DOR: 20.1001.1.24234931.1401.9.1.7.8

Original Article
Received: 03/23/21
Accepted: 05/23/21

Volume 9, Issue 1, Spring & Summer, p. p. 21-24
Journal of Renewable and New Energy
jrenew.ir

Numerical Investigation of Leakage Flow Occurring in a Hydrogen-Fuelled Co Flow Planar All-Porous Solid Oxide Fuel

Majid Kamvar[1*]

1- Departmen of Mechanical Engineering, Parand Branch, Islamic Azad University, Parand, Iran
* P.O.B. 3761396361 Parand, Iran, , mahdi_108108@yahoo.com
Received: 23 March 2021 Accepted: 23 May 2021

Abstract
The All Porous Solid Oxide Fuel Cell (AP-SOFC) is a concept that links the dual and single chamber Solid Oxide Fuel Cell (SOFC), combining advantages of both. The AP-SOFC does not need any sealant and crack generation in its electrolyte component does not terminate cell operation. In this study, the performance of a hydrogen-fuelled co flow planar AP-SOFC is investigated numerically for the first time. Governing equations include species, mass, momentum, charge and energy solved fully-couple with electrochemical equations. Due to lack of study on hydrogen-fuelled AP-SOFC, first the performance of a conventional hydrogen-fuelled SOFC is modeled and the results are compared with experimental results for the validation purpose, then changes in the model are made to apply the electrolyte porosity. Results show a 29% decline in maximum power density produced by the AP-SOFC compared to its conventional scheme with the same inputs. The main reason for this reduction in the cell performance is mostly the flow leakage of oxygen from the near air channel inlet to the fuel channel side. This leakage leads to displace the maximum cell temperature point.

Keywords: Solid Oxide Fuel Cell, All-porous, Hydrogen, Leakage, Steady state

1. INTRODUCTION

Fuel cells are an efficient technology for generating electricity through direct electrochemical conversion of a fuel and an oxidant without thermal conversion [1]. SOFCs are gaining considerable attention due to their high efficiency and the fuel flexibility [2-6]. SOFCs work at high temperatures between 500 and 950°C [7]. These high operating temperatures have both advantages and disadvantages. On one hand, above 650°C they enable direct internal reforming of simple hydrocarbons at the anode as well as the fuel flexibility of using hydrogen, carbon monoxide and simple hydrocarbon fuels in one and the same device, on the other hand they can lead to thermal stresses, especially during thermal cycling, that might lead to crack formation within SOFC components [8].The high operating temperature also gives rise to increased materials degradation, as far as this is thermally activated [9-12]. In dual chamber SOFCs, the strict separation of fuel and oxidant is a key requirement [13], with the need for reliable sealing between the electrode compartments [14]. One applicable way to simplify the cell structure is to use a single chamber instead of two fully separated chambers and expose a uniform mixture of fuel and oxidant gases on both the anode and cathode simultaneously. This simplified design is titled as single chamber solid oxide fuel cell (SC-SOFC) and was demonstrated by Hibino and Iwahara for the first time in 1993 [15].

SC-SOFCs, compared to conventional SOFCs, bring some advantages including lower weight as well as smaller volume (specially with the planar type) and also remove the need for complex sealants. Thus, the manufacturing process is potentially more cost-effective. However, the presence of 'spectator' species at the two functional layers of SC-SOFCs (for example transport of hydrogen to the cathode functional layer with no chemical interaction) leads to very low performance compared to conventional SOFCs [16] due to reactant dilution. A number of studies on SC-SOFC have been performed using numerical approaches and published in [2, 9, 12-27] in order to enhance this low performance. Reported SC-SOFC performances show that high power density and high fuel efficiency cannot be achieved simultaneously in an SC-SOFC. This is due to flammability and flow pattern issues. Among these studies, Kamvar et al. [2] performed a comparison study between different anode and cathode configurations on SC-SOFC. Their results revealed that the Ohmic losses played a key role in cell performance improvement. Kamvar et. al. in their recent work [16] numerically investigated the effect of different support types on the cell performance. Their results showed that the anode-supported scheme revealed the best performance compared to the other two support types. They also reported that lack of oxygen at the cathode side of a cathode-supported cell was an obstacle that limited the cell performance around open circuit voltage conditions., Many useful reports have been published in the area of the dual chamber SOFCs. However, a number of novel

numerical studies have been recently performed in the SOFC area. Kong et. al. [28] proposed a novel interconnector design named X-type interconnect. Their numerical results showed that the cell with this novel design presented better performance compared to the cell with conventional interconnect. Schluckner et. al. [29] studied the influence of different possible flow configurations and electrical contact positions on the temperature distribution within the cell. They claimed that it was not possible to move the maximum cell temperature to the cell centre by way of varying the electrical contact positions. Moreno-Blanco et. al. [30] numerically studied the effect of the channel-electrode interface area on the performance of planar SOFC. They found that the size (width) and number of channels in a co-flow arrangement had a direct effect on the cell performance.

Guo et al. [31] successfully designed a novel concept of dual chamber SOFC technology with porous electrolyte named All Porous Solid Oxide Fuel Cell (AP-SOFC) which forms a link between dual and single chamber SOFCs. Their cell used methane fuel without any external reformer or steam addition. The porous structure of the electrolyte allowed gaseous species transport through the electrolyte. Therefore, the presence of cracks in the electrolyte or sealant failure are of no concern in AP-SOFCs and fuel-oxygen concentration management is performed easily to keep the system away from the risk of explosion.

Recently, Xu et. al. [32] developed numerical models for button AP-SOFC as presented in Guo's et al experimental study. Their results focused on electrolyte porosity optimisation to control the oxygen transport to the anode to prevent the risk of simple combustion (and explosion) as well as methane coking and carbon deposition in the anode which would considerably reduce the cell performance. Xu et. al. in their other study [33] investigated the thermal effects in AP-SOFC. They conducted parametric studies for various operating parameters such as voltage, inlet gas temperature and different cell structures to optimise the cell performance.

The aim of this study is to present a numerical model of a planar hydrogen-fuelled AP-SOFC to be able to evaluate the flow leakage content and position occurring within the cell and its effect on the cell performance for the first time. Using hydrogen as fuel brings advantages including: i) avoiding coking problems, and ii) it simplifies the overall anode chemistry. However, the leakage flow from within the porous electrolyte can decline the cell performance.

2. Problem Definition

A 2D numerical steady state condition model was used to predict the performance of a planar AP-SOFC. In the planar type of AP-SOFC, the porous electrolyte is sandwiched between two porous electrodes. As shown in Figure 1, two fully separated chambers are used to feed fuel and oxidant individually and the porous structure of the electrolyte allows the gaseous species transport from anode to cathode and vice versa. The cell consists of five layers; an anode current collecting layer made of nickel (Ni), an anode functional layer made of a cermet of nickel with yttria-stabilised zirconia (50%Ni-50%YSZ), a porous electrolyte of YSZ, a cathode functional layer made of a composite of YSZ and lanthanum strontium manganite (50%YSZ-50%LSM), and a cathode current collection layer of pure LSM. To present a more realistic prediction of the cell performance, all geometrical, micro-structural and thermo-physical parameters of the current cell follow the experimental base case reported by Timurkutluk et al. [34]. The geometrical data of the model considered in this study are tabulated in Table 1. A 0.3 electrolyte layer porosity is applied to the AP-SOFC scheme.

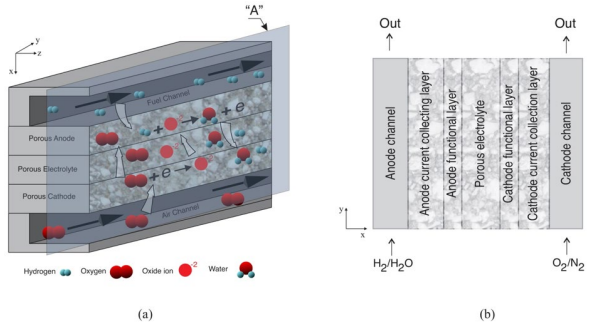

Figure 1. (a) Schematic illustration of a single cell of planar-type AP-SOFC, (b) cross-section of planar-type AP-SOFC representing the computational domain (detailed "A")

Table1. Geometrical data

Description	Symbol	Value
Channel length	L_{ch}	10 [mm]
Channel height	H_{ch}	0.5 [mm]
Anode current collecting layer thickness	t_a	50 [μm]
Anode functional layer thickness	t_{af}	20 [μm]
Electrolyte thickness	t_e	50 [μm]
Cathode current collector thickness	t_c	50 [μm]
Cathode functional layer thickness	t_{cf}	20 [μm]

3. Results and Discussion

The governing equations were solved through finite element analysis in the commercial software COMSOL MULTIPHYSICS®. A triangular mesh was opted. The mesh distribution was such that more elements were concentrated in the functional layers where more calculation volume existed.

In order to show the accuracy of the model results, a validation was performed. Due to lack of experimental data in the area of AP-SOFC with

hydrogen fuel, the results were compared to experimental data provided by Timurkutluk et al. [34] for a dual chamber SOFC using hydrogen as a fuel. The base cell of their study consisted of Ni/YSZ/LSF materials for anode/electrolyte/cathode layers respectively, at 750^{o}C operating temperature, where this temperature is maintained as inlet temperature in current modelling work.

In this section, a comprehensive analysis of the steady state performance of an all-porous solid oxide fuel cell with hydrogen fuel is examined for the first time. In order to have more realistic cell performance, all input parameters used in the validation section are maintained.

Results include the polarization plot of the AP-SOFC with hydrogen fuel, the x-component total flux of the hydrogen and water gas components on the axis passing through the interface between the electrolyte and the cathode electrode and the x-component total flux of the oxygen gas component through the interface between the electrolyte and the anode electrode, distribution of x component velocity of gas mixture and temperature contours.

4. Conclusions

The performance analysis of an all-porous solid oxide fuel cell with hydrogen fuel was performed using a two-dimensional numerical model based on the finite element method and focusing on the study of the fluid flow inside the cell layers. The results showed that the maximum power density produced by the all-porous cell was 2540 W/m^2, which showed a 29% decrease compared to the conventional solid oxide fuel cell with the same input. Comparing the distribution of the x component of the total flux of different gas components on the interface between the electrolyte and the anode electrode, it was observed that the oxygen gas component had more diffusion and leakage compared to the other two gas components. This leakage occurred mostly near the cathode chamber inlet from cathode side to anode side. The velocity distribution between the anode and cathode channels showed that in none of these channels the fluid flow reached a fully developed state and the fluid velocity in the anode channel was 11.4 % higher compared to the cathode channel due to gas leakage (Especially near the cell inlet from the cathode electrode to the anode electrode). Comparison of temperature contour between conventional and all-porous solid oxide fuel cells showed that in the all-porous design, the temperature distribution is more homogeneous, so that under the same conditions, the maximum temperature in the conventional type occurs in the middle of the electrolyte layer and near the outlet while this maximum temperature point for the all-porous type occurred in the cell center.

5. References

[1] EG and G Technical Services, Inc. Science Applications International Corporation, *Fuel Cell Handbook,* sixth edition, US Department of Energy, 2002.

[2] M. Kamvar, M. Ghassemi and M. Rezaei, Effect of catalyst layer configuration on single chamber solid oxide fuel cell performance*, Journal of Applied Thermal Engineering*, Vol. 100, pp.98-104, 2016.

[3] J. Kupecki, K. Motylinski, A. Zurawska, M. Kosiorek and L. Ajdys, Numerical analysis of an SOFC stack under loss of oxidant related fault conditions using a dynamic non-adiabatic model, *Int. J. Hydrogen Energy*, Vol. 44, pp. 21148-21161, 2019.

[4] E.A. El-Hay, M.A. El-Hameed and A.A. El-Fergany, Optimized Parameters of SOFC for steady state and transient simulations using interior search algorithm, *J. Energy*, Vol. 166, pp.451-461, 2018.

[5] J. Moreno-Blanco, F. Elizalde-Blancas, J.M. Riesco-Avila, J.M. Belman-Flores and A. Gallego-Munoz, On the effect of gas channels-electrode interface area on SOFCs performance, *Int. J. Hydrogen Energy*, Vol. 44, pp. 446-456, 2019.

[6] A. Amiri, S. Tang and R. Steinberger-Wilckens, M.O. Tadé: Evaluation of Fuel Diversity in Solid Oxide Fuel Cell Systems, *Int. J. Hydrogen Energy*, Vol. 43, pp. 23475-23487, 2018.

[7] R. Bove and S. Ubertini, *Modeling Solid Oxide Fuel Cells, Methods, Procedures and Technologies*, First Edition, Springer, 2008.

[8] Y. Wang, W. Jiang, Y. Luo, Y. Zhang and Sh. Tu, Evolution of thermal stress and failure probability during reduction and re-oxidation of solid oxide fuel cell, *J. Power Sources*, Vol. 371, pp. 65-76, 2017.

[9] Y. Hao, Z. Shao, J. Mederos, W. Lai, D. G. Goodwin and S. M. Haile, Recent advances in single-chamber fuel cells: Experiment and modeling, *Solid State Ionics*, Vol. 177, pp. 2013-2021, 2006.

[10] S. Ahn, Y. Kim, J. Moon, J. Lee and J. Kim, Influence of patterned electrode geometry on performance of co-planar, single-chamber, solid oxide fuel cell, *J. Power Sources*, Vol. 171, pp. 511-516, 2007.

[11] M. Yano, A. Tomita, M. Sano and T. Hibino, Recent advances in single-chamber solid oxide fuel cells: A review, *Solid State Ionics*, Vol. 177, pp. 3351-3359, 2007.

[12] N. Akhtar, *Single-Chamber Solid Oxide Fuel Cells: Modeling and Experiments*, PhD thesis, Department of Chemical Engineering, University of Birmingham, Birmingham, UK, 2010.

[13] M. Yano, A. Tomita, M. Sano and T. Hibino, Recent advances in single-chamber solid oxide fuel cells: A review*, Solid State Ionics* Vol. 177, pp. 3351-3359, 2007.

[14] N. Akhtar, S. P. Decent and K. Kendall, Numerical modelling of methane-powered micro-tubular, single-chamber solid oxide fuel cell, *J. Power Sources*, Vol. 195, pp. 7796-7807, 2010.

[15] T. Hibino and H. Iwahara, Simplification of solid oxide fuel cell system using partial oxidation of methane*, Chemistry Letters*, Vol. 22, pp. 1131-1134, 1993.

[16] M. Kamvar, M. Ghassemi and R. Steinberger-Wilckens, The numerical investigation of a planar single chamber solid oxide fuel cell performance with a focus on the support types, *Int. J. Hydrogen Energy*, Vol. 45, pp. 7077-7087, 2020.

[17] Ch. Y. Chung and Y. Ch. Chung, Performance characteristics of micro single-chamber solid oxide fuel cell: Computational analysis*, J. Power Sources*, Vol. 154, pp. 35-41, 2006.

[18] M. Liu, Zh. Lu, B. Wei, X. Huang, Y. Zhang and W. Su, Numerical modeling of methane-powered micro-tubular, single-chamber solid oxide fuel cel, *J. Power Sources*, Vol. 195, pp. 7796-7807, 2010.

[19] N. Akhtar, S. P. Decent, D. Loghin and K. Kendall, A three dimensional numerical model of a single-chamber solid oxide fuel cell, *Int. J. Hydrogen Energy*, Vol. 34, pp. 8645-8663, 2009.

[20] N. Akhtar, S. P. Decent and K. Kendall, A parametric analysis of a micro-tubular, single-chamber solid oxide fuel cell (MT-SC-SOFC), *Int. J. Hydrogen Energy*, Vol. 36, pp. 765-772, 2011.

[21] X. Jacques-Bedrad, T.W. Napporn, R. Roberge and M. Meunier, Performance and ageing of an anode-supported SOFC operated in single-chamber conditions, *J. Power Sources*, Vol. 153, pp. 108-113, 2006.

[22] B. Morel, R. Roberge, S. Savoie, T. W. Napporn and M. Meunier, Temperature and performance variations along single chamber solid oxide fuel cells, *J. Power Sources*, Vol. 186, pp. 89-95, 2009.

[23] Y. Hao and D. G. Goodwin, Numerical Modeling of Single-Chamber SOFCs with Hydrocarbon Fuels, *J. Electrochem. Soc.*, Vol. 154, pp. B207-B217, 2007.

[24] N. Akhtar and K. Kendall, Micro-tubular, solid oxide fuel cell stack operated under single-chamber conditions, *Int. J. Hydrogen Energy*, Vol. 36, pp. 13083-13088, 2011.

[25] N. Akhtar, Micro-tubular, single-chamber solid oxide fuel cell (MT-SC-SOFC) stacks: Model development, *Chemical Engineering Research and Design*, Vol. 90, pp. 814-824, 2012.

[26] N. Akhtar, Modeling of novel porous inserted micro-tubular, single-chamber solid oxide fuel cells (MT-SC-SOFC), *Chemical Engineering Journal*, Vol. 179, 2012, pp. 277-284.

[27] Y. Hao and D.G. Goodwin, Efficiency and fuel utilization of methane-powered single-chamber solid oxide fuel cells, *J. Power Sources*, Vol. 183, pp. 157-163, 2008.

[28] W. Kong, Zh. Han, S. Lu, X. Gao and X. Wang, A novel interconnector design of SOFC, *Int. J. Hydrogen Energy*, Vol. 45, pp. 20329-20338, 2020.

[29] C. Schluckner, V. Subotic, S. Preibl and C. Hochenauer, Numerical analysis of flow configurations and electrical contact positions in SOFC single cell and their impact on local effects, *Int. J. Hydrogen Energy*, Vol. 44, pp. 1877-1895, 2019.

[30] J. Moreno-Blanco, F. Elizalde-Blancas, J.M. Riesco-Avila, J.M. Belman-Flores and A. Gallegos-Munoz, On the effect of gas channels-electrode interface area on SOFCs performance, *Int. J. Hydrogen Energy*, Vol. 44, pp. 446-456, 2019.

[31] Y. Guo, M. Bessaa, S. Aquado, M. Cesar Steil, D. Rembelski, M. Rieu, J. Viricelle, N. Benameur, Ch. Guizard, C. Tardivat, Ph. Vernoux and D. Farrusseng, An all porous solid ocide fuel cell (SOFC): a bridging technology between dual and single chamber SOFCs, *Energy Environ. Sci*., Vol. 6, pp. 2119-2123, 2013.

[32] H. Xu, B. Chen, P. Tan, J. Xuan, M. Mercedes Maroto-Valer, D. Farrusseng, Q. Sun and M. Ni, Modelling of all-porous solid oxide fuel cells with a focus on the electrolyte porosity design, *Applied Energy*, Vol. 235, pp. 602-611, 2019.

[33] H. Xu, B. Chen, P. Tan, Y. Zhang, Q. He, Zh. Wu and M. Ni, The thermal effects of all-porous solid oxide fuel cells, *J. Power Sources*, Vol. 440, Article 227102, 2019.

[34] B. Timurkutluk, S. Celik, C. Timurkutluk, M.D. Mat and Y. Kaplan, Novel electrolytes for solid oxide fuel cells with improved mechanical properties, *Int. J. Hydrogen Energy*, Vol. 37, pp. 13499-13509, 2012.