Effect of Non-Uniform Inlet Flow Rate on the Preheating Process of a Solid Oxide Fuel Cell Unit

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Abstract

This study simulates the preheating process of a solid oxide fuel cell unit with the cross-flow configuration, and investigates the effect of the non-uniform inlet flow pattern and the non-uniform deviation on the maximum temperature gradient and preheating time. The numerical method is accuracy and reliable through the comparison with the analytical solution of previous literature. The results show that the effect of non-uniform inlet flow pattern on the maximum temperature gradient is obvious, and the effect in the fuel side is more obvious than that in the airside. The best choice of the inlet flow pattern is C, which the fuel side is uniform and the airside is the progressively increasing profile. Additionally, the effect of non-uniform inlet flow pattern on the preheating time is slight, but the effect of non-uniform deviation on the preheating time should be considered.

Keywords: Non-uniform, Preheating, Cross-flow, Solid oxide fuel cell, Maximum temperature gradient, Preheating time

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Introduction

The structure of a solid oxide fuel cell (SOFC) includes an anode, a cathode, an electrolyte, and an inter-connector, and its operating temperature is 600-1000°C. The SOFC has wider usage of the fuel, such as methane, ethanol, etc. Because the electrolyte is solid, the SOFC is easier to be produced different geometries such as cylindrical and plate form. The plate shape is easy to stack, so it becomes more popular in the application. Figure 1 shows the schematic of a plate solid oxide fuel cell unit.



Fig. 1 Schematic of a plate solid oxide fuel cell unit

The SOFC must be heated up before the normal operation because of its high operating temperature. When the SOFC is to be an assistant power, it will not satisfy the necessary of the market if its time of heat up is too long. The quick rate of temperature increasing of a SOFC can short the heat up time, but this will occur large temperature gradient that can induce the damage of the seal due to the thermal stress. In the past two decades, there are many literature [1-12] focus on the transient analysis of a SOFC, and investigate the performance of its heat up, start up, and shut down process.

Author has published papers [13,14] for investigating the effect of non-uniform inlet flow rate on the thermal and electrical performance of a SOFC with the cross-flow configuration in the steady state. Most of the previous literature [1-12] analyzes the preheating time and temperature gradient of a SOFC at the heat up process with coflow or counter flow configuration. Recently, the application of a cross-flow configuration on a SOFC becomes popular because of its easy of inlet arrangement. Because the properties and variables are function of x and y direction, few literature focus on the transient analysis of a SOFC at the heat up process in the cross-flow configuration. Moreover, the inlet positions of fuel and air as well as the design of flow distributor will induce a non-uniform inlet flow, this non-uniform factor must affect the efficiency of preheating process of a SOFC. Therefore, this study investigates the effect of the non-uniform inlet flow rate on the transient performance of a SOFC unit with a cross-flow configuration at the heat up process.

Analysis

In the preheating process, the velocity increasing of the preheating gas (i.e. flow rate increasing) will decrease the temperature gradient and preheating time of a fuel cell. Moreover, the temperature increasing of the preheating gas will decrease the preheating time, but increase the temperature gradient [4]. If someone selects more flow rate of the preheating gas and higher preheating temperature for shorting the preheating time and dropping the temperature gradient, it must need more energy for this promotion. Therefore, this study considers the preheating model as previous literature [9], which has a constant preheating energy from a preheating burner as shown in Fig. 2.



Fig. 2 The preheating model of a solid oxide fuel cell unit

Figure 2 depicts the process of preparing preheating gas with a methane burner. The methane combusts with lean air in the burner for maintaining the low oxygen in the exhaust, because the exhaust gas will be the fuel of the SOFC. In order to avoid producing high temperature gradient due to the exhaust gas with over 1000K, a heat exchanger exchanges the heat from the exhaust gas to the fresh air. When the flow rate of the air increases, the exit temperature of the gas will decrease. This study set the temperature difference between the preheating gas/air and the cell temperature at the inlet corner to be 100K [9].

 $T_{gas,in} = T_{air,in} = T_c(0,0) + 100 \tag{1}$

This study keeps the flow rate of the methane and lean airflowing into the burner to be constant, so the energy of the exhaust gas is also constant when the combustion is stable. Because the preheating temperature of the gas and air in the exit of the heat exchanger must be kept based on Eq. (1), the flow rate of the air in the inlet of the heat exchanger should be controlled. This inlet flow rate of the air can be calculated according to the energy conservation as following.

 $n_{air}=n_{gas i} c_{p,i} X_i (T_{gas,burn}-T_{gas,in}) / {}_j c_{p,j} X_j (T_{air,in}-T_0)$ (2) This study considers the configuration of the fuel and airflowing direction is crossflow. The flow distributor arranges the fuel and airflowing into each channel, which is always a part of the inter-connector for stacking easily as shown in Fig. 3.



Fig. 3 Schematic of the flow distributor in the fuel side of a SOFC unit

Figure 3 only shows the fuel distributor for easy demonstration. Meanwhile, the inlet of the fuel usually locates one side of the distributor, and the fuel flows into each channel through the geometry inside the distributor. The location of the fuel inlet and the design of the distributor will induce a non-uniform inlet flow rate of each channel. This study assumes the distributor will produce a straight line of non-uniform profile, and considers the inlet position of the fuel and air may be one side of the distributor. Therefore, the non-uniform inlet flow rate of the SOFC unit has 8 patterns as shown in Fig. 4. Moreover, this study also considers the uniform pattern (both the fuel and air inlet is uniform profile) for the comparison. Actually, the design of the distributor will induce the different slopes of the straight line of non-uniform profile. This study ignores the existence of the rib in the channels, and expresses the relationship between the flow rate along the cross section and the slope in the following.

$$n_{gas}(y) = (n_{gas}/k_{gas})(2d_{gas}y/l_y + 1 \cdot d_{gas})$$
(3)
$$n_{air}(x) = (n_{air}/k_{air})(2d_{air}x/l_x + 1 \cdot d_{air})$$
(4)

Meanwhile, the l_x and l_y represent the length in the x and y, respectively. The d stands for the deviation away the average flow rate. The different value of d will represent different slopes.



Fig. 4 Non-uniform patterns in this study

This study assumes the anode, cathode, and the electrolyte to be a combination, which is named the cell. Moreover, the scale in the x and y direction are far larger than the scale in the z direction, so this study neglects the change of variables in the z direction. Therefore, the analysis becomes a two dimensional problem. This study takes the energy conservation for the fuel, air, cell, and inter-connector in the following.

For the fuel $\frac{-}{t} \left({}_{j} n_{gas} X_{j} c_{p,j} T_{gas} \right) + \frac{-}{x} \left({}_{j} n_{gas} X_{j} c_{p,j} T_{gas} \right) = (ha)_{i-gas} \left(T_{i} - T_{gas} \right) + (ha)_{c-gas} \left(T_{c} - T_{gas} \right)$ (5) For the air $\frac{-}{t} \left({}_{j} n_{air} X_{j} c_{p,j} T_{air} \right) + \frac{-}{y} \left({}_{j} n_{air} X_{j} c_{p,j} T_{air} \right) = (ha)_{i-air} \left(T_{i} - T_{air} \right) + (ha)_{c-air} \left(T_{c} - T_{air} \right)$ (6) For the cell $\frac{-}{r_{t}}(-c_{p}T)_{c} - (k_{-})_{c} \frac{{}^{2}T_{c}}{{}_{x^{2}}} - (k_{-})_{c} \frac{{}^{2}T_{c}}{{}_{y^{2}}} = (ka)_{i-c} \frac{(T_{i}-T_{c})}{{}_{-i-c}} + (ka)_{i-c} \frac{(T_{i}-T_{c})}{{}_{-i-c}} + (ha)_{c-gas}(T_{gas} - T_{c}) + (ha)_{c-gas}(T_{gas} - T_{c}) + (ha)_{c-air}(T_{air} - T_{c})$ (7) For the inter-connector $\frac{-}{r_{t}}(-c_{p}T)_{i} - (k_{-})_{i} \frac{{}_{-}^{2}T_{i}}{{}_{x^{2}}} - (k_{-})_{i} \frac{{}_{-}^{2}T_{i}}{{}_{y^{2}}} = (ka)_{i-c} \frac{(T_{c}-T_{i})}{{}_{-i-c}} + (ka)_{i-c} \frac{(T_{c}-T_{i})}{{}_{-i-c}} + (ha)_{i-gas}(T_{gas} - T_{i}) + (ha)_{i-air}(T_{air} - T_{i})$ (8)

Because this study neglects the z direction, the convection area and conduction area due the ribs in channels are merged into the parameter of a.

Author has published some papers of a SOFC performance simulation applying the FlexPDE software and Fortran code developing by himself [13,14]. The software of FlexPDE has been proved to be reliable. Therefore this study utilizes this software to simulate the transient performance in the heat up of a SOFC unit.

Results and Discussion

Figure 5 shows the accuracy comparison according to the analysis case [4]. The literature [4] analyzes the preheating process of an one dimensional SOFC unit when the fuel gas is static and only the air preheats the fuel cell, so it has two energy equations for the air gas and the solid, respectively. Moreover, the literature [4] assumes the temperature of air equals to that of solid, so it becomes a one energy equation problem in this analysis case. This study applies the FlexPDE software to solve the Eq. (12) [4], which results are shown in Fig. 5 by the continue line with square symbol. In order to prove the numerical method is reliable, this study tries to follow the analytical solution in Appendix [4], but the calculating values are unreasonable (maybe there are typos in the reference). Therefore, this study directly describes the analytical line of Fig. 3 in the literature [4], and shows them in the Fig. 5 by the symbol of solid circle. In the Fig. 5, it shows that the continue line with square symbol match well with the solid circle. Therefore, the FlexPDE solution is accuracy and reliable. Moreover, author uses the software to solve the Eq. (5)-(8) of this study with the same conditions [4], which the cell temperatures are shown in Fig. 5 by the dashed line with solid square symbol. In this figure, the continue line has obvious difference to the continue line with square symbol (one equation model), and the shape of the lines at x=0 are also different, because the boundary condition for the solid at x=0 of one equation [4] and four equations is different, which one is function of time and another is the adiabatic. Moreover, the one equation model assumes the thermal equilibrium, and the energy equation of solid also includes the convection effect, which will over predict the heat transfer along the x direction. Although the cell temperature in one equation model at x=0 is higher than that in four equation model of this study due to the different boundary condition, the cell temperature along the x direction in one equation model drops more quickly than that in four equation model due to the convection term in the one equation model.



Fig. 5 Accuracy comparison

Figure 6 depicts the temperature distribution of one-equation model [4] and fourequation model of this study when the time is 90s. Meanwhile, the dashed line with square, triangle, gradient, and right triangle symbol respects the cell, fuel, air, and separator temperature, respectively. In this figure, the cell, separator, and fuel temperature are similar and all of them have same pattern at x=0, because the cell and separator are solid and the fuel is static, which have the adiabatic condition at x=0. The air temperature is higher than all of them because its inlet condition is a function of time. The temperature of one-equation model near x=0 is between the fuel temperature and other temperature of the four-equation model, because its inlet condition is the combination of heat flux and function of time.



Fig. 6 Temperature distributions of one-equation and four-equation model at 90s of the accuracy comparison case

Figure 7 shows the center temperature response in different convergent conditions when both the fuel and air preheat the SOFC unit, and their configuration is cross-flow. In this figure, this study analyze a same condition with different convergent conditions from 0.05 to 0.005. The results show that the temperature response approachs to the case of 0.005 when the convergent condition decreases, and the temperature response in the convergent condition of 0.009 has already coincided with the case of 0.005. Therefore, this study selects the convergent condition of the numerical analysis to be 0.009 for the following analysis.



Fig. 7 Center temperature response of the cell in different convergent conditions

Figure 8 depicts the maximum temperature gradient response of the cell at different non-uniform pattern and deviation. In this figure, this study considers 9 non-uniform inlet flow patterns, which include 8 patterns in Fig. 3 and one uniform pattern (both the fuel and air are uniform inlet flow). Moreover, this study also considers these 9 patterns with three kinds of non-uniform deviation, which are 0.25, 0.5, and 0.75. The cell temperature is atmosphere temperature when the SOFC begins the starting, so the airflow rate will be adjusted to large for providing suitable preheating temperature of the fuel and air according to the Eq. (2). Along with the increasing of the preheating time, the cell temperature becomes higher and simultaneously the airflow rate decreases for getting higher preheating temperature of the fuel and air. Once the cell temperature at the reference position arrives 798K, the airflow rate is kept a constant and the preheating temperature stays the value of 898K for the operation of a SOFC. In the Fig. 8, the results show that the maximum temperature gradient occurs at about 350s no matter the different non-uniform patterns or different deviations. Moreover, all analyzing cases have finished the preheating process after 800s. However, the preheating time slightly becomes longer when the deviation is larger. In Fig. 8(a), the maximum temperature gradient is close to zero at 600s, and it is higher than zero at 600s when the deviation is 0.5, and 0.75. Therefore, the effect of non-uniform pattern and deviation on the occurring time of the maximum temperature gradient can be neglected. However, the non-uniform patterns and deviations obviously affect the value of maximum temperature gradient and slightly affect the preheating time.

In Fig. 8, this study marks the same color for same inlet flow distribution in the fuel side, and finds the maximum temperature gradient response rank from high to low is blue, green, and red. This means that the fuel inlet flow distribution rank for a good preheating is the uniform profile, progressively increasing profile, and progressively decreasing profile. Moreover, the maximum temperature gradient response rank in the same color group of Fig. 8 is the result with delta symbol, no symbol, and square symbol. This means that the inlet flow distribution rank of the air for a good uniform preheating is the progressively increasing profile, uniform profile, and progressively decreasing profile. Therefore, the non-uniform inlet flow of fuel dominates the maximum temperature gradient, and the best profile in the fuel side is uniform. The non-uniform profile in the airside also affects the maximum temperature gradient, and the progressively increasing profile is the optimal design for a good uniform preheating.



Fig. 8 The maximum temperature gradient response of the cell at different nonuniform pattern and non-uniform deviation

Figure 9 depicts the difference bewteen the maximum and minimum cell temperature in different non-uniform patterns and deviations in order to analyze the effect of these two factors on the preheating time. This figure shows that the effect of different non-uniform pattern on the preheating time is slight, and the better uniform preheating in Fig. 8 has little quick preheating. Moreover, the effect of non-uniform deviation on the preheating time is more obvious, and the preheating time is close to 600s, 650s, and 700s for d=0.25, 0.5, and 0.75, respectively.



Fig. 9 The difference bewteen the maximum and minimum cell temperature in different non-uniform patterns and deviations

Conclusion

This study applies a software to analyze the preheating process of a solid oxide fuel cell unit considering the different non-uniform inlet flow patterns and deviations. This study prove accuracy and reliable of the software through comparing the previous analytical solution. The results indicate that the effect of non-uniform inlet flow pattern on the maximum temperature gradient is obvious, and the effect in the fuel side is more obvious than that in the airside. The best choice of the inlet flow pattern is C, which the fuel side is uniform and the airside is the progressively increasing profile. Additionally, the effect of non-uniform inlet flow pattern on the preheating time is slight, but the effect of non-uniform deviation on the preheating time should be considered.

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