Contents lists available at ScienceDirect







journal homepage: www.elsevier.com/locate/jpowsour

# Two-dimensional model of distributed charge transfer and internal reforming within unit cells of segmented-in-series solid-oxide fuel cells

## Huayang Zhu\*, Robert J. Kee

Engineering Division, Colorado School of Mines, Golden, CO 80401, USA

#### A R T I C L E I N F O

Article history: Received 10 January 2011 Received in revised form 8 April 2011 Accepted 13 April 2011 Available online 21 April 2011

Keywords: SOFC Modeling Segmented in series Distributed charge transfer Internal reforming

### 1. Introduction

Fig. 1 illustrates the layout of a segmented-in-series (SIS) solidoxide fuel cell (SOFC) module in which planar SIS cells are arrayed as narrow strips on the outside of a porous support structure. Fuel flows inside the support and the cathode sides of the SIS are exposed to air on the outside. Each cell is composed of a membrane-electrode assembly (MEA) and an interconnect structure. The MEA consists of a cermet anode (e.g., Ni-vttria-stabilized zirconia, Ni-YSZ), dense electrolyte (e.g., YSZ), and composite cathode (e.g., strontium-doped lanthanum manganate-YSZ, LSM-YSZ). The cathode in the present study is a two-layer design using a pure LSM current collection layer above an LSM-YSZ functional layer. Each layer is usually a few tens of microns thick and the support structure is on the order of a millimeter thick. The width of each cell is typically on the order of a few millimeters. As illustrated here, a porous catalyst layer at the interface between the support structure and the fuel channel can promote reforming hydrocarbon fuels.

Oxygen ions  $O^{2-}$  are produced within the cathode by the electrochemical reduction of gas-phase oxygen, using electrons supplied from the anode of the neighboring cell. Electric current is produced along the width of the MEA as the oxygen ions that are transported across the dense electrolyte are electro-oxidized by the fuel H<sub>2</sub>. Oxygen ions are transported across the dense electrolyte within the MEA, but the cells are isolated such that oxygen ions cannot

## ABSTRACT

This paper develops a computational model to represent details of reactive porous-media transport, elementary catalytic chemistry, and electrochemistry within unit cells of segmented-in-series solid oxide fuel cell (SIS-SOFC) modules. Because the composite electrode structures are thin (order of tens of microns), electrochemical charge-transfer chemistry can proceed throughout the composite electrode structures. Modeling such spatially distributed charge transfer is significantly more complex than modeling situations where the charge transfer can be represented at an interface between electrode and electrolyte. The present model predicts electric-potential fields of electrode and electrolyte phases, with the charge-transfer rates depending upon local electric-potential differences and the local gas-phase composition. The paper summarizes the underpinning physical and chemical models and uses examples to illustrate and interpret important aspects of SIS performance.

© 2011 Elsevier B.V. All rights reserved.

be transported between cells. The inset in Fig. 1 shows that each cell is connected electrically in series with the lateral neighboring cells. The electrons produced within the anode of one cell are conducted into the cathode of the neighboring cell. Electric current from the anode interconnect at one end of the module is delivered to an external circuit, with electrons being returned to the cathode interconnect at the other end of the module. At the full system level, multiple modules can be connected electrically either in series or parallel.

## 1.1. Potential advantages of SIS

Segmented-in-series architectures offer several potential benefits. Electrical current is carried laterally through width of each cell, which can produce significant ohmic losses, especially in the cathode where the materials can have relatively high electrical resistance *R*. However, connecting many cells electrically in series builds up module voltage, thus reducing ohmic  $(I^2R)$  losses because the high voltage reduces current *I* for a certain electrical power. Overall cell performance benefits by reducing lateral electrical resistance, which is usually accomplished by using short cell widths. One objective of the present paper is to determine optimal cell widths.

The SIS approach confines Ni to the thin anode structure, thus reducing cost by significantly reducing the amount of Ni required in comparison to more common Ni–YSZ anode-supported SOFC architectures. The SIS supports do not carry electrical or ionic current, and thus can be fabricated from relatively low-cost materials such as partially stabilized zirconia (PSZ). The MEA layers can be fab-

<sup>\*</sup> Corresponding author. Tel.: +1 303 273 3890; fax: +1 303 273 3602. *E-mail address*: hzhu@mines.edu (H. Zhu).

<sup>0378-7753/\$ –</sup> see front matter @ 2011 Elsevier B.V. All rights reserved. doi:10.1016/j.jpowsour.2011.04.023



Fig. 1. Section of a segmented-in-series module.

ricated using relatively low-cost screen-printing technology. The model presented in this paper provides quantitative tool to assist evaluating design alternatives.

#### 1.2. Prior literature

Alternative SIS-SOFC architectures have been studied since the mid 1960s [1–3]. Initial efforts considered cells that were applied as rings to the exterior of cylindrical porous support tubes. Later designs considered planar cells that were applied to flat porous support structures (e.g., Fig. 1). Mitsubishi Heavy Industries continues to develop SIS architectures on circular tubes [4] and Rolls-Royce is developing planar architectures [5,6]. Rolls-Royce uses the name Integrated Planar Solid Oxide Fuel Cell (IP-SOFC) to describe their design. Recently, Liu et al. have fabricated cone-shaped anode-supported SIS-SOFCs with good performance [7,8].

Barnett et al. have published a number of studies concerning system design and optimization [9-12]. Zhan and Barnett suggested using an inner reforming or partial-oxidation catalyst (as illustrated in Fig. 1) to enable the use of hydrocarbon fuels. The porous support structure also serves as a barrier layer that facilitates the use of hydrocarbon fuels without carbon deposits [13,14]. Based on modeling and experimental efforts, Barnett et al. have achieved high power density by reducing the lateral resistance losses across the electrodes and maintaining large active cell area through lowering the cell width and interconnect area [9,11,12]. Lai and Barnett [9] presented a model to analyze SIS performance as functions of cell and interconnect geometry, support material, cell area-specific resistance, and electrode sheet resistance. These results showed that power densities around 1 W cm<sup>-2</sup> can be obtained using cell widths of about 1-2 mm. Lai and Barnett also reported that the cathode electrical resistance can be significantly reduced by applying a porous LSM current-collection layer above the cathode [11]. Using Ni-YSZ| YSZ|Pt-YSZ cells operating on humidified H2 at 800 ° C and atmospheric pressure, Pillai et al. [12] measured power densities of approximately 0.7 W cm<sup>-2</sup> using cell widths of approximately 1.2 mm and interconnect widths of approximately 0.2 mm.

Haberman and Young have developed three-dimensional computational-fluid-dynamics (CFD) models to investigate the effects of fuel and air flow as well as heat and mass transport at the system level for IP-SOFC designs [15–17]. Several other groups have also developed planar SIS models that incorporate porous-media transport, coupled with reforming chemistry and electrochemistry [18,19]. Cui and Cheng developed two-dimensional axisymmetric models for the tubular SIS-SOFC to analyze the effects of the cell geometry on the electrical performance and species transport [20].

Compared to prior literature, the present model makes significant advances in the fundamental representation of chemistry and electrochemistry. Electric potentials for both ion- and electronconducting phases are modeled throughout the entire cell. Hence, both ionic and electron fluxes are predicted throughout the system. Electrochemical charge-transfer chemistry depends on the local temperature, gas-phase composition, and electric-potential differences between phases. The spatial extent of the charge-transfer region depends on electrode structure, including primary particle sizes, phase densities, porosity, tortuosity, etc. Reactive porousmedia gas-phase transport is represented using a Dusty-Gas model. The model also represents elementary catalytic chemistry (typically tens of elementary reactions) within the composite anode and within the catalytic layer at the interface between the fuel flow and the support structure. The elementary catalytic chemistry represents the internal reforming or partial oxidation of hydrocarbon fuels as well as other thermal chemistry such as water-gas-shift process.

#### 2. Physical and chemical model

This paper focuses on the design and performance of individual unit cells, including the interconnect region and the underlying support structure. However, the fuel flow within the channels and the exterior air flow are not directly modeled. The model is formulated in terms of continuum differential equations that describe the electric potentials for the electrode and electrolyte phases as well as Faradaic charge transfer between phases. The porous-media transport of gases within the pore spaces is modeled with a Dusty-Gas model. Catalytic reforming and partial oxidation of fuels is based upon elementary reaction mechanisms.

Fig. 2 illustrates the structure of the unit cell, including nominal dimensions. The figure calls attention to a "unit width" and an "active width". The unit width is the width of the cell repeating unit, which includes interconnect and cell-isolation features. The active width is the width over which the anode and cathode structures overlap. Electrical current is produced primarily within the active width. As illustrated in Fig. 2, the present paper considers the lateral widths of features within the interconnect regions to be fixed at 80 µm. Assuming a fixed interconnect structure, the model is used to determine unit width that maximizes cell performance.

Because the anode and cathode thicknesses are on the order of  $50 \,\mu$ m, the electrochemical charge-transfer processes are likely to be distributed throughout most of the porous electrode structure [21]. Therefore, SIS models should accommodate charge-transfer electrochemistry throughout the MEA. Because a detailed discus-

Download English Version:

https://daneshyari.com/en/article/1293386

Download Persian Version:

https://daneshyari.com/article/1293386

Daneshyari.com