Numerical comparison of planar and micro-tubular solid oxide fuel cells

Düzlemsel ve silindirik katı oksit yakıt pillerinin sayısal karşılaştırılması

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Highlights

- ❖ *This study investigates the performance of planar and micro-tubular solid oxide fuel cells.*
- ❖ *The increasing temperature and pressure increase the performance of both SOFC.*
- ❖ *The planar SOFC outperforms the micro-tubular SOFC.*

Graphical Abstract

This study investigates numerically effects of cell configuration and operating conditions (temperature and pressure) on performance by using COMSOL software.
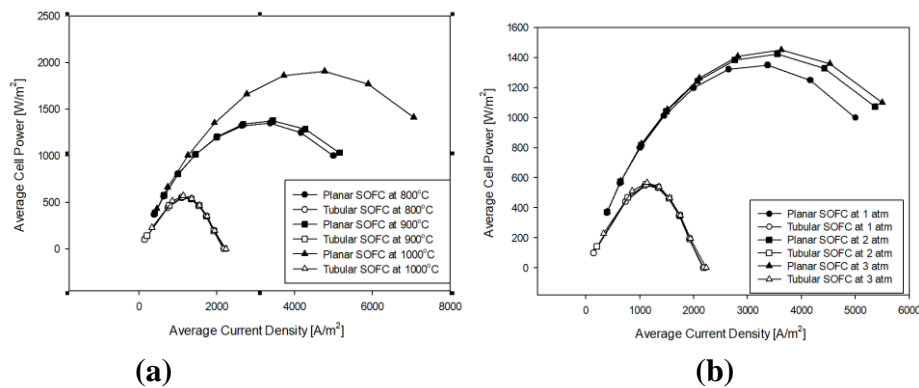

(a)   **(b)**

Figure. The power curves of micro-tubular and planar SOFC at different temperatures (a) and pressures (b).

Aim

This study aims to investigate the effect of fuel cell configuration and operating conditions on fuel cell performance.

Design & Methodology

In this study, a numerical model was developed using COMSOL software.

Originality

Although there are studies in the literature for different configurations, studies comparing the performance of these fuel cells are very limited.

Findings

The performance of the planar and micro-tubular fuel cell was analyzed at different temperatures (800 ° C-900 ° C - 1000 ° C) and different pressures (1-2-3 atm).

Conclusion

Although micro-tubular type shows very good performance for lower average current density, it can be concluded that the planar SOFC outperforms the micro-tubular SOFC and the increasing temperature and pressure increase the performance of both SOFC.

Declaration of Ethical Standards

The authors of this article declare that the materials and methods used in this study do not require ethical committee permission and/or legal-special permission.

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Araştırma Makalesi/Research Article

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ÖZ

Katı oksit yakıt pilleri (KOYP), düzlemsel ve silindirik şeklinde olmak üzere birçok farklı geometride tasarlanabilen yüksek verimli bir güç üretim sistemidir. Çalışma performansları aynı prensiplere dayanmakla birlikte, parametreler her geometri için farklıdır. Bu çalışma, sonlu elemanlar yöntemi (FEM) tabanlı KOYP modelleri geliştirerek hücre konfigürasyonunun performans üzerindeki sayısal etkilerini araştırmaktadır. Konfigürasyonun yakıt hücresi üzerindeki etkileri voltaj, ortalama hücre akım yoğunluğu ve ortalama hücre gücü açısından incelenmektedir. Bu etkiler, COMSOL yazılımı kullanılarak polarizasyon ve güç eğrileri ile gösterilmiştir. Bu çalışmanın sonucunda, her iki tipte kendi avantajlarına sahip olmasına rağmen, verilen işletme şartlarında düzlemsel KOYP performansının silindirik KOYP performansından daha iyi olduğu söylenebilir.

Anahtar Kelimeler: Düzlemsel KOYP, mikro-silindirik KOYP, performans, sayısal analiz.

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ABSTRACT

Solid oxide fuel cell (SOFC) is a highly efficient power generation system that can be designed in many different geometries including planar and tubular types of fuel cell. Although their operating performance is based on the same principles, parameters may be unique for each geometry. This study investigates numerically effects of cell configuration on performance by developing a finite element method (FEM) based SOFC models. The effects of configuration on the fuel cell are investigated in terms of voltage, the average cell current density, and the average cell power. These effects are illustrated with polarization and power curves by using COMSOL software. As the most convenient results of this study, although both types have their own advantages, it can be concluded that the performance of the SOFC increases with the planar geometry compared to micro-tubular type under the studied operating conditions.

Keywords: Planar SOFC, micro-tubular SOFC, performance, numerical analysis.

1. INTRODUCTION

With the growing population and industrialization, energy demand all over the world is increasing rapidly. Fossil fuels that have been used for this demand are limited. Because of that reason people have turned to a new search as regards sustainable energy. One of the most promising devices is the fuel cells.

Fuel cells are devices that generate electrical energy directly from oxidizing a fuel. They have many advantages. They are used for its high efficiency, fuel flexibility, low cost, and low emissions. Fuel cells are generally categorized according to their operating temperature and supporting zone. Solid oxide fuel cells are one of the high- temperature fuel cell types. Solid oxide fuel cells (SOFC) stand out with their high efficiency and widespread industrial usage. Ceramic materials used in its products provide low cost and durability. Operating temperatures may vary depending on electrolyte materials. Most of SOFC operate at temperatures of approximately 800-1000 ° C. When material selections and sealing materials are kept under

control, this temperature can drop down to 600 ° C. High temperature is very important for operating performance as it increases the ionic transport coefficient of oxygen in the cells. Also, high-temperature exhaust gases are very suitable for cogeneration applications. Thanks to these advantages, SOFCs can be used efficiently in combined heat-power systems [1,2]. SOFCs have different design features such as micro-tubular and planar. Micro-tubular SOFCs are advantageous compared to planar ones since the sealing is not problematic as in planar ones.

Several studies have been reported on the performance and design of solid oxide fuel cells. Nam et al. [3] stated that particle size is the most important parameter for cell performance with the micro model they made in three-phase boundaries. They concluded that smaller particle size increased cell performance for large three-phase boundaries. In the model they developed, Costamagna et al. [4] stated that the thickness and internal structure of the electrodes are very important for cell performance and should be optimized according to the active surface area. Yakabe et al. [5] simulated flow events using a finite volume method in their study on a planar solid oxide fuel cell with the opposite flow. In the model, it was assumed that the gas flow in the porous anode is

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governed by Darcy's Law. From the simulated results, it has concluded that the shift reaction effectively reduces the concentration polarization when the fuel utilization is high. Chen et al. [6] examined the effects of working conditions and cell design parameters in the two-dimensional electrolyte-supported planar solid oxide fuel cell model. They tried to reach the maximum current density by changing the thickness of the cathode electrode between 1-3 mm and changing the electrolyte thicknesses in the range of 30 μm, 300 μm, 500 μm. In their planar SOFC geometry, Liu et al. [7] designed parallel, counter, and cross-flow in the channel and compared them with experimental values. The results by the 3D models show that the stack cell performances and the optimal rib widths are all very similar for counter-, and cross-flow designs. Cheng et al. [8] designed a tubular SOFC and examined the cell performance and efficiency effects according to different current collector parameters. By using the model, tubular cells operating under three different modes of the current collection, including inlet current collector, outlet current collector, and both inlet and outlet collector, are proposed and simulated. Serincan et al. [9] investigated the effects of temperature, fuel flow rate, fuel composition, anode, and cathode pressure on a micro-tubular fuel cell performance by computational fluid dynamics (CFD). Akhtar et al. [10] have demonstrated a parametric study for a microtubular solid oxide fuel cell. They examined parameters such as inlet velocity, working pressure, mixing ratio, current density, porosity, permeability, and relative radiation emission according to the boundary conditions they set for the cell by COMSOL Multiphysics. Aman et al. [11] examined the performance change by changing the cathode surface area, electrolyte conductivity, and anode current density parameters in the model they made using the COMSOL Multiphysics. Homel et al. [12] operated CO as a fuel in both tubular and planar SOFC. Ilbas and Kümük [13] investigated the parameters (support thickness, oxidant type, operating temperature, and pressure) affecting the performance of a cathode and an electrolyte supported planar SOFC numerically. Ilbas and Kümük [14] developed a mathematical model to determine the performance of cathode-supported planar SOFC fuelled low calorific value coal gases. Ilbas et al. [15] investigated the effect of ammonia used in electrolyte-supported SOFC numerically. Firstly, they compared the use of ammonia and hydrogen in the electrolyte-supported SOFC and then examined the effect of ammonia in different supported SOFC.

There exist numerous studies on the modelling of planar and micro-tubular SOFC, however, there is little done for comparing these two different geometries. The main goal of this study is to investigate the performance of planar and micro-tubular type SOFCs with the same thicknesses of electrolyte and electrode. Besides, fuel cells have compared at different temperatures and pressure by being analyzed numerically.

2. MODELING

The geometries of the planar and micro-tubular SOFCs used in the analysis are shown in Fig. 1(a) and (b).The unit cell contains porous cathode and anode, electrolyte, current collector, anode, and cathode flow channels. Porous anode, electrolyte, and cathode layers are defined as homogeneous in terms of porosity, permeability, and conductivity. The electrolyte layer is thin enough to allow ion exchange.
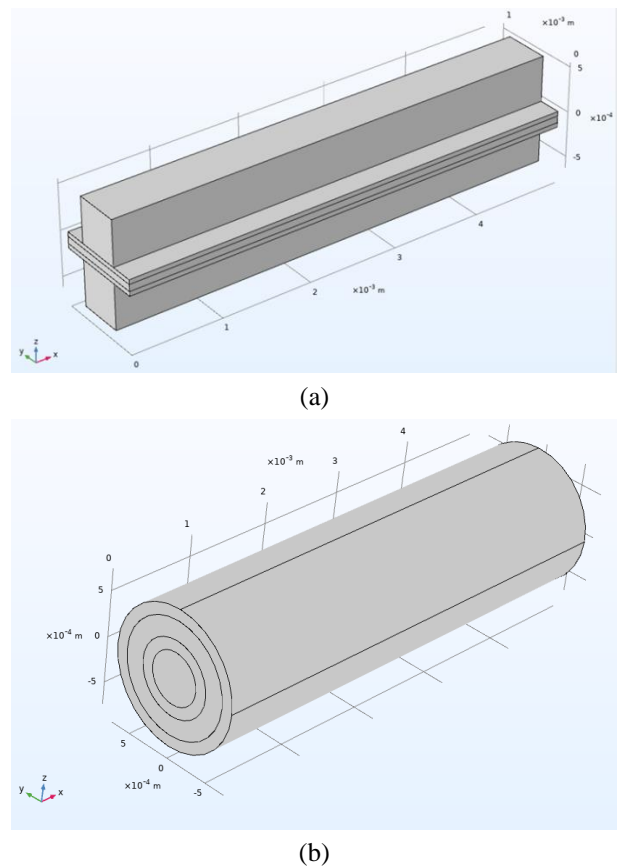

(a)

(b)

Fig. 1. Schematic of model planar (a), and micro-tubular (b) solid oxide fuel cell

In a solid oxide fuel cell, oxygen decomposes into O^{2-} ions in the triple-phase region located in the cathode of the cell and move from the electrolyte layer to the anode. Fuel also decomposes into ions in the anode layer and releases electrons. These electrons move through the outer circuit to the cathode layer. When hydrogen is used as fuel, the chemical reactions occur in anode and cathode electrodes can be expressed in Eqs. (1) and (2), respectively.

$$H_2(g) + O^{2-} \rightarrow H_2O(g) + 2e^- \qquad (1)$$

$$\frac{1}{2}O_2(g) + 2e^- \rightarrow O^{2-} \qquad (2)$$
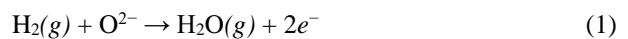
The mathematical model is expressed by the conservation of momentum, mass, electrical charge, and energy with appropriate constitutive laws. The conservation laws are given in Eq. (3)-(5).

Mass conservation of a gas species evolving in a porous media within an infinitesimal volume can be written as:

$$\varepsilon \frac{\partial \rho Y_i}{\partial t} + \varepsilon u \cdot \nabla(\rho Y_i) = -\nabla m_i + \omega_i \qquad (3)$$

where i denotes the generic ith species, ρ is density, ε is the porosity of the medium, ω_i is the rate of production or consumption, m_i is the mass diffusion flux, Y_i is the mass fraction, and u is the gas velocity.

Momentum conservation for a moving gas can be expressed as:

$$\rho \frac{\partial u}{\partial t} + \rho u \cdot \nabla u = -\nabla P + \mu \nabla^2 u + \rho f \qquad (4)$$

where f represents the generic body forces, ∇P is pressure gradient, μ is the dynamic viscosity. Equation (4) is a simplified formulation of the Navier–Stokes equations, specifically, near the incompressible limit. This form is generally employed in fuel cells gas flow simulation within the gas channels.

Energy conservation can be expressed in different forms. When e defines the energy per unit mass, the following equation for the conservation of energy is derived:

$$\rho \frac{\partial e}{\partial t} + \rho u \cdot \nabla e = -\nabla Q + S_q \qquad (5)$$

where S_q is the volumetric heat source term and Q is the heat flux vector-only from conduction.

The electron and ionic generation are described by the Butler–Volmer equation:

$$j = j_0 \left[\exp \left(\frac{\alpha_1 \, n \, F \, \eta_{act}}{R \, T} \right) - \exp \left(\frac{\alpha_2 \, n \, F \, \eta_{act}}{R \, T} \right) \right] \qquad (6)$$

In equation (6), j_0 is the exchange current density, α_1 and α_2 are the transfer coefficients related to, respectively, the forward and backward reaction, n is the number of electrons transferred per reaction and η_{act} is the activation loss.

Equilibrium voltage can be written as:

$$E_{eq} = - \frac{\Delta G^0}{2F} + \frac{RT}{4F} \ln \frac{P_{O2} P^2_{H2}}{P^2_{H2O}} = E^0 + \frac{RT}{4F} \ln \frac{P_{O2} P^2_{H2}}{P^2_{H2O}} \qquad (7)$$

where R is gas constant, F is Faraday constant, T is temperature, ΔG^0 is the standard free-energy change of the reaction at standard pressure, E^0 is standard cell potential, P is partial pressures.

The values of input parameters used in both SOFC models are stated in Table 1.

Table 1. Input parameters used in both SOFC models

Parameter	Unit	Value
Cell length	mm	50
Electrodes thickness		0.5
Electrolyte thickness		0.75
Pressure	atm	1~3
Temperature	°C	800~1000
Permeability	m^2	10^{-10}
Exchange current density, cathode	A/m^2	0.01
Exchange current density, anode	A/m^2	0.1
Electrolyte conductivity	S/m	5
Current collector conductivity	S/m	5000
Cell voltage	V	0.75

3. RESULTS AND DISCUSSIONS

The mathematical models developed have been examined numerically by COMSOL Multiphysics. The software used has a solid oxide fuel cell module for numerical modelling. The planar and micro-tubular models were developed and analyzed under different operating temperatures and pressures.

3.1 Polarization Curve

Fig.2 shows the polarization curve, which has remissible activation losses, ohmic losses, and very small mass transport losses, at 800°C for micro-tubular and planar SOFC. The starting region of this curve describes the activation region which shows that the reaction rate is quite fast. We can see the losses in the starting region are higher in the planar fuel cell compared to micro-tubular SOFC. The middle region is nearly a straight line that tells about the ohmic losses. Electrolyte resistance causes these losses. The last part of the curve shows the concentration losses in the fuel cells.
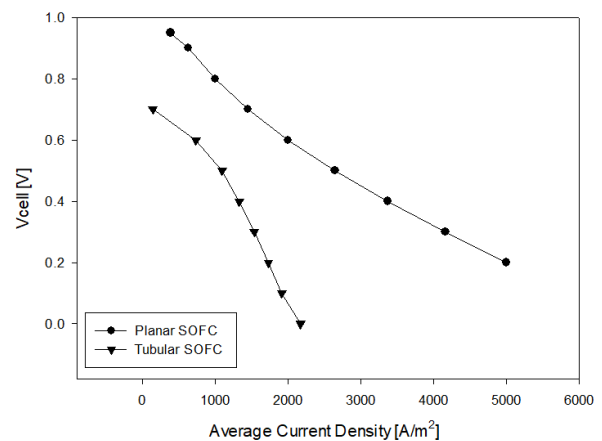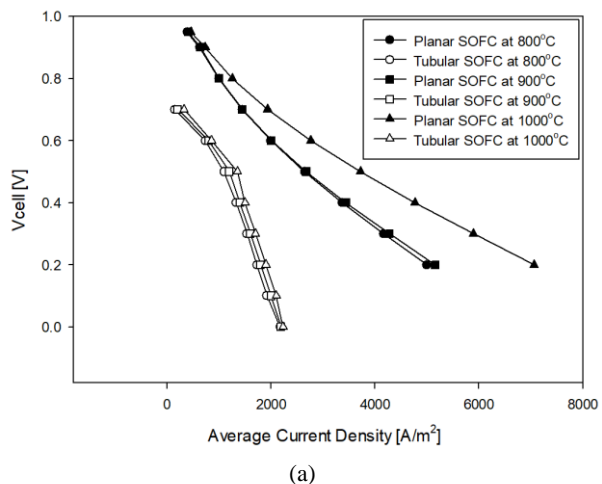

Fig. 2. The polarization curve for comparison micro-tubular and planar SOFC at 800°C

As can be seen in Fig. 2, the current density in the micro-tubular SOFC has increased faster because ohmic losses are dominant in the micro-tubular SOFC. Fig.3 proves the polarization curves of micro-tubular and planar SOFC at different temperatures (a) and pressures (b).
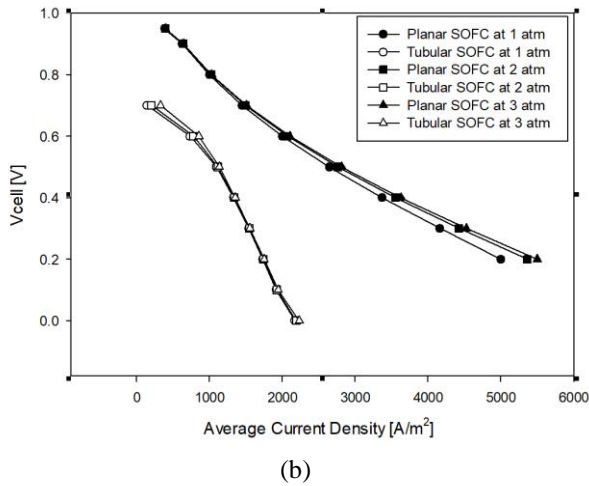

(a)

(b)

Fig. 3. The polarization curves of tubular and planar SOFC at different temperatures(a) and pressures (b).

As can be seen in Fig. 3, the average current density increases for both fuel cells as the temperature and pressure increase. This increase is more pronounced in planar SOFC, while less in micro-tubular SOFC. As the pressure increases, the concentration losses decrease because of the reactant diffusion decreases in the fuel cell. So, Nernst potential and average current density increase.

3.2. Cell Power

Fig. 4 express the variation of power density per square meter with an increase of current density at 800°C. In both fuel cells, power density initially increases with increasing current density and achieves a peak value. After getting a peak value power densities decrease with more increase in current density.
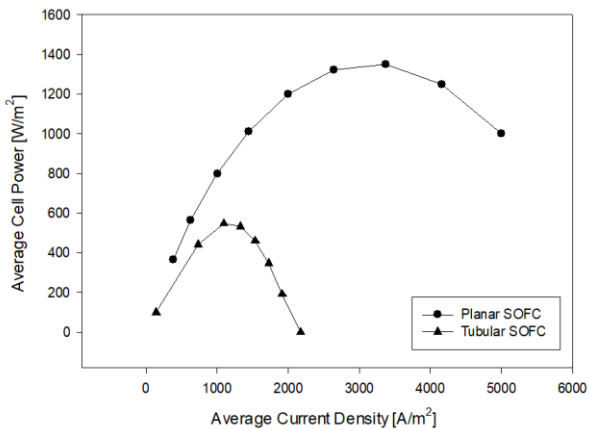

Fig. 4. The power curve for comparison micro-tubular and planar SOFC at 800°C

As can be seen in Fig. 4, in terms of average power density, planar SOFC is about twice as advantageous as micro-tubular SOFC. This is because planar SOFC has a shorter current path, which leads to lower ohmic loss and high power density. Fig.5 shows the power curves of micro-tubular and planar SOFC at different temperatures (a) and pressures (b).
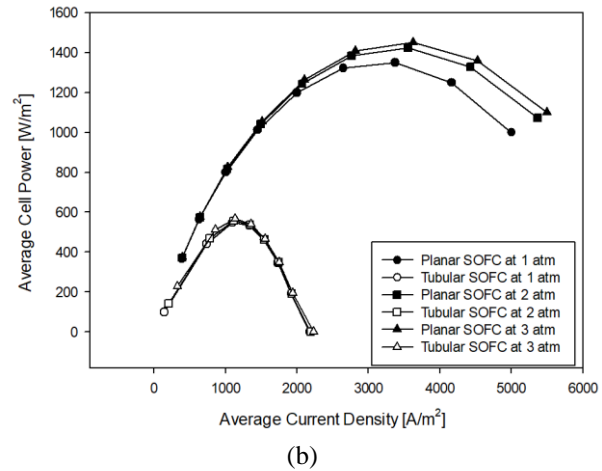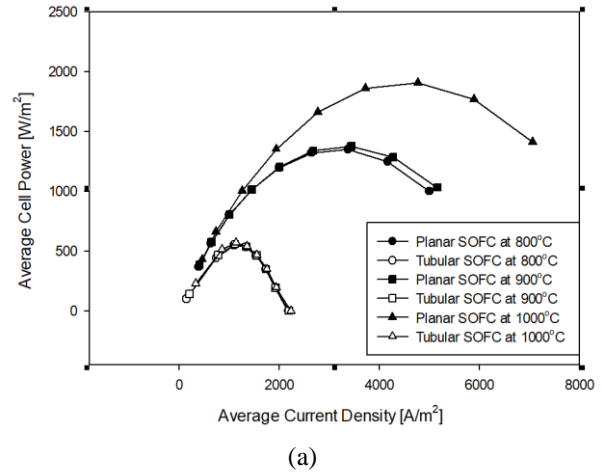

(a)

(b)

Fig. 5. The power curves of micro-tubular and planar SOFC at different temperatures (a) and pressures (b).

At operating temperature of 900° C, maximum power densities of 1376 and 556 W/m^2, and at operating temperature of 1000°C,maximum power densities of 1908 and 569 W/m^2 were achieved on micro-tubular and planar cells, respectively. Also, at operating pressure of 2 atm, maximum power densities of 1422 and 556 W/m^2, and at operating pressure of 3 atm, maximum power densities of 1457 and 567 W/m^2 were achieved on micro-tubular and planar cells, respectively. As can be seen in Fig. 5, micro-tubular SOFC was less affected by temperature and pressure changes than planar SOFC. However, the average power density increases with increasing temperature and pressure in both fuel cell configurations. This is because the conductivity of the electrolyte is improving and the ohmic resistances are considerably reduced at high temperatures and pressures.

6. CONCLUSION

In this paper, micro-tubular and planar SOFC models were developed to determine the performance of both SOFC configurations under different operating conditions.

It has been observed that the performance of a planar SOFC higher than a micro-tubular SOFC. Furthermore,

the rise in temperature and pressure has further increased the average cell power of both planar and micro-tubular SOFC.

In the planar SOFC, the average current density is increased by 29% while the cell power is increased by about 31% when the temperature is increased from 800°C to 1000°C. In the micro-tubular SOFC, the average current density and cell power are increased by about 5% when the temperature is increased from 800°C to 1000°C. As a result of these analyzes, micro-tubular SOFC has been less affected by temperature increase than planar SOFC.

When the pressure increased from 1 atm to 3 atm, the average cell power increased by 12% and %8 planar and micro-tubular SOFC, respectively.

In general, altough micro-tubular type shows very good performance for lower average current density, it can be concluded that planar SOFC outperforms the micro-tubular SOFC under the studied operating conditions. It is also concluded that as temperature and pressure increase, power density has increased for both types of fuel cells.

ACKNOWLEDGEMENT

DECLARATION OF ETHICAL STANDARDS

The authors of this article declare that the materials and methods used in this study do not require ethical committee permission and/or legal-special permission.

AUTHORS' CONTRIBUTIONS

Mustafa ILBAS: Performed the numerical analyses and analyse the results.

Fethi Mustafa CIMEN: Performed the numerical analyses and analyse the results. Wrote the manuscript.

Berre KUMUK: Performed the numerical analyses and analyse the results.

CONFLICT OF INTEREST

There is no conflict of interest in this study.

REFERENCES

[1] Torabi A., Etsell T. H., Sarkar P., "Dip coating fabrication process for micro-tubular SOFCs", **Solid State Ionics**, 192 (1): 372-375,(2010).

[2] Mench M.M., "Fuel Cell Engines",**Wiley**, USA, 525s, (2008).

[3] Nam J.H., Jeon D.H., "A comprehensive micro-scale model for transport and reaction in intermediate temperature solid oxide fuel cells", **Electrochimica Acta**, 51 (17), 3446–3460,(2006).

[4] Costamagna P, Costa P, Antonucci V., "Micro-modeling of solid oxide fuel cell electrodes", **Electrochimica Acta** , 43: 375–94,(1998).

[5] Yakabe H., Hishinuma M., Uratani M., Matsuzaki Y., Yasuda I., "Evaluation and modeling of performance of anode-supported solid oxide fuel cell", **Journal of Power Sources,** 86(1–2): 423–431,(2000).

[6] Cui D., Yang C., Huang K., Chen F., "Effects of testing configurations and cell geometries on the performance of a SOFC: A modeling approach", **International Journal of Hydrogen Energy**, 35(19): 10495–10504 (2010).

[7] Liu S., Kong W., Lin Z., "Three-dimensional modeling of planar solid oxide fuel cells and the rib design optimization", **Journal of Power Sources**, 194(2): 854-863,(2009).

[8] Cui D., Liu L., Dong Y., Cheng M., "Comparison of different current collecting modes of anode supported micro-tubular SOFC through mathematical modeling", **Journal of Power Sources**, 174(1): 246–254, (2007).

[9] Serincan M.F., Pasaogullari U., Sammesb N.M., "Effects of operating conditions on the performance of a micro-tubular solid oxide fuel cell (SOFC)", **Journal of Power Sources**, 192(2): 414–422, (2009).

[10] Akhtar N., Decent S., Kendall K., "A parametric analysis of a microtubular, single-chamber solid oxide fuel cell (MT-SC-SOFC)", **International Journal of Hydrogen Energy**, 36(1): 765-772,(2011).

[11] Aman A., Gentile R., Xu Y., Orlovskaya N.," Parametric Study of Electrolyte-Supported Planar Button Solid Oxide Fuel Cell", **Comsol Reference Guide** (2012).

[12] Homel M, Gür TM, Koh JH, Virkar AV. "Carbon monoxide-fueled solid oxide fuel cell", **Journal of Power Sources,**195(19): 6367-6372, (2010).

[13] Ilbas M, Kümük B. "Numerical modelling of a cathode-supported solid oxide fuel cell (SOFC) in comparison with an electrolyte-supported model". **Journal of the Energy Institute**, 92(3): 682-692,(2019).

[14] Ilbas M, Kümük B. "Modelling and analysis of a model solid oxide fuel cell running on low calorific coal gases". **International Journal of Hydrogen Energy**, 45(5): 3577-3583, (2020).

[15] Ilbas M, Kümük B, Alemu MA, Arslan B. "Numerical investigation of a direct ammonia tubular solid oxide fuel cell in comparison with hydrogen.", **International Journal of Hydrogen Energy**, In Press.