



## A simple analysis of current collection in tubular solid oxide fuel cells

Anil V. Virkar<sup>a,\*</sup>, Fred F. Lange<sup>b</sup>, Michael A. Homel<sup>c</sup>

<sup>a</sup> Department of Materials Science & Engineering, 122 S. Central Campus Drive, University of Utah, Salt Lake City, UT 84112, United States

<sup>b</sup> Materials Department, University of California, Santa Barbara, CA 93106, United States

<sup>c</sup> Materials and Systems Research, Inc., 5395 West 700 South, Salt Lake City, UT 84104, United States

### ARTICLE INFO

#### Article history:

Received 6 January 2010

Received in revised form 15 February 2010

Accepted 16 February 2010

Available online 20 February 2010

#### Keywords:

Solid oxide fuel cells

Tubular

Current collection

Portable power

Distributed power

### ABSTRACT

A transmission line analysis is presented for the axial current collection in tubular solid oxide fuel cells (SOFC). Closed form analytical solutions are obtained for two modes of current collection: (1) Current collection at one end. (2) Current collection across opposite ends. The analysis shows that cell resistance is lower for current collection at one end compared to that at the opposite ends, with the best case scenario being current collection at both ends. In addition, the analysis shows that for the case of tubular cells, performance may not indefinitely increase with increasing temperature. Experimental data are presented on planar and tubular cells that demonstrate significant differences in temperature dependence. It is projected that under certain conditions, performance of tubular cells may actually decrease with increasing temperature. A design of tubular cells with spines which can substantially lower current collection losses is described.

© 2010 Elsevier B.V. All rights reserved.

### 1. Introduction

Currently both planar and tubular geometries of solid oxide fuel cells (SOFC) are under development by various organizations. The planar geometry is primarily being developed for large scale applications, ranging between  $\sim 1$  and  $>10$  kW. The modularity of SOFC stacks allows for the construction of hundreds of kW or even MW class systems. Two types of tubular geometries are currently under development. The first is the Siemens–Westinghouse design, in which cathode-supported cells are used with the electrolyte covering part of the cylindrical surface except for a strip for interconnection and anode covering part of the electrolyte surface, which is electrically isolated from the interconnection/cathode [1]. Cell to cell contact is made along the length of the cell using a nickel felt. Thus, current flow through the support electrode (cathode) is ideally circumferential. Systems as large as 200 kW have been demonstrated. The second design uses anode-supported cells of axi-symmetric geometry, in which current collection is at the ends of the cell [2]. In this second design, current flow through electrodes is along the length of the cell. In this geometry, the longer the cell, the greater are the losses associated with current collection. Thus, in this geometry, the design considerations need to address current collection losses. This approach has been primarily used for portable power sources of approximately 20–200 W in size, although larger units of several kW in size have been made and

tested. For portable power applications, the cells are typically a millimeter in diameter, and often called micro-tubular SOFC [3,4].

Several authors have addressed the issue of current collection in tubular SOFC. The models vary in degree of complexity and detail. Current collection in tubular SOFC of the Siemens–Westinghouse design has been recently addressed [5,6]. Current collection in micro-tubular SOFC of  $\sim 1$  mm in diameter and  $\sim 1$  cm in length has been modeled using simple equivalent circuits [7,8]. Detailed models which take into account momentum, heat, and mass transport and electrochemical coupling have been developed by Cui et al. [9,10] and Zhu and Kee [11]. The analysis by Zhu and Kee [11] also determines species concentrations along the length of the cell.

All of the reported models provide numerical solutions. The ones which take into account detailed transport and multi-dimensional nature of the problem, are not amenable to closed form analytical solutions. Numerical approaches are thus necessary to address such complexities. If the objective is to obtain closed form solutions, however, simplifying assumptions are necessary. Closed form solutions are very useful as they allow the evaluation of the role of various parameters on performance with considerable ease, and also have predictive capability often not possible with numerical solutions.

The objective of this manuscript is to provide an analysis of axial current collection in tubular cells in which cell length is an important consideration. The analysis is based on a transmission line model, which lends itself to simple second order, ordinary differential equations resulting in closed form analytical solutions. The analysis takes into account the electrolyte resistance, cathode and anode polarization resistances, and anode and cathode electronic

\* Corresponding author. Tel.: +1 801 581 5396; fax: +1 801 581 4816.  
E-mail address: [anil.virkar@utah.edu](mailto:anil.virkar@utah.edu) (A.V. Virkar).

## Nomenclature

$\rho_e$	ionic resistivity of the electrolyte ( $\Omega \text{ cm}$ )
$t_e$	electrolyte thickness (cm)
$\rho_a$	electronic resistivity of the anode (accounting for any applied current collection layers) ( $\Omega \text{ cm}$ )
$t_a$	anode thickness (including any applied current collection layers) (cm)
$\rho_c$	electronic resistivity of the cathode (accounting for any applied current collection layers) ( $\Omega \text{ cm}$ )
$t_c$	cathode thickness (including any applied current collection layers) (cm)
$\lambda_a^s$	geometric factor of anode spine
$\lambda_c^s$	geometric factor of cathode spine
$\ell$	cell length (cm)
$R_{ct}^a$	anode polarization resistance ( $\Omega \text{ cm}^2$ )
$R_{ct}^c$	cathode polarization resistance ( $\Omega \text{ cm}^2$ )
$\varphi_a(x)$	anode potential at $x$ (V)
$\varphi_c(x)$	cathode potential at $x$ (V)
$E_o$	Nernst voltage (V)
$E_t$	terminal voltage (V)
$I(x)$	current per unit circumference at position $x$ ( $\text{A cm}^{-1}$ )
$I(0)$	net current per unit circumference measured in the external circuit ( $\text{A cm}^{-1}$ )
$I_c(x)$	current per unit circumference through the cathode along the length of the cell ( $\text{A cm}^{-1}$ )
$I_a(x)$	current per unit circumference through the anode along the length of the cell ( $\text{A cm}^{-1}$ )
$Q$	activation enthalpy ( $\text{kJ mol}^{-1}$ )
$R_i = \rho_e t_e + R_{ct}^a + R_{ct}^c$	net area specific resistance of the cell ( $\Omega \text{ cm}^2$ ) (local)
$a = \sqrt{((\rho_a/t_a) + (\rho_c/t_c))/\rho_e t_e + R_{ct}^a + R_{ct}^c} = \sqrt{((\rho_a/t_a) + (\rho_c/t_c))/R_i}$	inverse characteristic length ( $\text{cm}^{-1}$ )

resistances. Two types of current collection strategies are evaluated and the corresponding values of cell resistance as a function of cell length are determined. Based on these calculations, strategies for the design of tubular cells are presented. Additionally, the effect of temperature on cell performance is qualitatively addressed. It is shown that differences in the schemes of current collection between planar and tubular cells also translate into fundamental differences in the temperature dependence of stack/bundle performance. Experimental results on the effect of temperature on the performance of a planar (button) cell and a tubular cell are presented.

## 2. Analysis

In what follows, an analysis is presented for current collection at one end of the cell and at the opposite ends of the cell. Using this analysis, it is shown that the best case scenario consists of current collection at both ends.

### 2.1. Current leads at one end

The following are simplified calculations of current collection and performance of a tubular SOFC. The calculations are given for unit thickness along the cell circumference. It is assumed that the thicknesses of the various layers are much smaller than the cell diameter, and the cell diameter is much smaller than the cell

length.<sup>1</sup> This assumption is consistent with typical cell dimensions, namely, cell thickness  $\sim 0.1$  cm, cell diameter  $\sim 1$  cm, and cell length  $\sim 10$  cm. The calculations are given with the assumption that oxidant and fuel compositions do not vary substantially along the length of the cell, which allows one to assume that the Nernst voltage is the same along the length of the cell. In reality, such an assumption may not be accurate for operation at very high fuel and oxidant utilizations, although it is applicable to the vast majority of practical situations. This assumption also allows for simple analytical solutions and is thus deemed of interest for preliminary design considerations and the selection of design parameters for tubular solid oxide fuel cells (SOFC). These solutions also facilitate the prediction of the temperature dependence of the performance of tubular SOFC, not previously reported in studies based on numerical models.

Fig. 1(a) shows a schematic of a cell of length  $\ell$  with current collection at one end. The lengths of arrows in the electrodes (anode and cathode) qualitatively indicate the magnitude of local current – higher close to the current collection tabs and progressively lower at the opposite end. Within the electrolyte, this is shown qualitatively by the spacing between vertical arrows; smaller distance between arrows closer to the current collection tabs indicating higher local current density. At any position along the length of the tube,  $x$ , the magnitudes of the current in the anode and the cathode are the same, but their directions are opposite. Fig. 1(b) is a detailed cross-section of the upper side of the cell showing the directions of currents; this cross-section identifies the various cell parameters. The various resistivities are:  $\rho_e$  = electrolyte ionic resistivity ( $\Omega \text{ cm}$ );  $\rho_a$  = anode electronic resistivity ( $\Omega \text{ cm}$ ); and  $\rho_c$  = cathode electronic resistivity ( $\Omega \text{ cm}$ ). For the case of graded electrodes, e.g., with applied current collector layers (e.g. copper at anode, silver at cathode), the electronic resistivities refer to appropriate averages including any geometric factors. The various thicknesses are:  $t_e$  = electrolyte thickness (cm),  $t_a$  = anode thickness (cm), and  $t_c$  = cathode thickness. The area specific polarization resistances are:  $R_{ct}^a$  = anode polarization resistance ( $\Omega \text{ cm}^2$ ) and  $R_{ct}^c$  = cathode polarization resistance ( $\Omega \text{ cm}^2$ ). The area specific resistance of a cell element or tri-layer (cathode/electrolyte/anode) is given by  $R_i = \rho_e t_e + R_{ct}^a + R_{ct}^c$  in  $\Omega \text{ cm}^2$ .

It is assumed that  $\rho_e \gg \rho_a, \rho_c$ , which is typically the case.

An equivalent circuit for an element of the cell between  $x$  and  $x + dx$  is shown in Fig. 2.

The units of  $R_i/dx \cdot 1$  are  $\Omega$ . The ‘1’ in the denominator refers to unit length along the circumference. If the cell radius is  $r$ , then the resistance of the element will be given by  $R_i/dx \cdot 2\pi r$ .

The electrical potential difference between the cathode and the anode at position  $x$  is given by

$$\varphi_c(x) - \varphi_a(x) = E_o + R_i \frac{dI(x)}{dx} \quad (1)$$

Eq. (1) is based on simple application of the Ohm's law for the cell element of length  $dx$  with internal voltage source  $E_o$ . Note also that

$$\varphi_a(x + dx) - \varphi_a(x) = -I(x) \frac{\rho_a}{t_a} dx \quad (2)$$

or

$$\frac{d\varphi_a(x)}{dx} = -I(x) \frac{\rho_a}{t_a} \quad (3)$$

<sup>1</sup> The analysis given here is applicable even if the diameter is not much greater than the thickness, or even if the cell cross-section is not circular (may be elliptical). These geometric factors can be readily included in the analysis without altering the basic approach and the resulting forms of the differential equations.

Download English Version:

<https://daneshyari.com/en/article/1290102>

Download Persian Version:

<https://daneshyari.com/article/1290102>

[Daneshyari.com](https://daneshyari.com)