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Dynamic Response Analysis of the Planar and Tubular Solid Oxide Fuel Cells to the Inlet Air Mass Flow Rate Variation

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ABSTRACT

The purpose of present study is to investigate the dynamic response of two conventional types of solid oxide fuel cells to the inlet air mass flow rate variation. A dynamic compartmental model based on CFD principles is developed for two typical planar and tubular SOFC designs. The model accounts for transport processes (heat and mass transfer), diffusion processes, electrochemical processes, anode and cathode activation and ohmic polarizations, among others. Using developed model, the dynamic response of the cell to the step change of the air feed stream conditions is investigated. The results show an almost slow electrical response of the cell to the air mass flow rate step variation which is estimated to be about one hour. Moreover, it can be concluded that the effect of the inlet air flow conditions on a tubular solid oxide fuel cell performance is more noticeable than its effects on a planar SOFC. However, the electrical response time of the tubular type SOFC is calculated about ten times more than the planar type.

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1. INTRODUCTION

Solid oxide fuel cells are the most reliable high temperature fuel cells for industrial power generation applications. SOFC systems have been proposed for electric utility power generation in both large central station power plants and distributed generation stations [1]. High operating temperature of SOFCs creates some desirable points, for example in this system, expensive catalysts are not required for the electrochemical reaction. The high temperature also means that a gas turbine can be effectively combined with an SOFC in a hybrid manner to form a single unit for self-sustainable distributed energy system [2].

To function efficiently, a SOFC needs to maintain a high operating temperature, which facilitates the ion conductance of the solid oxide electrolyte and the high electrochemical reaction kinetics. However, too high temperature may lead to localized ‘‘hot spots’’, electrode sintering and a chemical reaction between the electrode and the electrolyte. On the other hand, thermal management of the cell and using the excess generated heat in a co-generation system is an important issue in high temperature fuel cells like SOFC [1]. Therefore, the temperature of a SOFC has to be controlled within a narrow range for safety and efficiency. An issue which can improve a SOFC’s performance includes optimization of the fuel-oxidant ratio or the stoichiometry of the oxidant. In addition, the air mass flow rate should be large enough to maintain effective cooling of the cell as well as to reduce the concentration polarization of the cathode side. So, properly thermal management of the cell could be provided via the inlet mass flow rate controlling [2]. Generally, the input airflow conditions might be a proper controlling parameter for the cell temperature and the other output characteristics of the cell, because of its significant effect on the cell temperature, species concentration and consequently the electrical outputs. To carry out the dynamic effects of the input airflow conditions, detail

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analysis of the dynamic phenomena occurring inside the SOFC is required. Therefore, a suitable mathematical model must be established to consider the complicated multi-physic dynamic phenomena occurring inside the fuel cell. Considerable number of research work have been conducted on the SOFC dynamic modeling, aiming to simulate transient phenomena such as load change and start up. Achenbach [3] analyzed the dynamic operation of a planar solid oxide fuel cell. He examined the transient cell voltage performance due to temperature changes and current density. Gemmen and Johnson [4] investigated a variety of transient cases, including representative load increase and decrease and system shutdown. Wang et al. [5] investigated the steady state and transient behavior of a co-flow planar solid oxide fuel cell with the volume-resistance characteristic modeling technique. Xie and Xue [6] developed an isothermal transient model for button solid oxide fuel cell. The model investigates the transient response of the button cell to the step change of load voltage, oxygen concentration and hydrogen concentration. In two literatures published by present authors, [7, 8] the heat-up and start-up behavior and load change response of a tubular SOFC is studied using a 2D transient numerical model.

In this study, the dynamic response of the solid oxide fuel cells to the inlet air mass flow rate is investigated theoretically for two conventional types of SOFCs) and the results are compared to each other. For this purpose, the typical experimented tubular and planar SOFC designs is considered to explore the dynamic effects of the inlet air flow perturbations [9, 10]. Understanding these phenomena is applicable for control of the cell temperature and electrical characteristics and consequently thermal management of the SOFC via the inlet air conditions adjustment.

2. GEOMETRY AND CONFIGURATION OF SOFC MODELS

2. 1. Tubular Solid Oxide Fuel Cell Figure 1 shows a schematic view of a single tubular solid oxide fuel cell in a cell stack. Each single cell is separated from the other cells by two symmetry lines in both sides of the cell tube. The computational domain and the flow streams of fuel and oxidant in a typical tubular SOFC are highlighted on the figure. Due to symmetry, only half of the cell unit (between the cell symmetry axis and the symmetry line between two adjacent cells) is considered. The closed end of the cell is assumed to be flattened for numerical model simplification. As shown by the figure 1, the computational domain includes the air and fuel channels, anode, cathode, electrolyte and the supporting tube layers. The fuel entrance is at the closed end of the cell. The geometrical characteristics of the tubular SOFC derived from reference [9].

2. 2. Planar Solid Oxide Fuel Cell The geometrical characteristics of the under-study planar SOFC stack are depicted in Figure 2. This figure shows a unit of a counter flow solid oxide fuel cell stack tested experimentally by Keegan et al. [10]. To reduce computational demand and complexity, a slice of the stack unite is taken as the geometrical model and it is assumed that all the slices in the whole stack work in the similar conditions. As shown in the figure 2, a 3D model is used for the transient behavior analysis of the planar solid oxide fuel cell. It is because that all three-dimensional effects of heat and mass transfer are noticeable in a planar solid oxide fuel cell especially for a transient analysis.

3. MATHEMATICAL MODEL

In some published literatures, we presented the transient form of the governing equations to investigate the load current change response of a SOFC unit cell [7].

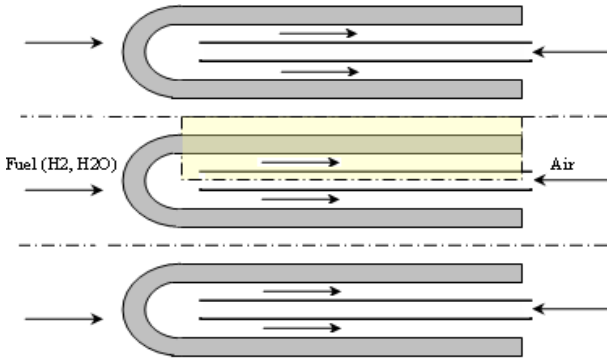

Figure 1. Schematic diagram of a tubular SOFC and the computational domain

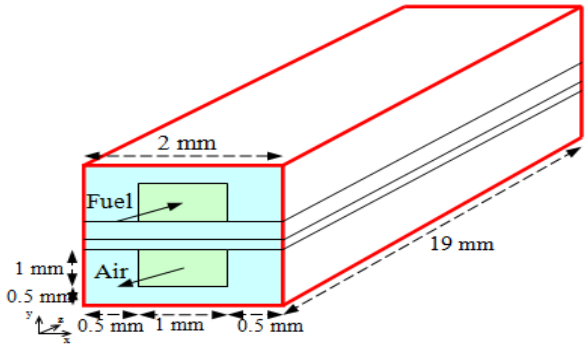

Figure 2. Geometrical specifications of a counter flow planar SOFC stack unit

In addition, the steady state and transient results of the model are evaluated and examined in these literatures. In the present study, we use the same transient model and governing equations to investigate dynamic behavior of two kinds of SOFC stack units for the inlet air mass flow rate variations and compare their responses.

3. 1. Electrochemical and Electrical Model In the simulation process, the cell ideal voltage, activation polarization and heat and mass sources is calculated by the electrochemical model. The concentration polarization due to the non-uniform distribution of the species existing in the air and fuel flow passages and the diffusion of the species within the porous electrodes is automatically taken into the account by the mass transfer model. The cell ideal and activation over potentials are given by following equations.

$$E = \frac{\Delta G}{nF} = E^0 + \frac{RT}{2F}\ln(\frac{P_{H_2}P_{O_2}^2}{P_{H_2O}}) \quad (1)$$

$$i = i_{0,eff}[\exp(\frac{\alpha_a n\eta_{act}F}{RT}) - \exp(\frac{\alpha_c n\eta_{act}F}{RT})] \quad (2)$$

where, α_a , α_c and n are anodic transfer coefficient, cathodic transfer coefficient and number of electrons which are released respectively. The molar sources of the species are calculated using following relations.

$$S_{H_2} = -\frac{i}{2F};\ S_{O_2} = -\frac{i}{4F};\ \ S_{H_2O} = \frac{i}{2F} \quad (3)$$

where i is the current density of the cell and F is the Faraday constant.

In the electrical model, the Laplace equation for the potential field is solved by subdividing the domain into control volumes and enforcing flux conservation on each cell.

$$i = -(\sigma\nabla\phi) \quad (4)$$

ϕ and σ are potential and ionic conductivity. Moreover, electrical potential equation is:

$$\nabla.(\sigma\nabla\phi) = 0 \quad (5)$$

This gradient is approximated using the numerical difference of the values of ϕ in each of the cells.

3. 2. Heat and Mass Transfer Model All aspects of fluid flow, heat transfer and mass transfer in the flow channels and porous electrodes are considered in present dynamic model. The transient form of mass, momentum, species and energy conservation equations in porous and gas channels are as follows in general form:

$$\frac{\partial(\varepsilon\rho)}{\partial t} + \nabla.(\varepsilon\rho\vec{u}) = 0 \quad (6)$$

where $\vec{u}$, ρ and ε are mixture velocity, density and volume fraction, respectively.

$$\frac{\partial(\varepsilon\rho\vec{u})}{\partial t} + \nabla.(\varepsilon\rho\vec{u}\vec{u}) = -\varepsilon\nabla p + \nabla.(\varepsilon\mu\nabla\vec{u}) + S_u \quad (7)$$

where, μ and P are mixture viscosity and pressure.
The source term of momentum equation is employed to consider Darcys law under the limiting condition where the permeability of porous media is small, resulting in low velocity. This term is equal to zero in the non-porous regions [11, 12].

$$S_u = -\frac{\varepsilon^2\mu}{K}\vec{u} \quad (8)$$

K is hydraulic permeability of porous media.

$$\frac{\partial(\varepsilon Y_j)}{\partial t} + \nabla.(\varepsilon\vec{u}Y_j) = \nabla.(D_{j,m}\nabla Y_j) + S_j \quad (9)$$

where, Y_j is the mass fraction of species j in the mixture. The source term of species equation is the species source term due to chemical reaction in the air or fuel channel. It is zero for the humidified hydrogen as the fuel because there is not any chemical reaction in the fuel or air channel [13].

$$\frac{\partial(\varepsilon\rho C_pT)}{\partial t} + \nabla.(\varepsilon\rho C_p\vec{u}T) = -\nabla.(k^{eff}\nabla T) + S_T \quad (10)$$

where, C_p, k^{eff}, T and S_T are the specific heat, the effective thermal conductivity, temperature and source term. The Joule volumetric heating source term in anode and cathode is due to Ohmic resistance and activation polarization. In the electrolyte, the Joule volumetric heating source term is due to Ohmic resistance. Also, in the anode – electrolyte interface the thermodynamic heat source, related to the electrochemical reactions is equal to the generation rate of the ineffective part of input energy (hydrogen heat value), which cannot be converted into the electricity. It is calculated as follows [12].

$$S_T = \frac{i^2}{\sigma} + i\eta + \frac{T\Delta S}{nF}i \quad (14)$$

It should be noted that for the tubular SOFC, a two dimensional axis-symmetric computational domain in cylindrical coordinate is considered, while a 3D model is adopted for the planar SOFC unit.

3. 3. Initial Setup and Boundary Conditions Generally, results of a primary steady state condition should be used as the initial conditions for the transient analysis. In this study, the initial cell setup for two types

of SOFC is described below. Tables 1 and 2 give initial setup of the tubular and planar SOFC cell units, respectively for the transient analysis. At the fuel exterior boundary, thermally adiabatic condition is put. Also, impermeability for species is assumed due to the symmetry between two adjacent cells. The simulation is based on a finite volume based code that uses separate modules for each sub-model. The governing transient transport equations are solved by the SIMPLE algorithm.

4. RESULTS

For verification purpose, the empirical parameters of the electrochemical model are calibrated to fit the output electrical data of the experimental work of Hagiwara et al. [9] and the test data of Keegan et al. [10] with the same geometries and test setups. The polarization curve results of the current model have been evaluated elsewhere in references [8, 11, 14] and the capabilities of the mathematical model and the code were discussed there. To calculate the response time of the cell to an input perturbation, we have to define a time constant to be able to evaluate and characterize different results and to compare different time scales. To date, no unique criterion is specified in the literature, for time constant of the cell dynamic response to an input perturbation. This criterion should be applicable for different types of input perturbations and a various output operating characteristics of the solid oxide fuel cells like species concentration, temperature and electrical power. In addition, the time constant definition should be enough inclusive to cover different order of time scales for various parameters. We suggest the time constant criterion of reaching 90% difference between initial and final steady state values.

4. 1. Tubular Cell Response to the Input Air Mass Flow Rate

To investigate the dynamic effects of the mass flow rate of input air, the cell dynamic response to a 5% increase in the air mass flow rate in a constant electrical load is analyzed for two kinds of solid oxide fuel cells. It is assumed that the load current is constant during transition while the effect of mass flow rate of inlet air increases on the cell output voltage. Performance is also investigated.

Figure 3 shows the longitudinal profiles of the cell temperature in different time steps up to the final steady state conditions. It is clear that with increasing the flow rate of air mass, the heat transfer rate from the cell body increases and thereby the cell temperature decreases, especially in the closed end of the cell. As shown in the figure, the cell maximum temperature decreases less than 22°C when the air mass flow rate increases 5%. In addition, the cell maximum temperature position shifts about 5cm toward the air flow downstream. It is reasonable that the hot spot shifts toward the downstream region when the mass flow rate increases, because the cooling effect of the air flow is dominant in the cell closed end. In addition, the air flow convective heat-transfer is the primary means to remove the generated heat and to avoid the occurrence of a hot spot in tubular SOFCs.

TABLE 1. The cell initial steady state operating conditions of the tubular SOFC with humidified hydrogen fuel [2]

Cell operating parameters	Value
Current density/output current	3500 A/m^2
Output current	104 A
Inlet air temperature	600 °C
Inlet fuel temperature	840 °C
Inlet air and fuel pressure	1.013 atm
Hydrogen utility factor	0.85
Inlet fuel mass flow rate	0.00065 gr/s
Oxygen utility factor	0.167
Inlet air mass flow rate	0.054 gr/s

TABLE 2. The inlet air and fuel conditions of the planar SOFC with humidified hydrogen fuel [15]

Cell operating parameters	Value
Air and fuel pressure	101.325 kPa
Inlet air temperature	750 °C
Inlet fuel temperature	750°C
Inlet fuel composition	97% H_2, 0.03% H_2O (0.782, 0.218)
Inlet air composition	21% O_2, 0.79% N_2 (0.233, 0.767)
Hydrogen utility factor	0.353
Inlet fuel mass flow rate	0.00001141g/s
Oxygen utility factor	0.473
Inlet air mass flow rate	0.0002287 g/s

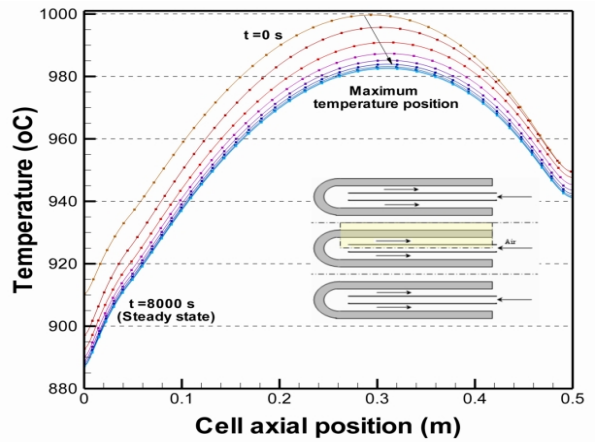

Figure 3. The cell temperature profiles with time for 5% increase of the air mass flow rate

Figure 4 shows how the oxygen mole fraction distribution along the cell is changed during an increase in the mass flow rate of input air. Despite very fast response of the oxygen concentration (less than 1s), very low variation of the oxygen mole fraction is observed. It is well documented that the effect of the air mass flow rate on the oxygen concentration and consequently on the cell performance is less noticeable in high mass flow rates (lower utility factors, e.g. 0.167 in this case study) [16]. However, its effect on the oxygen concentration distribution would be more important in lower ranges of air mass flow rate (higher oxygen utility factors).

The voltage and temperature time response of the cell to the inlet air mass flow rate is shown in Figure 5. As mentioned before, the average operating temperature of the cell decreases with increase of the air mass flow rate as a cooling fluid (at 600°C) and leads to decrease of the output voltage and generated power.

The electrical response time is calculated about 4150s (69 min) up to the new steady state condition (based on the above defined criterion). In addition, it is observed that the cell output voltage reduces about 2.5% (0.017 V) with 5% increase of the air mass flow rate. This voltage lost is just because of the cell temperature decrease and consequently increase of the internal voltage losses. As shown in the figure, the time variation of the cell voltage is simultaneous with the temperature variation because the temperature is the main reason of the output voltage variation with time constant of about 4200s or 70 min. Moreover, the other factor which influences the cell output voltage is the cathode oxygen concentration that affected by the mass flow rate of inlet air. However, about 22°C decrease in the cell temperature has the dominant effect on the cell output voltage despite the oxygen concentration raise.

4. 2. Planar Cell Response to the Input Air Mass Flow Rate Figures 6 and 7 show the longitudinal distribution of the planar SOFC temperature and oxygen mass fraction respectively due to 5% inlet air mass flow rate increase. As shown by Figure 6 the cell temperature decreases about 6°C uniformly gradually due to the excess heat removal from the cell surface. Also, Figure 7 shows maximum increase about 0.01 in the oxygen mass fraction in cathode electrolyte interface due to the raise in mass flow rate of inlet air.

The general effect of the mass flow rate of inlet air on the cell output voltage together with the time variation of oxygen mass fraction in cathode-electrolyte interface is depicted in Figure 8. As shown in figure 8, the voltage response time is about 300 s (5 min) for a planar cell unit which is 14 times smaller than the tubular cell unit (Figure 5). It could be observed that the output voltage has a sudden increase initially while it rises slowly after this fast response. The fast response part of the output voltage (up to 50% of total voltage change) is related to the effect of oxygen concentration variation on the cell voltage, whereas the slow part of the voltage response is due to the slow temperature variations during transition.

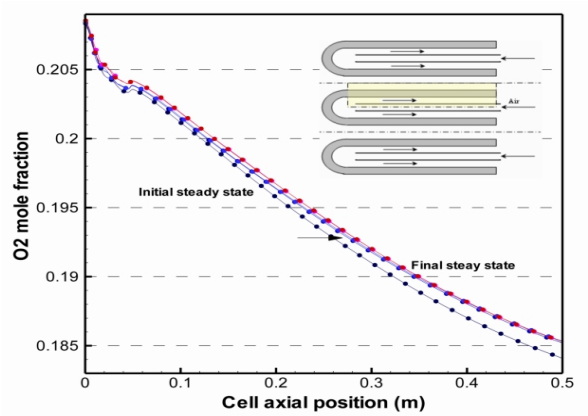

Figure 4. The oxygen mass fraction profiles along the cell with time for 5% increase of the air mass flow rate

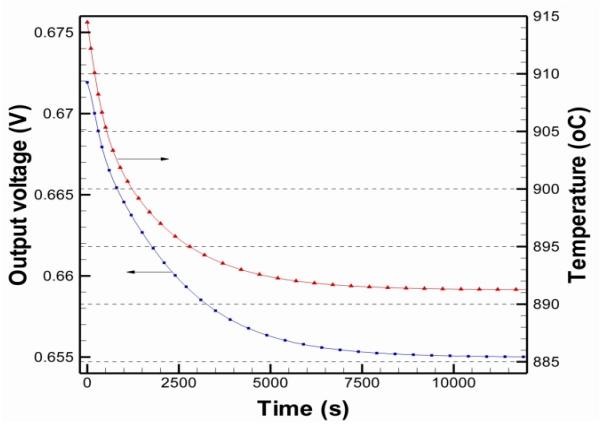

Figure 5. The voltage and temperature time response of the tubular cell to change in mass flow rate of the inlet air

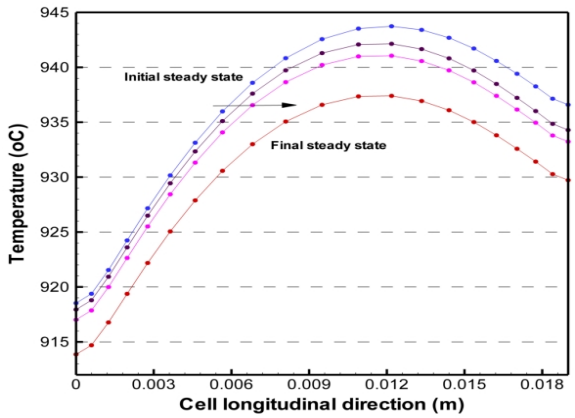

Figure 6. Longitudinal distribution of the electrolyte temperature in various time steps

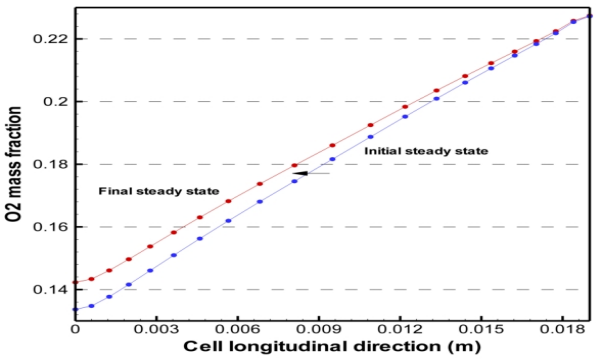

Figure 7. Longitudinal distribution of the cathode side oxygen mass fraction in various time steps

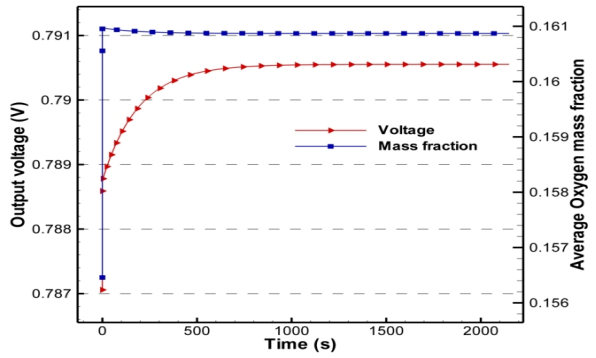

Figure 8. Output voltage and oxygen mass fraction time variation with the step up of the mass flow rate of inlet air

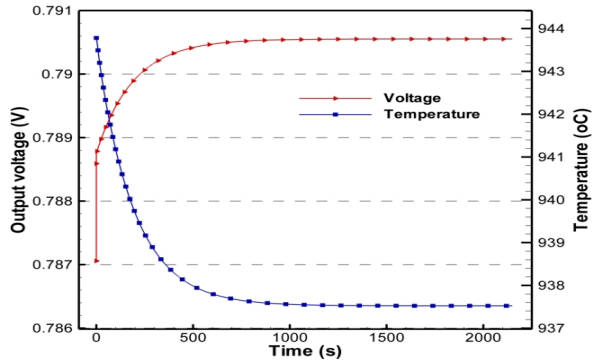

Figure 9. The voltage and temperature time response of the planar cell to change in the mass flow rate of inlet air

Although the mass fraction time response to oxygen is very fast (less than 0.1 s), the cell voltage follows the temperature time scale. However, the cell output voltage increases in spite of the cell temperature reduction as it could be seen in Figure 9. This behavior is opposite to the tubular cell behavior. This is because the effect of the inlet air variations on the oxygen concentration plays the main role on the cell performance in compare with just 6°C decrease of the electrolyte temperature in this case. Generally, the effect of lower mass flow rates of inlet air (higher utility factors, e.g. higher than 40% utility factors in this case study) on the voltage is dominant via the oxygen concentration variation. However, the effect of higher mass flow rates of inlet air (lower utility factors) on the voltage is dominant via the cell temperature variation. Anyway, it also depends on the inlet air temperature. When the inlet air temperature is very low it is clear that the effects of the inlet air variations on the cell temperature will play the main role on the cell performance. In addition, its effects on the oxygen concentration will lie on the next priority. Table 3 shows a summary of quantitative results.

The data in Table 3 indicates the response of the tubular and planar solid oxide fuel cells to the step change in inlet air conditions. Different response time scales (observed in the table for two types of SOFC) are due to some structural differences as well as the initial setup diversities between the tubular and planar solid oxide fuel cells. The thin electrodes and miniaturized body of the planar stack in compare with the tubular type lead to a 10 times quicker electrical response time to the inlet air condition perturbation. Beside this, different utility factors of the oxygen considered for two setups together with the different air flow passages result in the different quantitative responses of the thermal, electrical and mass transfer in two solid oxide fuel cell categories.

5. SUMMERY AND CONCLUSIONS

In this study, we considered the time constant criterion of reaching 90% difference between initial and final steady state values. It could be used in further studies on the dynamic behavior of the solid oxide fuel cells as a univalent criterion for analogy and application of the experimental and theoretical results. This criterion is applicable for different input perturbations and output operating characteristics of the solid oxide fuel cells like species concentration, temperature and electrical power.

TABLE 3. Summary of the above mentioned quantative results (An increase in mass flow of inlet air (5%))

	Planar type	**Tubulartype**
Cell temperature change	-6°C (0.06%)	-22°C (2%)
Output voltage change	+0.036 V (0.04%)	-0.017 V (2.5%)
O_2 mass fraction change	+0.01	+0.002
$\tau_{thermal}$	400 s (7 min)	4200 s (70 min)
$\tau_{electrical}$	300 s (5 min)	4150 s (69 min)
$\tau_{mass\ transfer}$	Less than 0.1 s	Less than 1 s

The change in mass flow rate of inlet air affects the cell performance via two factors of the cell temperature and the cathode oxygen concentration. In tubular solid oxide fuel cells, the convective heat-transfer of air flow is the primary means to remove the generated heat and to avoid the occurrence of a hot spot. In planar type of SOFCs, the inlet air flow has less effect on the cell temperature than the tubular types.

The effect of the air mass flow rate on the oxygen concentration and consequently on the cell performance is less noticeable in high mass flow rates (lower utility factors, e.g. 0.167 in the tubular cell case study). However, its effect on the oxygen concentration distribution would be more important in lower air mass flow rate ranges.

The output voltage response time depends on the time constants. The initial fast response of the output voltage is related to the effect of oxygen concentration variation on the cell voltage; whereas the slow part of the electrical response, is due to the slow temperature variations during transition.

The electrical response time of a tubular SOFC is about 10 times greater than a planar type. This is due to thicker support layer and also bigger active aria of a tubular cell unit in compare with a unit of planar cell which leads to slower diffusion of heat, species and electrical current. The mass transfer response time in a planar SOFC is estimated to be on the order of fractions of second and in a tubular SOFC, it is on the order of seconds. However, the thermal time constant is on the order of 100 seconds (minutes) for a planar cell and 1000 seconds (10 minutes) for tubular cells. The results show an almost slow electrical response of the cell to the step variation in mass flow rate of air which is estimated to be about one hour. However, the electrical response time of the tubular type SOFC is calculated about ten times more than the planar type.

6. ACKNOWLEDGMENT

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Time Constant

چکیده

هدف از این مطالعه، بررسی پاسخ دینامیکی دو نوع پیل سوختی اکسید جامد متداول (صفحه‌ای و لوله‌ای) به تغییر نرخ جریان هوای ورودی می‌باشد. بدین منظور، یک مدل محاسباتی دینامیکی بر مبنای دینامیک سیالات محاسباتی برای این دو نوع پیل اکسید جامد توسعه داده شده و پدیده‌های انتقال (انتقال جرم و حرارت)، پخش، الکتروشیمیایی، فعال‌سازی آند و کاتد و پلاریزاسیون اهمی بررسی شده است. با توسعه‌ی مدل، پاسخ دینامیکی پیل به تغییر پله شرایط جریان هوای تغذیه بررسی شده است. نتایج نشان دهنده یک پاسخ الکتریکی تقریبا آهسته پیل به تغییر پله نرخ جریان جرم هوا است که تقریباً حدود یک ساعت است. به‌علاوه می‌توان نتیجه گرفت که تاثیر شرایط جریان هوای ورودی بر عمکرد پیل سوختی لوله‌ای قابل توجه‌تر از نوع صفحه‌ای است؛ اما زمان پاسخ الکتریکی نوع لوله‌ای حدود ۱۰ برابر بیشتر از نوع صفحه‌ای است

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