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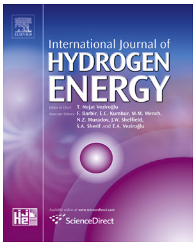

Effects of changes in solid oxide fuel cell electrode thickness on ohmic and concentration polarizations

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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.

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

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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 °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.

Theoretical method

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 [26] revealed, more electronic current flows through CCCL. So, the cathodes appear in Figs. 1 and 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 (in the web version) 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.

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