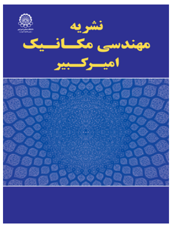

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Numerical Simulation of a Biogas-fueled Solid Oxide Fuel Cell and the Investigation of the Influence of Operating Conditions

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ABSTRACT: Using biogas, rather than pure hydrogen, in a solid oxide fuel cell (SOFC) can help the green energy production chain. This research investigates the influence of operating conditions on the performance of a biogas-fueled SOFC. In this regard, a 3D numerical model is developed using a finite volume approach and Fluent software. User Defined Functions are employed to introduce the steam reforming processes inside the SOFC. The second-order upwind scheme and SIMPLE algorithm are used for the discretization of governing equations and the pressure-velocity coupling. The results indicate that the power density first increases and then decreases by increasing the steam-to-fuel (S/C) ratio. Increasing the biogas methane content causes the performance of the SOFC to improve by enhancing the rates of reforming reactions. At a voltage of 0.5V and an operating temperature of 1073K, increasing the biogas methane percentage from 45% to 65%, causes the power to increase by 15%. Also, increasing the operating temperature enhances the SOFC performance by increasing the rates of reforming and electrochemical reactions and the electrolyte ionic conductivity. At a voltage of 0.5V, for a biogas methane percentage of 65%, increasing the operating temperature from 1073K to 1273K leads to a 132% growth of power. It is also found that the optimal S/C ratio decreases with temperature and increases with biogas methane content and lies within the range of 0.3-1.2.

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1- Introduction

SOFCs due to their operation at high temperatures, can utilize alternative hydrogen fuels, including methane, biogas, and other hydrocarbons [1]. The introduction of water vapor at the fuel cell inlet induces steam reforming reactions, mitigates the risk of carbon deposition, and enhances fuel flexibility [2]. Finding the optimal amount of water vapor to be added to the fuel in a SOFC fueled with biogas is a challenging task. Adding too little water to biogas can impede the formation of steam-reforming reactions or lead to carbon deposition. Conversely, adding too much water can result in a performance drop of fuel cells due to fuel deficiency [3]. Previous research activities in investigating the performance of biogas-fed solid oxide fuel cells with added water vapor have generally employed a thermodynamic approach [4], focusing on specific biogas [5], a limited range of steam-to-fuel ratios [6], and a fixed operating temperature [7].

This study aims to provide a more comprehensive understanding of the steam reforming process in a biogas-fed solid oxide fuel cell to cover the mentioned gaps. For this purpose, a three-dimensional numerical model is developed, and the influence of biogas composition, steam-to-fuel ratio, and operating temperature on the behavior of a biogas-fed solid oxide fuel cell is investigated.

2- Mathematical model

In order to simulate a SOFC, it is necessary to solve a set of partial differential equations that describe the transport phenomena within the fuel cell. These equations include the mass conservation equation, momentum equation, energy equation, species transport equation, and phase potential equation.

The direct utilization of biogas fuel containing CH_4 and CO_2 in a SOFC necessitates the occurrence of reforming reactions within the anode electrode. The primary reforming reactions include the steam reforming and water-gas shift reaction, shown in equations (1) and (2), respectively [8]:

$$\text{SR:}\ CH_4 + H_2O \rightarrow 3H_2 + CO \tag{1}$$

$$\text{WGS:}\ CO + H_2O \rightarrow CO_2 + H_2 \tag{2}$$

The reaction rates for the steam reforming and water-gas shift reactions are calculated according to equations (2) and (3):

$$R_{SR} = K_{rf}\left(P_{CH_4}P_{H_2O} - \frac{P_{CO}(P_{H_2})^3}{K_{pr}}\right) \tag{3}$$

$$R_{WGS} = K_{sf}\left(P_{H_2}P_{CO} - \frac{P_{H_2}P_{CO_2}}{K_{Ps}}\right) \tag{4}$$

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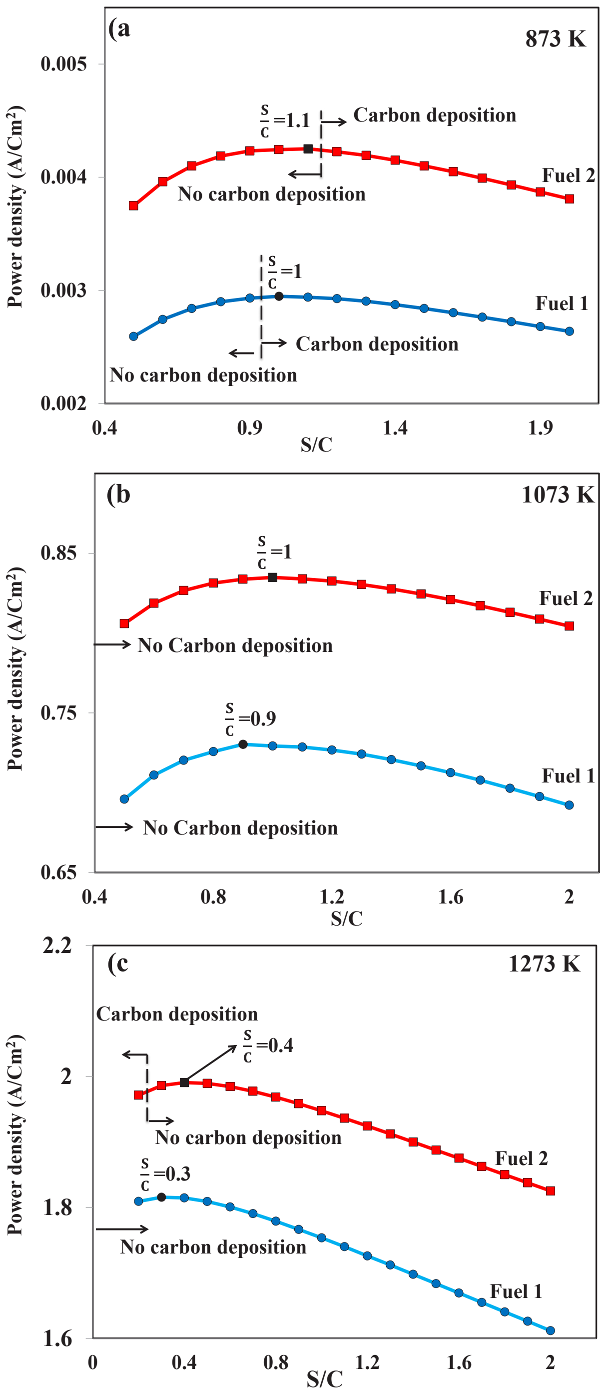

Fig. 1. The effect of S/C ratio on the performance of a fuel cell under various operating conditions

The influences of steam reforming reactions on the species transport and energy equations are considered by using User Defined Functions (UDFs) in ANSYS FLUENT software.

3- Result and Discussion

This research investigates the influence of operating conditions on the performance of an SOFC. To this end, two types of biogases with different methane fractions (at 45% and 65% molar ratios), three different operating temperatures (873, 1073, and 1273 K), and a wide range of S/C ratios (from 0.2 to 2) are examined.

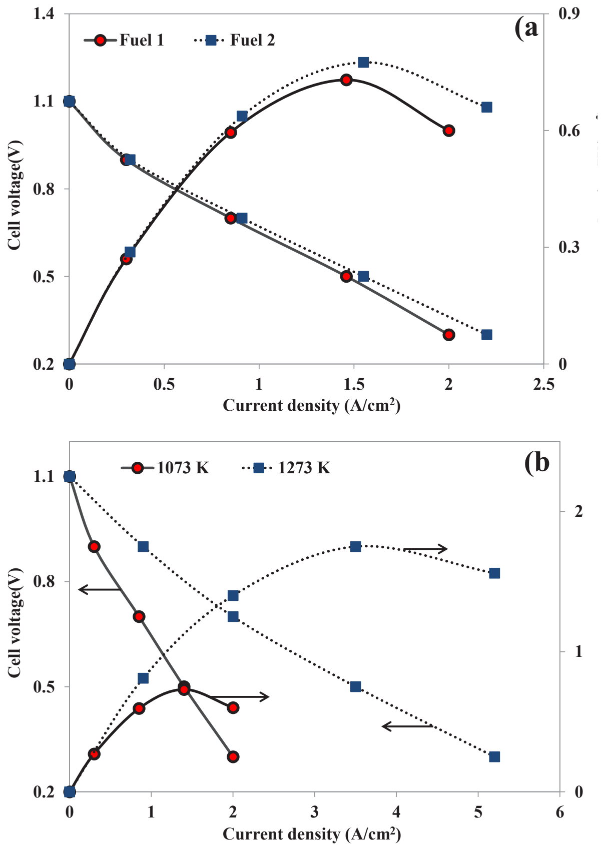

Fig. 2. Comparison of power density and polarization curves (a) effect of fuel type (b) effect of temperature

Figure 1 illustrates the power density of the SOFC under various operational conditions. In this figure, Fuel 1 and 2 have the methane-to-carbon dioxide ratios of 0.82 and 1.85, respectively. It is observed that the power density initially increases and then decreases with the increase of S/C ratio. Also, as a result of the increase in temperature (regardless of fuel type and S/C ratio), the fuel cell performance improves due to a noticeable enhancement in reforming reaction rates. Furthermore, the optimal S/C ratio, leading to a maximum power output, decreases with the increase of temperature. Figure 1 also indicates that the methane-rich fuel (i.e., Fuel 1) leads to higher power densities and higher optimal S/C ratios, as compared to Fuel 2. Figure 1 shows that the risk of carbon deposition is higher at lower temperatures and for fuels with higher methane contents.

The influence of each fuel type and operating temperature on both polarization and power curves are depicted in Figure 2. It is observed in Figure 2a that the power output of Fuel 2 (with a higher methane content) is considerably higher than that of Fuel 1 (with a lower methane content), and the difference is more pronounced at lower voltages. Also, for both fuels, the maximum power occurs at the operating voltage of 0.5V. Figure 2b indicates that a higher operating temperature of 1273K results in a higher power output, and the difference between the two operating temperatures is more pronounced at lower operating voltages.

4- Conclusion

This study was concerned with the numerical study of a biogas-fueled solid oxide fuel cell under different operating conditions. In general, with an increase in operating temperature and fuel methane content, the rates of reforming reactions significantly increased, leading to more rapid consumption of methane, and increased hydrogen production and power density.

The optimal S/C ratio has decreased with an increase in the operating temperature. For instance, at 873 K, the optimal S/C ratios for different biogas compositions were in the range of 1-1.2, while at 1273 K, they were within the range of 0.3-0.4. The optimal S/C ratio increased with the biogas methane content. For example, at an operating temperature of 1073 K, the optimal S/C ratios were 0.9 and 1 for biogas with methane molar fractions of 45% and 65%, respectively. Furthermore, the results indicated that the risk of carbon deposition was higher at lower temperatures and for fuels with higher methane contents.

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