F}{RT} \eta_{\text{act}}^{\text{ca}}\right) - \exp\left(-\frac{2\beta_r^{\text{ca}} F}{RT} \eta_{\text{act}}^{\text{ca}}\right)\right], \quad (15)$$

herein, $\eta_{\text{act}}^{\text{an}}$ and $\eta_{\text{act}}^{\text{ca}}$ are the anode and cathode activation over-potentials, respectively:

$$\eta_{\text{act}}^{\text{an}} = \varphi_{\text{el}} - \varphi_{\text{io}} - \eta_{\text{conc}}^{\text{an}} = \varphi_{\text{el}} - \varphi_{\text{io}} - \frac{RT}{2F} \ln\left(\frac{p_{\text{H}_2}^0}{p_{\text{H}_2\text{O}}^0} \frac{p_{\text{H}_2\text{O}}^{\text{TPB}}}{p_{\text{H}_2}^{\text{TPB}}}\right), \quad (16)$$

$$\eta_{\text{act}}^{\text{ca}} = \varphi_{\text{io}} - \varphi_{\text{el}} - \eta_{\text{conc}}^{\text{ca}} = \varphi_{\text{io}} - \varphi_{\text{el}} - \frac{RT}{4F} \ln\left(\frac{p_{\text{O}_2}^0}{p_{\text{O}_2}^{\text{TPB}}}\right), \quad (17)$$

where α_f and β_r are the forward and reverse reaction symmetry factors, respectively;

E_{H_2} and E_{O_2} are the activation energies for the anode and cathode electrochemical reactions, respectively. T_{ref} is the reference temperature, $i_{\text{ref}}^{\text{an}}$ and $i_{\text{ref}}^{\text{ca}}$ are often deduced from experiments or assigned empirically at the reference temperature T_{ref} and F is the Faraday constant. $\eta_{\text{conc}}^{\text{an}}$ and $\eta_{\text{conc}}^{\text{ca}}$ are the anode and cathode concentration over-potentials.

p_i^0 is the partial pressure of reactant species i at the fuel (or air) channel-electrode interface.

p_i^{TPB} is the local partial pressure of i at the TPB reaction sites.

Table 2 lists the boundary settings for the mass transport equations. Since the electrochemical reactions are assumed to happen around the electrode-electrolyte interface, the species molar sources are set on the corresponding boundaries.

2.5 Model parameters and model validation

The model is implemented in the commercial finite element software COMSOL MULTIPHYSICS[®]. The Direct solver MUMPS is used to solve the coupled charge transport and gas transport equations with a relative convergence tolerance of 1×10^{-6} . A rectangular structured grid is used to discretize the geometric construction.

To verify the validity of the model, a button cell with the same parameters and settings from [39] is built and tested. All relevant parameters, including those from the reference and those fitted, are listed in **Table. 3**. **Fig. 3** shows the comparison of the numerical results with the experimental I - V relationship. The numerical model result matches very well with the experiment result, thus justifies the parameters and settings of the button cell model. After validating this group of parameters and settings, a planer SOFC model channel width $w_{\text{ch}}=1.0$ mm and rib width $w_{\text{rib}}=1.0$ mm is built based on the same conditions (unless specified differently) for a following study.

For the following study on planar SOFC, two kinds of meshes with different sizes are built to ensure the mesh independence of the calculated result. Mesh A has 1120 cells, while the mesh B has 2400 cells. The calculated result shows that the deviation between the result from mesh A and the result from mesh B is less than 0.01%; and the mesh A is adopted in the following research.

3. Results and discussion

3.1 Comparison of physical quantity distribution

In order to investigate the performance discrepancy between the ASC and ACSC, two models are developed with the same parameters and settings as described in Table 3, except for the thicknesses of the electrode layers. The anode and cathode thicknesses of the ASC model are 0.5 and 0.05 mm, respectively, while the corresponding values for the ACSC model are 0.35 and 0.35 mm, respectively. With the model parameters in Table 3 (basis case), the calculated average current density of ASC is $i_{\text{ave}}=6388 \text{ A m}^{-2}$, which is 17% less than the current density of the ACSC, $i_{\text{ave}}=7713 \text{ A m}^{-2}$. The performance discrepancy between the ASC and the ACSC may be attributed to the different ohmic and concentration

polarizations in electrodes: the average ohmic polarization in cathode of ACSC stack is 4.8 mV, which is only about one fifth of that in ASC (27 mV). Similarly, the average concentration polarization in cathode of ACSC is 35 mV, while that of ASC is 99 mV. On the contrary, the average ohmic and concentration polarizations in anode of ACSC are 0.32 mV and 19 mV, respectively, which close to that in ASC 0.25 mV and 15 mV. As a result, the total ohmic and concentration polarizations in the ACSC are quite smaller than that in the ASC, which is the main reason for the ACSC better performance.

To further analyze the reason for this discrepancy, the distributions of oxygen concentrations, current densities and potentials in both the ACSC and ASC are examined in the following. **Fig. 4a** illustrates the distribution of oxygen concentration within the ASC cathode. Although the c_{O_2} in y direction is distributed uniformly, it varies considerably in x direction. Especially in the zone covered by the cathode rib, the c_{O_2} is quite small; and the minimum c_{O_2} is only $2.03 \times 10^{-6} \text{ mol m}^{-3}$. This is because that a very thin cathode will extremely limits the oxygen diffusion in the x direction. Compared with ASC, the ACSC cathode has more wide variation of c_{O_2} in the y direction (shown in **Fig. 4b**), because the relative thicker cathode extends the oxygen transmission distance in y direction. However, it is interesting to note that the relatively thicker cathode would also provide a wider alleyway to enhance the oxygen transport along the x direction. Therefore, as shown in **Fig. 4c**, for the $x > 1.2 \text{ mm}$ zone, the c_{O_2} under the rib cover zone in an ACSC is significantly larger than that in an ASC.

Fig. 4c shows the comparison of the c_{O_2} distributions over the cathode-electrolyte interface in the ASC and the ACSC. Obviously, for a typical ASC, the oxygen

concentration beyond the $x > 1.4$ mm zone is very close to zero. This phenomenon has also been encountered in paper [18, 30], which is to a great degree caused by the high current and thin cathode thickness. So, numerically, the electrochemical reaction can't occur in this zone due to the lack of the oxygen. Consequently, the produced current density is almost zero in this zone, as shown in **Fig. 4d**. For the ACSC, however, the c_{O_2} distributions within the rib covered zone (i.e., the $x > 1.2$ mm zone) are larger than that in an ASC. This means larger electric current density can be produced within cathode rib covered zone of the ACSC cathode than that in the ASC. It is worth to note that although the c_{O_2} over the cathode-electrolyte interface under the channel covered zone of ACSC ($x < 1$ mm) is smaller than that of ASC, their produced electric current densities are similar. That is attributed to the lower ohmic loss in the ACSC than in the ASC, which is further supported by the calculated electric potential shown in **Fig. 5**. In conclusion, compared with the ASC, the ACSC design can greatly improve the oxygen concentration under the rib covered zone in the cathode side and extend the active reaction zone thereby significantly improving the cell performance. In other words, the extremely thin cathode thickness is an important factor that contributes to the performance reduction of the ASC stack.

Fig. 5 shows the cathode potential distributions both within the ASC and the ACSC. In the ASC cathode, although there is a small electric potential gradient in y direction, a large gradient is seen in the x direction. The electric potential, φ_{el} , drops from 0.781 to 0.729 V, which means the ohmic polarization within the cathode of the ASC is 52 mV. This notable cathode ohmic over-potential of the ASC stack is attributed to the following two factors: i) the narrow cross-section of electric current transport path in the x direction; ii) the relatively small cathode electrical conductivity. Apparently, the cathode ohmic

polarization within the ACSC cathode is only 8 mV, which is less than one sixth of that in the ASC. From these results, it is apparent that the ACSC cathode benefits from a larger cathode thickness, which provides a larger cross-sectional area for the electric current transport path in the x direction, the lack of which is the main factor contributing to the poor performance of the ASC stack.

3.2 The effect of parameters and operating conditions

In this section, the effects of cell parameters and operating conditions on its performance are compared for the ASC and the ACSC designs. As shown in **Fig. 6**, the differences between the ACSC and ASC performances decrease with the increasing of the cathode conductivity. The performance of ASC is sensitive to cathode conductivity. While the cathode conductivity increases from 769.2 to 7692 S m⁻¹, the average output current density increases by 38%. This conclusion can be supported by **Fig. 5**. The performance of the ASC will be greatly increased by increasing the cathode conductivity, because of the very serious cathode ohmic polarization caused by the narrow cross section of the electric conducting path in the x direction. On the contrary, as the ohmic loss in the ACSC cathode is already very small, limited effect on the performance can be obtained by increasing the electric conductivity. As shown in **Fig. 6**, the average current density of the ACSC only increased by 1.2%, while the electric conductivity of the cathode increases from 3077 to 7692 S m⁻¹.

Fig. 7 depicts the dependence of the average current density on the cathode porosity. Apparently, the performance of the ACSC is much better than that of the ASC for any practical cathode porosity. Furthermore, the gap between ACSC and ASC increases with increase in cathode porosity. It is interesting to note that although larger cathode porosity

can cause smaller cathode concentration polarization, the performance of the ASC decrease with the increasing of the cathode porosity. That is attributed to the serious cathode ohmic polarization caused by the thin ACS cathode thickness. Although the bigger cathode porosity leads to a smaller concentration loss, it might also greatly reduce the cathode electric conductivity resulting in the increase of the x direction conducting resistance that leads to a more serious ohmic polarization loss. Thus, the performance of the ASC decreases with the increase of the cathode porosity due to the increase of the total loss.

Fig. 8 shows the impact of the tortuosity factor on the average current density. With the increase of the cathode tortuosity factor, the average current density gradually reduces. The average current densities drop 18% and 8% for ACSC and ASC, respectively, while the cathode tortuosity factor increases from 2 to 5. This is because the cathode concentration polarization in ACSC is greater than that in ASC due to a thicker cathode layer. However, it should be noted that even for the unusually large tortuosity factor case, the performance of the ACSC with a thicker cathode is better than that of the ASC.

Fig. 9 gives the output current density of ASC and ACSC in the range of the typical output potential zone. It is evident that two curves are nearly parallel to each other. This result indicates that the ACSC has a constant advantage over the ASC irrespective of the variations of both the output current and the output potential.

4. Conclusions

This study has proposed a novel bi-electrode supported solid oxide fuel cell (ACSC) design. To establish the advantages of the ACSC, both the ASC and the ACSC models are established. The oxygen concentration distribution and electric potential distribution within the ASC and ACSC cathodes are compared in detail. Furthermore, the performance

differences between the ASC and ACSC are carefully investigated in the wide ranges of the cathode electric conductivity, porosity, tortuosity factor and the output electric potential.

The conclusions are summarized as follows:

i) With the basis case parameters, the average current density of the ASC is 17% compared with that of the ACSC;

ii) The ACSC design improves the oxygen concentration distributions under the rib covered zone, extends the active reaction zone and reduces the cathode ohmic loss. The cathode electric potential difference is only 8 mV, which is less than one sixth of that in ASC;

iii) Although the difference in the performance between the ACSC and the ASC changes with the variation of the cathode electric conductivity, porosity, tortuosity factor, and output electric potential, the ACSC always out-performs the ASC.

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Table. 1

Equation	Boundary	Rib-cathode interface	Rib-anode interface	Cathode-electrolyte interface	Anode-electrolyte interface	Others
Electron conduction equation	Boundary type	Reference potential ($\varphi_{e,rib/Ca}$)	Reference potential ($\varphi_{e,rib/An}$)	Normal inward current density	Normal inward current density	Electric Insulation
	Boundary setting	$V_{op}(0.7)$	E_0	i_{trans}^{ca}	$-i_{trans}^{an}$	
Ion conduction equation	Boundary type			Inner current source	Inner current source	Electric Insulation
	Boundary setting			$-i_{trans}^{ca}$	i_{trans}^{an}	

Note: ("Electric Insulation" means that the normal component of the electric current is zero).

Table. 2

Equation	Boundary	Anode-channel interface		Anode-electrolyte interface		Others
Fuel transport equation	Boundary Type	H ₂ molar concentration	H ₂ O molar concentration	H ₂ normal inward molar flow	H ₂ O normal inward molar flow	Insulation
	Boundary setting	$c_{\text{H}_2}^0 = p_{\text{H}_2}^0 / RT$	$c_{\text{H}_2\text{O}}^0 = p_{\text{H}_2\text{O}}^0 / RT$	$-i_{\text{trans}}^{\text{an}} / 2F$	$i_{\text{trans}}^{\text{an}} / 2F$	
	Boundary	Cathode-electrolyte interface		Anode-electrolyte interface		Others
Air transport equation	Boundary Type	O ₂ molar concentration	N ₂ molar concentration	O ₂ normal inward molar flow	N ₂ normal inward molar flow	Insulation
	Boundary setting	$c_{\text{O}_2}^0 = p_{\text{O}_2}^0 / RT$	$c_{\text{N}_2}^0 = p_{\text{N}_2}^0 / RT$	$-i_{\text{trans}}^{\text{ca}} / 4F$	0	

Table. 3

Parameter	Value
Fuel input mass flow rate (gr/s) [39]	0.000094
Air input mass flow rate (gr/s) [39]	0.0049
Input air temperature (°C) [39]	800
Input fuel temperature (°C) [39]	800
Input hydrogen mole fraction [39]	0.8
Input air and fuel pressure (kpa) [39]	101
Anode thickness (mm) [39]	0.5
Electrolyte thickness (mm) [39]	0.025
Cathode thickness (mm) [39]	0.03
Tortuosity τ	3.5
Porosity $\mathcal{E}$	0.3
Pore radii r_g (m)	5×10^{-7}
Activation energies for cathode E_{O_2} (J mol ⁻¹)	130×10^3
Forward and reverse reaction symmetry factors of cathode α_i^{ca} , β_i^{ca}	0.75, 0.5
Empirical constant i_{ref}^{ca} (A m ⁻¹)	860
Empirical constant i_{ref}^{an} (A m ⁻¹)	2000
Activation energies for cathode E_{H_2} (J mol ⁻¹)	120×10^3
Forward and reverse reaction symmetry factors of anode α_i^{an} , β_r^{an}	1, 0.5
Open circuit voltage V_{op} (V)	0.7
Contact resistance $ASR_{contact}$ (Ω cm ²)	0.03

Fig. 1

Fig. 2

Fig. 3

Fig. 4 (a)

Fig. 4 (b)

Fig. 4 (c)

Fig. 4 (d)

Fig. 5 (a)

Fig. 5 (b)

Fig. 6

Fig. 7

Fig. 8

Fig. 9