



Effect of thickness of $Gd_{0.1}Ce_{0.9}O_{1.95}$ electrolyte films on electrical performance of anode-supported solid oxide fuel cells

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ABSTRACT

In the present paper, we investigated the electrical performance of anode-supported solid oxide fuel cells (SOFCs) composed of $Gd_{0.1}Ce_{0.9}O_{1.95}$ (GDC) electrolyte films of 1–75 μm in thickness prepared by simple and cost-effective methods (dry co-pressing process and spray dry co-pressing process), and discussed the effect of thickness of the GDC electrolyte films on the electrical performance of the anode-supported SOFCs. It was shown that reducing the thickness of the GDC electrolyte films could increase the maximum power densities of the anode-supported SOFCs. The increase of the maximum power densities was attributed to the decrease of the electrolyte resistance with reducing the electrolyte thickness. However, when the thickness of the GDC electrolyte films was less than a certain value (approximately 5 μm in this study), the maximum power densities decreased with the decrease in the thickness of the GDC electrolyte films. The calculated electron fluxes through the GDC electrolyte films increased obviously with reducing the thickness of the GDC electrolyte films, which was the reason why the maximum power densities decreased. Therefore, for anode-supported SOFCs based on electrolytes with mixed electronic–ionic conductivity, there was an optimum electrolyte thickness for obtaining higher electrical performance.

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1. Introduction

Low temperature solid oxide fuel cells (SOFCs) have attracted much attention due to low operating temperatures enhancing the long-term performance stability, widening the material selection, lessening the sealing problem, enabling the use of low-cost metallic interconnects and accelerating the commercialization of SOFCs [1–3]. However, low operating temperatures result in the increase of electrolyte resistance and high electrode overpotential, which reduce the electrochemical performance of SOFCs. In order to lower the operating temperature of SOFCs while keeping their electrochemical performance, the following approaches are normally adopted: reducing the electrolyte thickness, developing alternative electrolyte materials with high ionic conductivity at low temperatures, and minimizing electrode polarization resistance [4–6]. Over the past few years, considerable effort has been devoted to the development of anode-supported SOFCs based on a thin-film electrolyte of doped ceria [7–19].

Good electrical performance has been obtained for anode-supported SOFCs with ceria-based electrolyte films. For instance,

Zhen et al. [11] applied a spin-coating method to fabricate an anode-supported single cell that consisted of a 19 μm $Gd_{0.2}Ce_{0.8}O_{1.9}$ (GDC) electrolyte, a Ni-GDC anode and a $La_{0.6}Sr_{0.4}Co_{0.2}Fe_{0.8}O_3$ (LSCF)-GDC cathode. The single cell exhibited a maximum power density of 386 mW cm^{-2} at 600 °C. Xia et al. [12] developed a screen-printing method to prepare a $Sm_{0.2}Ce_{0.8}O_{1.9}$ (SDC) electrolyte film with the thickness of 30 μm and demonstrated a maximum power density of 397 mW cm^{-2} at 600 °C for a single cell with a Ni-SDC anode and a $Sm_{0.5}Sr_{0.5}CoO_3$ (SSC)-SDC cathode. Leng et al. [13] successfully fabricated an anode-supported SOFC with thin-film GDC electrolyte of 10 μm prepared *in situ* by solid-state reaction and showed a maximum power density of 578 mW cm^{-2} at 600 °C for a single cell assembled with a LSCF-GDC cathode and a Ni-GDC anode. Hibino et al. [18,19] fabricated an anode-supported single cell with GDC electrolyte film of approximately 20–40 μm in thickness by a spin-coating method, and showed a maximum power density of 769 mW cm^{-2} at 600 °C for a single cell with a SSC cathode and a Ni-GDC anode. Though high quality electrolyte films have been fabricated and high electrical performance has been achieved, no effect of thickness of electrolyte film on the electrical performance of anode-supported SOFCs is investigated in detail. That is, there is no report about the optimization thickness of electrolyte films.

There are certain theoretical and practical limitations to the reduction in electrolyte thickness that can be achieved. Steele [20]

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investigated ceramic ion conducting membranes and discussed the effect of electrolyte thickness on the surface exchange and diffusion coefficient of oxygen. Results showed that at a certain thickness the surface exchange reaction of oxygen becomes the rate-limiting step and thus further reduction in thickness is unsuitable for improving the surface exchange and diffusion of oxygen. From a practical standpoint, it is difficult to prepare electrolyte thin films of less than 1 μm without small pinholes or cracks which may decrease the electrical performance of anode-supported SOFCs [21]. In addition, doped ceria is prone to be reduced under reducing conditions [22]. The reduction of ceria from Ce^{4+} to Ce^{3+} may give rise to electronic conduction of ceria and thus result in a non-negligible loss in the open circuit voltage (OCV) of SOFC due to internal short circuit. The reduction of ceria may also cause lattice expansion of the ceria electrolyte at the fuel side and thereby lead to mechanical stability problems with the cell [23]. Thus, the effect of reduction of doped ceria electrolytes has to be considered when the thickness of doped ceria electrolytes is less than a certain value. Therefore, the unlimited reduction in the thickness of doped ceria electrolytes may be unsuitable for improving the electrochemical performance of anode-supported SOFCs. Thus, in this study, the main purpose is to investigate the relationship of thickness of GDC electrolyte films and electrical performance of anode-supported SOFCs based on the GDC electrolyte films.

To investigate the relationship of electrolyte film thickness and electrical performance, the preparation of gas-tight electrolyte films with different thickness is very important. Various film deposition techniques have been developed to prepare dense electrolyte films on porous substrate [4,11–19,24]. Each technique has its advantages and disadvantages. In this study, the GDC electrolyte films with different thickness were prepared by simple and rapid methods: dry co-pressing method and spray dry co-pressing method. The electrical performance of anode-supported SOFCs based on the GDC electrolyte films was investigated, and the effect of thickness of GDC electrolyte films on the electrical performance of anode-supported SOFCs was presented and discussed.

2. Experimental

2.1. Fabrication of anode-supported SOFCs

$\text{Gd}_{0.1}\text{Ce}_{0.9}\text{O}_{1.95}$ (GDC) nanopowders (Anan Kasei Co. Ltd., Japan) were used as electrolyte material. NiO-GDC nanocomposite powders synthesized by co-precipitation method [25] were used as anode material. $\text{La}_{0.8}\text{Sr}_{0.2}\text{Co}_{0.8}\text{Fe}_{0.2}\text{O}_3$ (LSCF) nanopowders synthesized by sol-gel method [26] were used as cathode material. To prepare anode-supported SOFCs with GDC electrolyte films of different thickness, the dry co-pressing and spray dry co-pressing processes were adopted.

The anode-supported SOFCs with thick GDC electrolyte films were fabricated by the dry co-pressing process. The NiO-GDC nanocomposite powders were pressed in a steel die of 20 mm diameter to form green NiO-GDC anode substrate. The GDC nanopowders were then added onto the surface of the green NiO-GDC anode substrate which was still contained in the steel die. And then, the GDC powder layer and NiO-GDC anode substrate were co-pressed at 100 MPa to form a green bilayer and subsequently co-sintered at 1300 °C for 5 h to form a dense GDC electrolyte film. The thickness of the GDC electrolyte film was controlled by changing the additive amount of the GDC nanopowders. Here, the GDC electrolyte films with the thickness of 16–75 μm were prepared. To prepare cathodes, the LSCF nanopowders were ball-milled with an organic vehicle to form LSCF cathode paste. The LSCF cathode paste was then screen-printed on the GDC electrolyte films supported

by the NiO-GDC substrates and sintered at 900 °C for 2 h to form completed single cells.

The anode-supported SOFCs with thinner GDC electrolyte films were fabricated by the spray dry co-pressing process. First, the GDC nanopowders were dispersed uniformly into methanol by ultrasonic dispersion to form GDC powder suspension. The NiO-GDC nanocomposite powders were then pressed uniaxially in the steel die of 20 mm diameter to form green NiO-GDC anode substrate. And then, the GDC powder suspension was spray-coated onto the pre-pressed green NiO-GDC anode substrate which was still contained in the steel die. The wet coating was dried naturally. After multiple coatings were done, the GDC powder layer and NiO-GDC anode substrate were co-pressed at 100 MPa to form a green bilayer and subsequently co-sintered at 1300 °C for 5 h to form a dense GDC electrolyte film. The thickness of one-pass spray-coated GDC powder layer was about 0.25 μm . The thickness of the GDC electrolyte films was controlled by changing the number of spray-coated GDC powder layers. Here, the GDC electrolyte films with the thickness of 1–30 μm were prepared. Finally, the LSCF cathode paste was screen-printed on the GDC electrolyte films supported by the NiO-GDC anode substrates and sintered at 900 °C for 2 h to form completed single cells.

2.2. Characterization of anode-supported SOFCs

Electrochemical performance of the fabricated anode-supported single cells with the GDC electrolyte films of different thickness was evaluated by means of an in-house test station. The single cell was placed between two concentric Al_2O_3 tubes. The sealing between the outer Al_2O_3 tubes and the cell was obtained by melting glass rings. The test section was initially heated up to 800 °C at a heating rate of 100 °C h⁻¹ and held for 2 h to melt the glass rings and form the glass sealing. After glass sealing, it was cooled down to testing temperature. Humidified H_2 (3 vol.% H_2O) was fed to the anode chamber and oxygen was supplied to the cathode chamber at a flow rate of 100 ml min⁻¹. The NiO in the anode was reduced to Ni *in situ* in the hydrogen atmosphere. The current–voltage (*I*–*V*) characteristics of the anode-supported SOFCs were measured at 500–600 °C. The microstructure and morphology of the anode-supported SOFCs after performance testing were examined by a field-emission scanning electron microscopy (FE-SEM, S4300, Hitachi, Japan).

3. Results and discussion

3.1. Microstructure of anode-supported SOFCs

After electrical performance tests, the microstructure of the anode-supported single cells was observed by SEM. Fig. 1 shows the typical cross-sectional SEM micrographs of the anode-supported single cells with the GDC electrolyte films of different thickness prepared by the dry co-pressing process and spray dry co-pressing process. It has been confirmed from SEM observations that all the anodes and cathodes are porous, crack-free and have uniform thickness. The only difference in all the prepared anode-supported single cells is the thickness of the GDC electrolyte films. The thickness of the GDC electrolyte films for the anode-supported single cells fabricated by the dry co-pressing process is 16, 30, 40, 50 and 75 μm , respectively. The thickness of the GDC electrolyte films for the anode-supported single cells fabricated by the spray dry co-pressing process is 1, 2, 3, 4 and 30 μm , respectively.

In addition, it can also be seen from Fig. 1 that all the GDC electrolyte films prepared by the dry co-pressing process and spray dry co-pressing process are dense except for some isolated pores and well adhered to the porous Ni-GDC anodes, and have

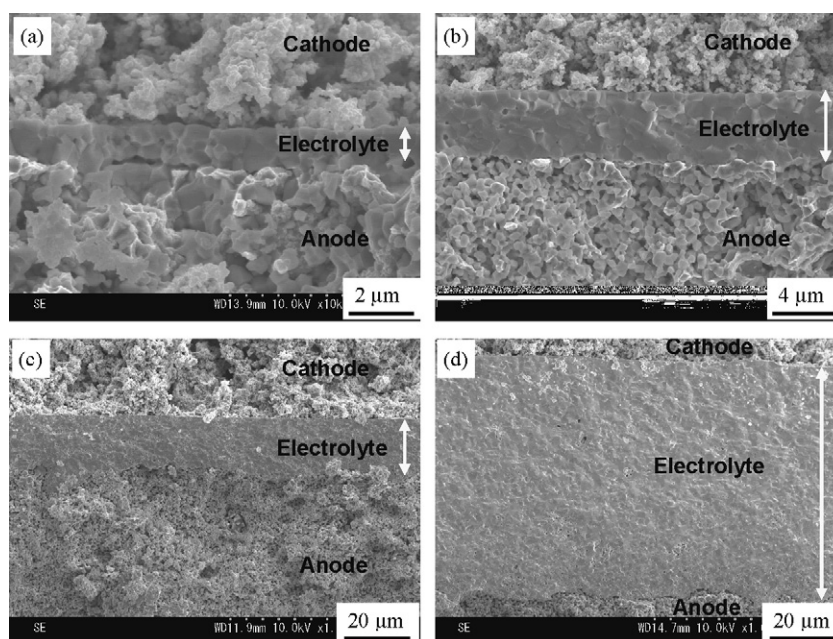


Fig. 1. Cross-sectional SEM micrographs of the anode-supported single cells with the GDC electrolyte films of (a) 1 μm , (b) 4 μm , (c) 16 μm and (d) 75 μm .

uniform thickness with the standard deviation of less than 3.7 μm for the GDC electrolyte films prepared by the dry co-pressing process and 0.3 μm for the GDC electrolyte films prepared by the spray dry co-pressing process. There are no cracks and delamination observed at the interface between the electrolyte and the electrodes, which indicates that the GDC electrolyte films prepared by the dry co-pressing process and spray dry co-pressing process have high mechanical stability.

3.2. I–V characteristics and effect of electrolyte thickness

The current–voltage and current–power density characteristics of the anode-supported single cells with the GDC electrolyte films of different thickness prepared by the dry co-pressing process and spray dry co-pressing process are shown in Fig. 2. It can be seen that the cell voltage decreases linearly with an increase in the current density for the electrolyte thickness of less than 16 μm . This result indicates that the ohmic polarization is mainly responsible for the reduction of cell voltage. For the electrolyte thickness of 75 μm , non-linear relationship between cell voltage and current density can be observed as in Fig. 2d at the lower current density regime, which may be attributable to the activation polarization contributing to the reduction of cell voltage at lower current density levels. The effect of the operating temperature on the OCV is summarized in Table 1. The OCV is seen to decrease with an increase in the operating temperature. The power density increases with increasing the operating temperature and all single cells show typical electrical performance.

Table 1
OCVs at different temperatures of the anode-supported single cells with different electrolyte thickness.

Electrolyte thickness (μm)	OCV (V)		
	500 °C	550 °C	600 °C
2	0.85	0.83	0.81
4	0.96	0.94	0.91
16	0.96	0.94	0.92
75	0.99	0.97	0.95

The different anode-supported single cells show different electrical performance. Furthermore, it can be seen from Fig. 2 that the electrical performance of the anode-supported SOFCs depends strongly on the thickness of the GDC electrolyte films when keeping other conditions identical. With the change of the thickness of the GDC electrolyte films, the electrical performance of anode-supported single cells also changes, and the maximum power density at 600 °C of the anode-supported single cells as a function of thickness of the GDC electrolyte films is shown in Fig. 3a.

In the anode-supported single cells fabricated by the dry co-pressing process, the anode-supported single cell with 16 μm GDC electrolyte film demonstrates the highest electrical performance, as shown in Fig. 2c. The maximum power densities are 174, 363 and 644 mW cm^{-2} at 500, 550 and 600 °C, respectively. These power densities are higher than those for anode-supported single cells with ceria-based electrolyte films of 10–30 μm in thickness reported in the previous literatures [11–13]. This indicates that the anode-supported single cells in this study have good electrical performance. With increasing the thickness of the GDC electrolyte films from 16 to 75 μm , the maximum power density at 600 °C decreases from 644 to 165 mW cm^{-2} .

In the anode-supported single cells fabricated by the spray dry co-pressing process, the anode-supported single cell with 4 μm GDC electrolyte film shows the highest electrical performance, as shown in Fig. 2b. The maximum power densities are 325, 548 and 771 mW cm^{-2} at 500, 550 and 600 °C, respectively. The maximum power densities of the anode-supported single cell with 4 μm GDC electrolyte film are higher than that of the anode-supported single cells with 16 μm GDC electrolyte film prepared in this study and with 20–40 μm GDC electrolyte film reported in the literatures [18,19]. This shows that better electrical performance is obtained by reducing the thickness of the GDC electrolyte film. However, with decreasing the thickness of the GDC electrolyte films from 4 to 1 μm , the maximum power density at 600 °C decreases from 771 to 94 mW cm^{-2} .

In addition, the electrical performance of the anode-supported single cell with the GDC electrolyte film of 30 μm prepared by the spray dry co-pressing process is similar to the electrical performance of the anode-supported single cell with the GDC electrolyte film of 30 μm prepared by the dry co-pressing process. This result

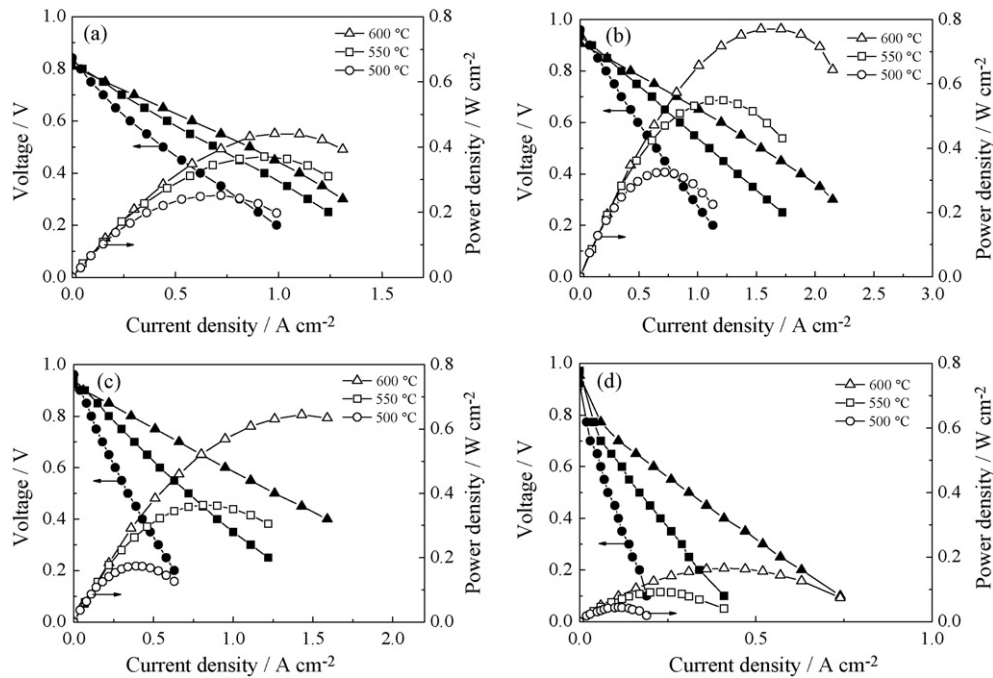


Fig. 2. *I*-*V* and *I*-*P* characteristics of the anode-supported single cells with the GDC electrolyte films of (a) 2 μm, (b) 4 μm, (c) 16 μm and (d) 75 μm.

indicates that the anode-supported single cells with thicker GDC electrolyte film of larger than 30 μm prepared by the spray dry co-pressing process may have the same electrical performance with the anode-supported single cells with thicker GDC electrolyte film of larger than 30 μm prepared by the dry co-pressing process. Thus,

the electrical performance of anode-supported single cells prepared by the dry co-pressing process and spray dry co-pressing process can be combined to evaluate the effect of thickness of the GDC electrolyte films.

The maximum power density of the anode-supported single cells increases with decreasing the thickness of the GDC electrolyte films when the thickness of the GDC electrolyte films is larger than approximately 5 μm, as shown in Fig. 3a. The increase of the maximum power density is attributed to the decrease of the electrolyte resistance with reducing the thickness of the GDC electrolyte films because of all the anode-supported single cells having the same anodes and cathodes. This result indicates that reducing the thickness of electrolyte layers can improve obviously the electrical performance of anode-supported SOFCs.

However, the maximum power density of the anode-supported single cells decreases with reducing the thickness of the GDC electrolyte films when the thickness of the GDC electrolyte films is less than approximately 5 μm, as shown in Fig. 3a. This indicates that reducing the thickness of the GDC electrolyte films is unnecessarily useful to improve the electrical performance of the anode-supported single cells when the thickness of the GDC electrolyte films is less than approximately 5 μm. The decrease of the maximum power density may be due to the increase of electronic conduction of the GDC electrolyte thin films, whose effect on electrical performance is larger than the effect of the decrease of electrolyte resistance. Thus, a peak maximum power density is obtained at the GDC electrolyte thickness of approximately 5 μm with reducing the thickness of the GDC electrolyte films.

The maximum power densities at 500 and 550 °C of the anode-supported single cells also show similar trend with the decrease in the thickness of the GDC electrolyte films, as shown in Fig. 3b. The peak maximum power densities are obtained at the GDC electrolyte thickness of approximately 5 μm, which means that the position of peak maximum power density is unaffected by the change of operating temperature. In addition, with reducing the thickness of the GDC electrolyte films, the change of power density at a certain cell voltage (e.g. 0.6 or 0.7 V) and operating temperature is similar with the change of the maximum power density, as shown in Fig. 3b. All the peak power densities are obtained at the GDC electrolyte

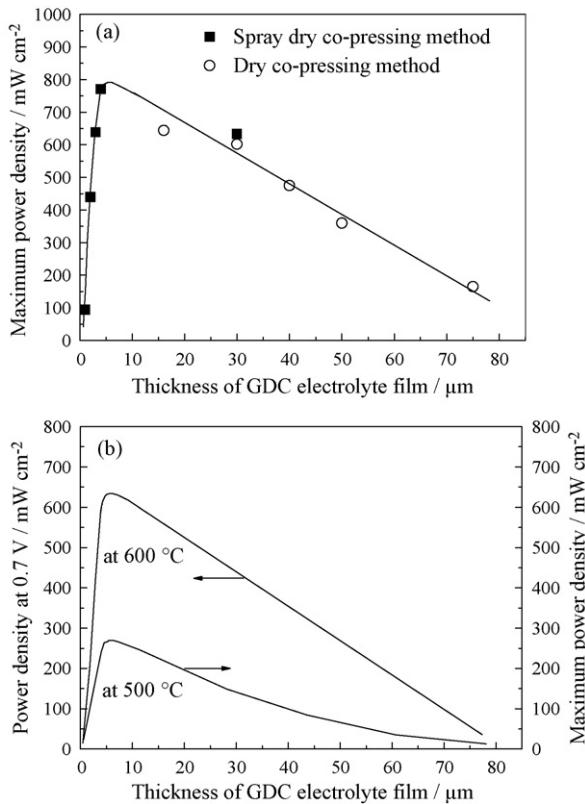


Fig. 3. Power densities of the anode-supported single cells with the GDC electrolyte films of different thickness: (a) maximum power densities at 600 °C and (b) power densities at 0.7 V at 600 °C and maximum power densities at 500 °C.

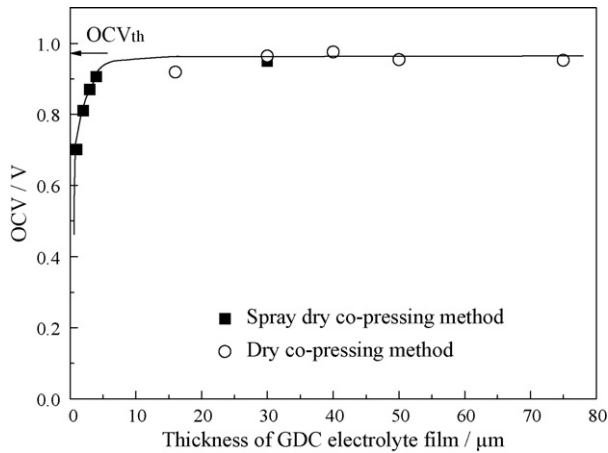


Fig. 4. OCVs at 600 °C of the anode-supported single cells with the GDC electrolyte films of different thickness.

thickness of approximately 5 μm , which means that the position of peak power density is unaffected by the change of cell voltage.

In addition, the grain size of GDC electrolyte affects the electronic and ionic conductivities of GDC electrolyte. It has been reported that the electronic and ionic conductivities of GDC increase quickly with the decrease in the grain size when the grain size of GDC is less than 35 nm [27,28]. This means that the effect of grain size on electronic and ionic conductivities may be very small when the grain size is larger than 100 nm. In this study, the grain size of GDC electrolyte films is in the range of 0.3–1.5 μm , and is unaffected by the thickness of GDC electrolyte films. Therefore, the effect of grain size of GDC electrolyte films on the electrical performance is expected to be negligibly small, and the position of peak power density may be unaffected by the grain size of GDC electrolyte films.

3.3. Effect of thickness of GDC electrolyte films on OCV

With the change of the thickness of the GDC electrolyte films, the OCVs of the anode-supported single cells also change obviously, and the relation of OCV at 600 °C and GDC electrolyte thickness is shown in Fig. 4. It can be seen that the OCV decreases with reducing the thickness of the GDC electrolyte films. Especially, when the thickness of the GDC electrolyte films is less than approximately 5 μm , the OCV decreases quickly with the decrease in the thickness of the GDC electrolyte films. This means that the OCV of the anode-supported single cells is strongly dependent on the thickness of the GDC electrolyte films at fixed operating conditions.

In general, the OCV of a SOFC is related to the density of electrolyte as well as the operating conditions. At fixed operating conditions, the OCV only depends on the density of electrolyte. The presence of connecting pores and cracks in the electrolyte may result in an OCV value lower than the theoretical value due to the gas leak. In this study, all the GDC electrolyte films are gas-tight, which have been approved by helium gas permeability tests, and the operating conditions of all the anode-supported single cells are the same. Thus, all the anode-supported single cells with the GDC electrolyte films of different thickness should have the same OCV. However, the OCV decreases with reducing the thickness of the GDC electrolyte films. This indicates that other factor affects the OCV of the anode-supported single cell with thin GDC electrolyte film. It is well known that ceria-based electrolytes are mixed ionic-electronic conductors [29], and the partial reduction of ceria from Ce^{4+} to Ce^{3+} under reducing conditions gives rise to electronic conduction. The electronic conduction of ceria-based electrolyte results in internal short circuit of SOFC, which lowers OCV of SOFC. With the increase

of the electronic conduction of ceria-based electrolyte, the OCV of SOFC may be lowered further.

In order to investigate the electronic conduction of GDC electrolyte films, theoretical calculation is made to examine the relationship between GDC electrolyte thickness and electronic conduction. For an ideal electrolyte, there is only ionic conduction and no electronic conduction. In reality, however, any electrolyte materials have both electronic and ionic conductivities even if one of them is negligibly small. If the electronic conduction is non-negligible in the electrolyte, the anode and cathode are partly short-circuited by the electron flux through the electrolyte itself.

In a steady state, both ionic and electronic currents are continuous through the electrolyte. Thus, the external current density extracted from electrodes to outer circuit must be the sum of ionic and electronic current densities in the electrolyte. In the open circuit condition, external current density is equal to zero, and the ion flux and electron flux are balanced everywhere inside the electrolyte. The expression [30] shown below can be used to calculate the electron flux (J_e) through the GDC electrolyte in the open circuit condition and the theoretical OCV (OCV_{th}):

$$J_e = -\frac{RT}{4FL} \int_{P_{O_2}^1}^{P_{O_2}^2} \frac{\sigma_{O^{2-}} - \sigma_e}{\sigma_{O^{2-}} + \sigma_e} d \ln P_{O_2} \quad (1)$$

$$OCV_{th} = \frac{RT}{4F} \int_{P_{O_2}^1}^{P_{O_2}^2} \frac{\sigma_{O^{2-}}}{\sigma_{O^{2-}} + \sigma_e} d \ln P_{O_2} \quad (2)$$

where R is the gas constant, T the absolute temperature, F the Faraday constant, L the electrolyte thickness, $\sigma_{O^{2-}}$ the ionic conductivity of the electrolyte, σ_e the electronic conductivity of the electrolyte, $P_{O_2}^1$ the oxygen partial pressure at the anode, and $P_{O_2}^2$ the oxygen partial pressure at the cathode. Thus, by changing electrolyte thickness, the relation of electron flux and GDC electrolyte thickness can be obtained. The calculation of the electron flux at 600 °C is based on the oxygen partial pressures of 1.00 and 1.24×10^{-27} atm, the ionic conductivity of 2.53×10^{-2} S cm^{-1} and the electronic conductivity of 5.48×10^{-8} $P_{O_2}^{-1/4}$ [5,31]. Here, the 5.48×10^{-8} is a calculated value based on the linearly proportional relationship between temperature and logarithm of electronic conductivity.

The calculated electron fluxes through the GDC electrolytes with different thickness are shown in Fig. 5. It can be seen that the electron flux increases with the decrease in the thickness of the GDC electrolyte film. When the thickness of the GDC electrolyte films is larger than approximately 10 μm , the electron fluxes

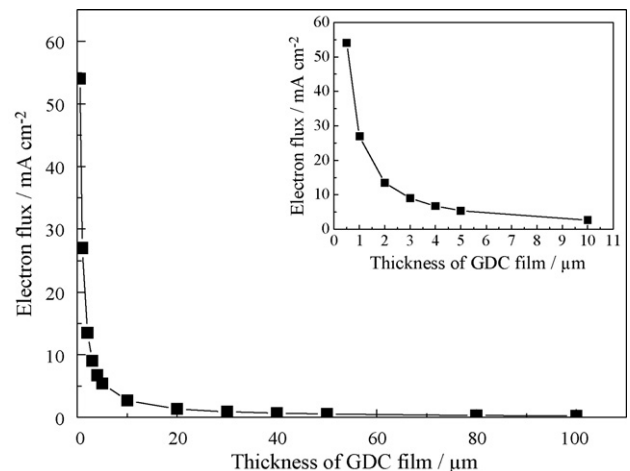


Fig. 5. Calculated electron fluxes through the GDC electrolyte films of different thickness at 600 °C.

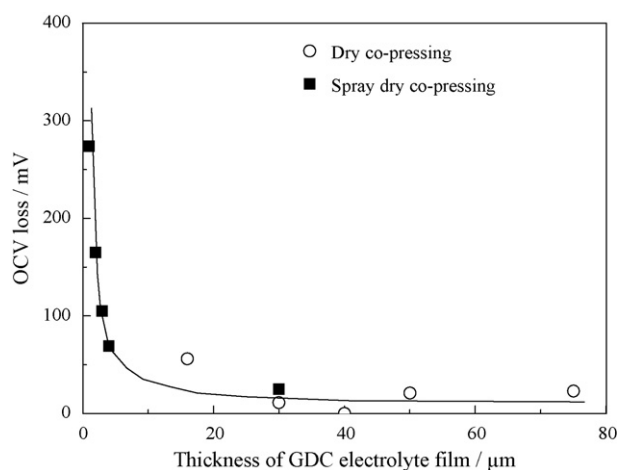


Fig. 6. OCV loss at 600 °C of the anode-supported single cells with the GDC electrolyte films of different thickness.

through the GDC electrolytes change slightly with reducing the GDC electrolyte thickness, that is, the electron fluxes through the GDC electrolytes can be considered as fixed value. But the electron flux through the GDC electrolyte film increases quickly with reducing the thickness of the GDC electrolyte films when the thickness of the GDC electrolyte films is less than approximately 5 μm . The inflexion of change of the calculated electron fluxes through the GDC electrolyte films is in good agreement with that of change of the measured power densities and OCVs of anode-supported SOFCs. The increasing electron flux through the GDC electrolyte may lower the OCV and power density of anode-supported SOFC.

According to Eq. (2), the OCV_{th} can be calculated. The calculated OCV_{th} at 600 °C is 0.975 V. Thus, the OCV loss can be obtained from the difference between calculated OCV_{th} and measured OCV. The relation of OCV loss and thickness of GDC electrolyte films is shown in Fig. 6. It can be seen that the OCV loss increases with the decrease in the thickness of GDC electrolyte films. In particular, the OCV loss increases quickly with reducing the thickness of GDC electrolyte films when the thickness of GDC electrolyte films is less than approximately 5 μm . With reducing the thickness of GDC electrolyte films, the change trend of OCV loss is similar to the change trend of electron flux through GDC electrolyte. This indicates that the increased electron flux through GDC electrolyte lowers the OCV of anode-supported SOFC and results in high OCV loss. This is the reason why the OCV and maximum power density of the anode-supported SOFC decrease with reducing the thickness of the GDC electrolyte thin film. Therefore, when the thickness of the GDC electrolyte films is less than approximately 5 μm , reducing the thickness of the GDC electrolyte films is unbeneficial for improving the electrical performance of anode-supported single cells due to the high electronic conduction of GDC electrolytes.

4. Conclusions

Anode-supported SOFCs with dense GDC electrolyte films of 1–75 μm were successfully fabricated by dry co-pressing process and spray dry co-pressing process. The effect of thickness of the GDC

electrolyte films on electrical performance of the anode-supported SOFCs was investigated systemically. Results showed that reducing the thickness of the GDC electrolyte films could improve the electrical performance of the anode-supported SOFCs. The anode-supported single cell with approximately 5 μm GDC electrolyte film demonstrated the highest electrical performance. When the thickness of the GDC electrolyte films is less than approximately 5 μm , the electron flux through the GDC electrolyte film increases quickly with the decrease in the thickness of the GDC electrolyte film, and thus further reduction in the thickness of the GDC electrolyte film is unsuitable for improving the electrical performance of the anode-supported SOFC.

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