Numerical simulation of flow distribution for external manifold design
in solid oxide fuel cell stack

Cheng Zhao ^{a, 1}, Jiajun Yang ^{b, 1}, Tao Zhang ^{a, *}, Dong Yan ^b,

Jian Pu ^b, Bo Chi ^b, Jian Li ^b

^a School of Naval Architecture & Ocean Engineering, Huazhong University of Science & Technology, 430074 Wuhan, Hubei, China, ^b School of Materials Science and Engineering, State Key Laboratory of Material Processing and Die & Mould Technology, Huazhong University of Science & Technology, 430074 Wuhan, Hubei, China

Abstract

In this study, a three dimensional model is constructed to investigate the flow distributions and the pressure variations for a 40-cell solid oxide fuel cell (SOFC) stack. Computational fluid dynamics (CFD) is used to optimize the design parameters of external manifold in the stack. The model consists of equations for the network with chamber structure of manifold. Simulation results indicate that the flow uniformity strongly depends on geometric shapes of manifold, including the joined position between tube and manifold, the dimension of manifold and the number of tubes. The ratio of flow velocity which describes the uniformity of flow distribution can be decreased by optimizing the geometrical structure of manifolds. In addition, it is

* Corresponding author. Tel./fax: +86 027 87543758

E-mail address: zhangt7666@hust.edu.cn (Tao Zhang)

¹ These authors contributed equally to this work.

found that the flow distribution can be intensively influenced by the gas resistance of the stack, which is closely related to the configuration of interconnect channels. The results summarize the importance of structure design of external manifold for stack performance. The numerical results are in good agreement with the experimental measurement in a 40-cell stack.

Keywords: Flow distribution; SOFC stack; External manifold; Simulation; Gas resistance

1. Introduction

A Solid oxide fuel cell is a device which the chemical energy is converted into electricity directly by electrochemical reaction [1]. The air and fuel flow through gas distributors of the interconnect, and diffuse into porous electrodes to generate electricity at operating temperature. Compared with other fuel cells, SOFC is gaining more attraction due to its higher energy transformation efficiency and lower manufacture cost [2-7]. In general, a planar single cell produces a voltage of 0.5-1V depending on the current load [8]. To obtain a higher power output, multiple cells are assembled seriously by interconnects to form a stack. According to the type of manifold structure, the designing of the stack can be mainly divided into external and internal manifold designs [9, 10]. The external manifold stack costs lower in construction because of the simplicity of interconnects and is considered to be more suitable for big power plants [10-12]. The structure of a typical external manifold stack is shown in Fig. 1.

The flow distribution inside the manifolds and channels plays a crucial role for the performance of a stack. An uneven flow distribution will result in the performance differences among cells in the stack, and thus reduce the fuel efficiency. Different technical solutions have been applied to predict the flow resistance and distribution in the stack. Theoretical analysis, in general, is used by building a simplified calculation model [13-16], which may bring out relative high errors for a complex 3-D actual stack. The experimental researches we found are mainly focused on developing the flow and temperature distributions for a given manifold [17, 18]. However, it is very

difficult to observe the actual gas flow paths at high temperature. These shortcomings mentioned above can be overcome by a computational fluid dynamic (CFD) approach to simulate the flow distribution and thermal management of stacks [19-24]. In recent years, some researches have studied the optimization of stack structure including manifold and channel of interconnect to achieve a more uniform flow and temperature distributions [25-36]. R.J.Boersma et al. developed an analytical model to investigate the flow distribution along the height of an internal manifold fuel cell stack [25]. Haruhiko Hirata et al. discussed the effect of channel height on flow field in a MCFC stack and draw a conclusion that the uniformity of the flow distribution was improved by decreasing in the channel height [26]. Chen simulated a two dimensional stack composed of 72 cells by changing the manifold width and the channel permeability to investigate the influence on the flow distribution [27]. Qu constructed a three dimensional stack by adding a gas distributor in the center of inlet manifold to enhance the flow uniformity [28].

Most of simulation researchers are focusing on internal manifold stack. This paper, however proposes the numerical simulation combined with experimental measurement to investigate the gas transport and pressure variation for an external manifold stack. The flow distribution in the stack was simulated by constructing a three dimensional model and compared the difference by changing the parameters of manifold structure and gas resistance. An experimental model was fabricated to verify the design of manifold structure by measuring flow rate and pressure drop in the stack.

2. CFD model and experiment

2.1 Geometric model of manifold

Fig. 2 shows three types of SOFC stack with different external manifold designs. The single inlet tube is placed on the top of the manifold, and the outlet tube is placed in the center of the manifold, as shown in Fig. 2a. The difference among Fig. 2a, Fig. 2b and Fig. 2c is the configuration of inlet tube in the manifold, in which the inlet tube is in the center of the manifold for a symmetrical stack structure in Fig. 2b. While the gas flows from the inlet tube to a buffer chamber to pre-distribute gas, and then passes through 5 tubes to manifold chamber is shown in Fig. 2c. The detailed stack parameters are given in Table 1.

Table 1

Parameters of Stack model and gas properties of fuel and air

Variable	Value
Depth of gas channel (mm)	1
Number of tubes	5
Manifold depth (mm)	15
Number of cells	40
Cell size(mm²)	150×150
Distance between channels (mm)	3.5
Area of channel (mm²)	150×130
Mass flow rate (L min⁻¹)	80
Inlet diameter (mm)	20 and 10

Outlet diameter (mm)	30
Air density (kg m^{-3})	1.205
Air viscosity ($\text{kg m}^{-1} \text{s}^{-1}$)	1.81e-5
H₂ density (kg m^{-3})	0.089
H₂ viscosity ($\text{kg m}^{-1} \text{s}^{-1}$)	1.01e-5

2.2 Grid generation and boundary conditions

The ANSYS ICEM CFD 13.0 [37] is used to generate the grids. Four sizes of grids are generated to conduct the grid independence tests and the average grid size is from 0.8mm, 1mm, 1.5mm to 2mm, respectively. To get a more accurate result, the boundary layer grid is assumed near the wall. The total number of grids is about 2.30, 4.08, 9.24 and 14.63 million with the same boundary layer grid. The mass flow rates in the channels are calculated to compare the influence of the different grid sizes. It is observed that the mass flow rates were increased gradually and appeared to be closer as the grid number increased, as shown in Fig. 3. Since the difference of mass flow rate was small for 9.24 and 14.63 million grids, thus for the compromise between accuracy and calculation efficiency, the average size of grid is set at 1mm and the total number of grids in the stack are about 9.24 million.

The mass flow rate is 80 standard liter per minute (SLM) for a 40-cell stack, which corresponds to 4.2m/s and 17.6m/s to 20mm and 10mm inlet tubes, respectively. Some boundary conditions are assumed that the outlet pressure is constant at 1atm, and the flow velocity is zero at wall due to ignoring slip wall effect. Because the fluid is considered to be in a porous media of flow channel, the pressure drop in channels can

be changed with the different permeability of the porous media. For a 150×130 mm reaction area of single cell, the measured pressure drop is about 380 Pa when 80 SLM of mass flow rate is fed into a 40-cell stack.

2.3 Mathematical model

The flow distribution in the stack was calculated by the CFD package ANSYS FLUENT 13.0 with SIMPLE (Semi-Implicit Method for Pressure-Linked Equation) method [37]. Calculation domains are divided into discrete meshes to solve the mass, momentum and turbulence equations. In order to simplify the calculations, several assumptions are proposed as follows [8, 27, 28].

- 1) The electrochemical reaction, heat exchange and mass transfer are ignored.
- 2) The air flow in the inlet tube is turbulent.
- 3) The working gas is incompressible.
- 4) The gas flow in the stack is steady.
- 5) The operation temperature is assumed to be constant.
- 6) The operation pressure of stack is 1atm.
- 7) Channels of interconnect are porous media with laminar flow.

According to above assumptions, mass conservation equations and momentum conservation equations are solved. The equations are given as below:

$$\frac{\partial \rho}{\partial t} + \text{div}(\rho U) = 0 \quad (1)$$

$$\frac{\partial(\rho U)}{\partial t} + \text{div}(\rho U U) = -\nabla p + \nabla \cdot \tau + S_i \quad (2)$$

Besides, the standard k - ε turbulence model is used in CFD which the Reynolds number (Re) is about 11400 in the inlet tube of 10mm diameter for air. The equations

can be solved at a turbulent flow by knowing the kinetic energy k and dissipation rate ε .

By treating with the boundary layer grid and standard wall function, a stable and accurate result can be obtained [37]. Two equations are given as below:

$$\frac{\partial(\rho k)}{\partial t} + \text{div}(\rho k U) = \text{div}\left[\left(\mu + \frac{\mu_t}{\sigma_k}\right)\nabla k\right] + P_k - \rho\varepsilon \quad (3)$$

$$\frac{\partial(\rho\varepsilon)}{\partial t} + \text{div}(\rho\varepsilon U) = \text{div}\left[\left(\mu + \frac{\mu_t}{\sigma_\varepsilon}\right)\nabla\varepsilon\right] + \frac{\varepsilon}{k}(C_{\varepsilon 1}P_k - C_{\varepsilon 2}\rho\varepsilon) \quad (4)$$

In the stack model, the air is fed into corrugated plate channel, and generates a pressure drop. To simplify the calculation model, porous media model is used to simulate the pressure drop in stack channels. The loss is added into the momentum conservation equations in the CFD calculation. The source term consists of two parts: viscous and inertial loss terms. For homogeneous porous media, the formula can be written as follows:

$$S_i = -\left(\frac{\mu}{\alpha}u_i + C_2\frac{1}{2}\rho|u|u_i\right) \quad (5)$$

Where α is the permeability and C_2 is the inertial resistance factor. As the flow velocity in the channel is very low, the flow can be considered as laminar. In this case, the inertial loss can be assumed to be zero and the momentum loss formula can be written as:

$$S_i = -\frac{\mu}{\alpha}u_i \quad (6)$$

The α can be computed from the pressure drop by experiment where the measurement is about 380 Pa with 80 SLM air passaged.

2.4 Experimental measurement

The purpose of the experiment is to measure the flow rate and the pressure drop in the stack with three different types of manifold. The measurement was operated at

room temperature, but can also be extended to high temperature according to the gas equation of state. A stack composed of 40 cells was constructed, and an anemometer (Dwyer 47) was used to measure the velocity of the gas at outlet of the channels. To verify the parameters used in the simulation, the pressure drops from the inlet to outlet of the stack were measured under different mass flow rates by a pressure sensor. The velocity at the four points was measured under 80 SLM in a single channel to improve the accuracy of the measurements, thus, the total measure data are 160 groups for a stack.

3. Results and Discussions

According to the results of CFD simulation and experiment, the flow distribution and the pressure variation in a 40-cell stack are analyzed. Mass flow rate and pressure drop in cell channels can be measured respectively. The flow distribution in the stack is evaluated and discussed by changing the operation parameters including the manifold configuration, the number of tubes, channel resistance and the gas properties. To describe the flow uniformity in the stack, the dimensionless mass flow rate and pressure drop are defined in Eq. (7) and Eq. (8).

$$\tilde{m}_n = \frac{m_n}{\bar{m}} \quad (7)$$

$$\Delta\tilde{P}_n = \frac{\Delta P_n}{\Delta\bar{P}} \quad (8)$$

Where n is the channel number from 1 to 40 for the stack, number 1 is the channel on the top and number 40 is the bottom channel; m_n and ΔP_n are the mass flow rates and pressure drop in each channel, respectively; $\bar{m}$ and $\Delta\bar{P}$ are the average mass flow

rate and average pressure drop of 40 channels. For an ideal stack, both of that are the same for the all channels, thus $\tilde{m}_n$ and $\Delta\tilde{P}_n$ are equal to 1.

3.1 The effect of manifold configuration

Three types of manifold configurations are as shown in Fig. 2: the inlet tube on the top of the manifold is 10 mm diameter (A), the inlet tube in the center of manifold is 20 mm diameter (B), and a gas buffer chamber is on the top of manifold (C). Fig. 4 shows simulation results for dimensionless mass flow rate in the channels which are varied with the channel number increased along the height of stack. For case A, the mass flow rates in the channels are very non-uniform due to high gas velocity in the manifold. But the flow rates are well uniform in the case B except for very high flow rate in the center of stack which can be attributed to the position of the inlet tube. The flow rates are increased from channel 1 to channel 10, and gradually stabilized on a constant value for case C. The flow rate is determined by the pressure drop for certain channel which can be obtained from the previous work [27]. Therefore, only the dimensionless mass flow rate is given in the following results.

Fig. 5 shows the overall pressure variations of three types of inlet tube connected with manifold. The pressure contours in all three configurations have the similar trends. The pressure in all three types of manifold gradually decreases along the flow field due to the gas resistance of channel which has been shown from the pressure contour. It is obvious that the pressure range of top-inlet manifold is wider than that of other two cases which results in non-uniform flow distribution, as shown in Fig. 5a, Fig. 5b and Fig. 5c. The pressure distribution on the surface of single cell is showed in Fig. 5d

which is in nearly similar pressure range and the direction of pressure drop. Based on the simulation results, the main pressure drop occurs in the flow channels of stack and the gas inlet tube plays an important role on the pressure variations and flow distributions.

The pressure from fuel and air sides may cause leakage from the seals under high gas flow velocity. Because the flow distribution is more uniform for case B and case C, it is easy to compare their flow velocity distributions and optimize their inlet manifold structure. Fig. 6 shows the flow velocity contours for two of inlet manifolds that the maximum flow velocity near the seals are about 0.47 m/s and 0.31 m/s, respectively. The flow velocity from case B is higher than that of case C, thus, case C shows more uniformly flow distribution and lower flow velocity in the sealing position. This suggests that the structure of buffer chamber manifold can effectively reduce the damage for the seals.

The flow uniformity depends strongly on the depth of manifold. Three kinds of manifold depth (15 mm, 20 mm and 25 mm) are constructed, as shown in Fig. 7. In order to compare reasonably with those three depths, the diameter of the tube connecting with manifold is increased from 10 mm, 13 mm to 16 mm, respectively. Fig. 8 is a plot of the dimensionless mass flow rate with different manifold depth at 80 SLM air flow rate. It can be observed that the mass flow rate presents non-uniform flow distribution between #1 and #9 channel in all three cases. However, higher manifold depth causes less flow distribution difference when manifold depth increased from 15 mm to 25 mm. The ranges of dimensionless mass flow rate are

0.9933-1.0015, 0.9972-1.0006, 0.9987 -1.0003 with three different manifold depths.

The results show that the larger manifold volume and tube diameter will be benefit to improve the flow distribution and pressure drop along inlet manifold length. This improvement expected to be applied in the design of external manifold.

3.2 The effect of tube connecting chamber and manifold

The tube is used to connect the buffer chamber and the manifold, and is very important for the gas distribution in the stack. To investigate the influence on the number of tubes to flow distribution, the number of tubes with 3, 5 and 8 has been constructed respectively which the diameter of tube is 10 mm, and the manifold depth is 15 mm.

Fig. 9 shows the dimensionless mass flow rate within different channels in stack. The flow rate in the channels is similar and close to 1 for all three cases, but the flow uniformity has been obviously enhanced while the inlet tubes are increased. To understand distinctly the influence of inlet tubes on flow distribution, the velocity streamlines of three cases are introduced as shown in Fig. 10. It can be found that several of vortexes have been formed in flow field of manifold, and the sizes of the vortexes are decreased while the number of tubes is increased. For the case of 3 inlet tubes, two of large vortexes with higher speed appear the region corresponding to from channel 1 to 18, which results in the loss of the energy and the non-uniform of the flow velocity in the manifold. It is coincided with the result that the flow rate becomes lower from channel 1 to 18. Although several of vortexes can also be seen on the other cases, it is very small and slowly dispersed in chamber of manifold. The flow

uniformity among the channels also can be explained for the 5 and 8 inlet tubes which the effect from vortexes is limited within 10 channels in the flow regions. From the above analysis, it can be observed that the flow in the channels of the stack become more uniform at smaller vortex in the manifold chamber when the number of tubes are increased to certain threshold value.

3.3 The effect of channel resistance from stack

When the fuel and air go through the channels, the pressure drop can be produced within stack. In general, the hydrogen is fuel on anode side of cell and is using the porous nickel foam as gas channel. On the other side, air in cathode side is distributed by the corrugated metallic plate. Assuming that the gas flow is very uniform in each cell of the stack, the relationship between mass flow rate of cell and resistance of channel can be investigated based on different gas resistance models. The resistance can be modified by changing the permeability of the porous media in CFD calculation, and it can be adjusted by modifying the design parameter of the corrugated metallic plate or the nickel foam. Chen et al. [27] and Qu [28] both have discussed the influence of permeability to the gas flow and the pressure variation. However, they investigated the effect using ten times of the permeability, which can only get a quantity result. Because four groups of pressure drop have discussed in our simulation model, hence we can evaluate different quantitative flow distribution in stack. Fig. 11 shows the dimensionless mass flow rate under different gas resistance for a 40-cell stack. It can be seen that the flow uniformity has been greatly improved with gas resistance increased, especially from channel #1 to #10. The gas resistance

along the vertical stack direction is also one of the key parameters in flow distribution. For the flow uniformity, it is preferable a stack with higher flow resistance in the channels. However, higher flow resistance within the stack will bring more problems, for example, the blower used on system will require higher power to overcome the pressure drop, thus reduce the efficiency of the stack, and the possibility of gas leakage is also increased under higher gas pressure. Therefore, flow resistance should be designed on a range to optimize the performance of SOFC system.

3.4 The effect of gas properties

In the fluid dynamic, the Reynolds number is an important parameter to describe the flow state in which the turbulent flow is the Re over 2000, otherwise, the flow is laminar [38]. The turbulent flow and laminar flow can be described by the standard $k-\varepsilon$ turbulence model and the laminar model in CFD simulation. According to the calculation formula, the maximum Re in the stack is about 11400 and 1500 for flow in cathode and anode respectively while the H_2 is fuel on anode channel, and the air is oxidant on cathode channel. Fig. 12a shows the dimensionless mass flow rate in channels with H_2 and air as fluids. It is clear that the flow distribution of H_2 is more uniform than that of air in the channels of a 40-cell stack. When different fluids are fed into manifolds and channels, the properties of flow dynamic are converted to pressure drop and caused flow distribution. As mentioned above, the H_2 exhibits laminar flow characteristic without fluid disruption between the different flow layers, hence the flow of H_2 in channels is very stable. As comparison, air is turbulent flow and presents highly irregular flow distribution due the unstable vortices appear on

many regions of manifold, resulting from the momentum and energy exchanges between the layers. It is obvious that the H_2 is better than the air on uniformity of the flow distribution. Fig. 12b shows the effect of the fluid properties on pressure drop in a 40-cell stack. The pressure drop in the anode side is less than that in the cathode side at the same channel structure of about 200 Pa and 370 Pa, respectively. The operation temperature of SOFC stack is about 750°C. It is very difficult to measure the flow distribution and pressure drop at the high temperature. With the aid of CFD approach, the relationship of fluid properties between room temperature and high temperature can be simulated. To simplify the calculation, only the density and viscosity of fluid are varied at different temperature in flow field simulation. It can be obtained the same trends on flow distribution and pressure drop at high temperature. However, the flow uniformity is improved and the pressure drop is increased due to the effect of gas expansion.

3.5 The measurement of flow distribution in stack

To confirm the uniformity of flow distribution to each channel of 40-cell stack, the mass flow rate of each channel was measured by an anemometer under room temperature. Besides, the pressure drop from the inlet to outlet in the stack was measured at different mass flow rates for anode and cathode. Fig. 13 presents the measured data about flow distribution in stack. From the measured result, the overall pressure drop from the inlet to outlet of manifold is about 400 Pa with 80SLM air fed into the stack. According to stack configuration with external manifold, those three of cases (A, B and C) are measured on flow velocity at the outlet of each channel for the

stack with the 40 channels is sequentially numbered from the top to bottom. The measured flow velocity is shown in Fig. 14 which also presents similar trends of flow distribution. For the top-inlet manifold, the flow velocity in the center of the channel is lower than the top and the bottom channel, however, the contrary distribution of flow velocity in the center-inlet manifold is higher in the center of each channel. It shows relatively uniformity of flow distribution in chamber inlet manifold which is ascribed to the effect of buffer chamber. Based on the analysis results, it is clear that the experimental data can predict flow distribution at different of pressure drops and geometrical configurations of stack.

4. Conclusion

A numerical model using the CFD method is applied to investigate the flow distribution and pressure variation by constructing a 40-cell stack with external manifold. The model considers different parameters which include inlet configuration and geometrical shape of manifold, channel resistance, gas properties and etc. Several of conclusions can be draw as follows:

- 1) For the external manifold stack, a buffer chamber on the top of manifold can redistribute gas and improve the uniformity of gas flow. The higher manifold depth and more inlet tubes can help the flow distribution because of low flow velocity in manifold. It has been verified from the experimental measurements.
- 2) The gas resistance from channels can cause different pressure drop in stack which can contribute to the uniformity of gas flow rate in each cell. But it is necessary to keep a balance between pressure drop and reliable gas seals in stack operation.

3) Assuming the air and H₂ present turbulent flow and laminar flow characteristic, the fluid of H₂ makes higher uniformity of flow distribution and less pressure drop in the stack owing to no gas disturbance between the flow layers, and the uniformity may be gradually improved with increasing temperature.

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Nomenclature

Q	total mass flow rate (kg s ⁻¹)
m_n	mass flow rate (kg s ⁻¹)
P	pressure (Pa)
t	time (s)
U	velocity vector (m s ⁻¹)
u	velocity (m s ⁻¹)
k	turbulent kinetic energy (m ² s ⁻²)
$C_{\varepsilon 1}$	turbulent model constant
$C_{\varepsilon 2}$	turbulent model constant

C_2 inertial resistance factor

S_i source term

Greek symbols

ρ density(kg m⁻³)

μ dynamic viscosity (kg m⁻¹ s⁻¹)

μ_t turbulent viscosity (kg m⁻¹ s⁻¹)

ε turbulent dissipation rate (m² s⁻³)

α permeability (m²)

σ_k turbulent model constant

σ_ε turbulent model constant

ΔP pressure drop (Pa)

τ stress tensor (kg m⁻¹ s⁻²)

Abbreviations

SOFC solid oxide fuel cell

CFD computational fluid dynamics

MCFC molten carbonate fuel cell

SLM standard liter per minute

FVM finite volume method

SIMPLE Semi-Implicit Method for Pressure-Linked Equation

Re Reynolds number

Subscript

i components of a vector in Cartesian coordinates

n

cell or channel number

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Figure captions

Fig. 1 Schematic diagram for structure of a typical external manifold stack.

Fig. 2 Schematic manifold representation of SOFC stacks: top-inlet (a), center-inlet (b) and buffer chamber-inlet (c).

Fig. 3 Grid independence tests for numerical simulation.

Fig. 4 Dimensionless mass flow rates for three manifold designs.

Fig. 5 The pressure contour for top-inlet (a), center-inlet (b), buffer chamber-inlet (c) of 40-cell stack and the surface of single cell (d).

Fig. 6 Velocity contour for center-inlet (a) and buffer chamber-inlet (b) in the 40-cell stack.

Fig. 7 Schematic representation of SOFC stacks with manifold depth (a) 15 mm, (b) 20 mm, (c) 25 mm

Fig. 8 Dimensionless mass flow rates for different manifold depths.

Fig. 9 Dimensional mass flow rates for different number of tubes to manifold.

Fig. 10 Velocity streamline in the manifold for different number of inlet tubes.

Fig. 11 Dimensionless mass flow rates for different pressure drop in 40-cell stack.

Fig. 12 Dimensionless mass flow rate (a) and pressure drop (b) for air and H₂ in 40-cell stack.

Fig. 13 The measurement of pressure drop under different mass flow rates for cathode and anode side.

Fig. 14 The measurement of mass flow rates for 40-cell stack: (a) top-inlet, (b)

center-inlet, (c) buffer chamber-inlet.

Pressure
Contour

[Pa]