Study on the surface structure effect of anode flow channel in proton exchange membrane fuel cell

C C Liu*

College of Big Data and Artificial Intelligence, Chizhou University, No.199, Muzhi Road, Guichi Distric, Chizhou, 247000, Anhui Province, China
'E-mail: ccliu@czu.edu.cn

Abstract. The paper mainly discusses the transport behavior of hydrogen gas in the anode flow channel of the Proton Exchange Membrane Fuel Cell. The flow pattern of hydrogen gas at the anode is affected by the surface structure of flow channel. In order to accurately simulate the transport characteristics of the hydrogen gas in the anode flow channel, a structured 3-D multi-block, staggered grid system is used for spatial discretization in numerical methods, and the finite volume method is used to sequentially iteratively solve the continuous and momentum conservation equations. The coupling between velocity and pressure in the flow field is calculated by the PISO algorithm. Two shapes design of three-dimensional smooth straight flow channel and three-dimensional bump straight flow channel are adopted in this paper. The hydrogen gas with Reynolds number 200 enters the smooth straight flow channel. The flow field inside the flow channel has been developed about 0.3 ms. At the same inlet Reynolds number and straight flow channels of three kind of bump height ratio (h/H=0.25, h/H=0.5, h/H=0.75), these calculation results are discovered that the height ratio of the bump increases and the backflow effect becomes more obvious. The current density of the Proton Exchange Membrane Fuel Cell is further analyzed by the flow field variation in the bump flow channel.

1. Introduction
Proton Exchange Membrane Fuel Cell (PEMFC) is a chemical reaction device that converts chemical energy into electrical energy. Fuel gas (hydrogen) enters the flow channel at the anode and dissociates into hydrogen ions and electrons through the diffusion layer and catalyst layer. The electrons move to the collector plate and the hydrogen ions move to the cathode through the proton exchange membrane. Therefore, the transmission pattern of hydrogen gas at the anode will be affected by many factors such as flow channel structure, temperature effect and fuel concentration. These factors will change the important key of PEMFC performance.

In the past, Le et al. [1] described the influence of fuel gas diffusion on electrodes in PEMFC. Amphlett et al. [2] and Costamagna et al. [3] used an electrochemical model to simulate fuel cell conditions with relevant conditions, gas pressure, and output results. Dutta [4] developed a theoretical analysis of gas flow, voltage and current, so as to understand the influence of gas flow on voltage and current. Hohlein [5] and Amphlett et al. [6] used methanol in the anode channel to decompose to obtain sufficient hydrogen as fuel gas, but the decomposition process did not affect fuel cell performance. Argyropoulos et al. [7, 8] conducted experiments on the hydrogen gas flow in the flow channel, and matched the electrode plate design to obtain the best conditions. Scott et al. [9] used the amount of produced hydrogen by methanol to discuss the relationship between the energy and power output by the fuel cell. Chen and Tsai [10] added bumps to the anode flow channel of PEMFC, and simulated the transport...
behavior of fuel gas by two-dimensional steady-state numerical calculation model with periodic boundary conditions. The bump height of the anode flow channel affected the current density of the fuel cell from these results.

Based on the above research, this paper will simulate the transient transmission process of hydrogen gas in the three-dimensional anode flow channel. By the variation of surface structure in the flow channel, the influence of the current density will be discussed through different flow characteristics.

2. Formulation

The schematic diagram of anode flow channel of PEMFC is shown in Figure 1. The lower wall of the flow channel is the electrode plate. The inner, outer and upper walls are the separator plates. By assuming incompressible three-dimensional laminar flow, gravity and surface tension are neglected. Two shapes design of three-dimensional smooth straight flow channel and three-dimensional bump straight flow channel are presented in the paper.

The governing equations are given below:

Continuity equation:

\[ \nabla \cdot (\rho \mathbf{u}) = 0 \] (1)

Momentum equation:

\[ \frac{\partial}{\partial t} (\rho \mathbf{u}) + \nabla \cdot (\rho \mathbf{u} \mathbf{u}) = -\nabla p + \nabla \cdot \mu (\nabla \mathbf{u} + \nabla \mathbf{u}^T) + \rho g + \mathbf{F} \] (2)

All symbols of Equations 1-2 are defined, \( \mathbf{u} \) is flow velocity, \( \rho \) is fluid density, \( p \) is pressure, \( \mu \) is viscosity coefficient, \( g \) is gravity, \( \mathbf{F} \) is surface tension source.

3. Numerical method

Upon inspection of the governing equations of the physical problem, it is recognized that finding the analytical solutions of the equations is impossible, owing to their nonlinearity and coupling. Instead, one has to develop a numerical method to simulate the physical phenomena. In the physical problem, these boundary conditions are assumed that hydrogen gas flow has an inlet velocity, with the pressure boundary of flow channel outlet and no slip of flow channel wall. A structured 3-D multi-block, staggered grid system is used for spatial discretization in numerical methods, and the finite volume method is used to sequentially iteratively solve the continuous and momentum conservation equations. The coupling between velocity and pressure in the flow field is calculated by the PISO Pressure-Implicit with Splitting of Operators (PISO) algorithm. PISO is a pressure-velocity calculation procedure for the Navier-Stokes equations developed originally for non-iterative computation of unsteady compressible flow, but
it has been adapted successfully to steady-state problems.

4. Results and discussions
In order to understand the transmission behavior of hydrogen gas in the anode flow channel, two shape designs of three-dimensional smooth straight flow channel and three-dimensional bump straight flow channel are shown in Figure 2 and Figure 3. All geometric dimensions and grid systems are in Table 1 and Table 2.

![Smooth straight flow channel](image1)
![Bump straight flow channel](image2)

**Table 1.** Geometric dimensions and grid system of anode flow channel.

| Type of flow channel | Geometric shape                        | Length(L) (mm) | Width(W) (mm) | Height(H) (mm) | Grid system |
|----------------------|----------------------------------------|----------------|---------------|----------------|-------------|
| Case 1               | smooth straight flow channel            | 29.5           | 1             | 1              | 65400       |
| Case 2               | bump straight flow channel (height ratio 0.25) | 29.5           | 1             | 1              | 70400       |
| Case 3               | bump flow channel (height ratio 0.5)    | 29.5           | 1             | 1              | 79600       |
| Case 4               | bump flow channel (height ratio 0.75)   | 29.5           | 1             | 1              | 82400       |
| Case 5               | bump flow channel (height ratio 0.5 and length 1.5mm) | 29.5           | 1             | 1              | 86400       |

**Table 2.** Geometric dimensions of bump.

| Geometric shape | Length(L) (mm) | Width(W) (mm) | Height(H) (mm) |
|-----------------|----------------|---------------|----------------|
| height ratio 0.25 | 1              | 1             | 0.25           |
| height ratio 0.5 | 1              | 1             | 0.5            |
| height ratio 0.75 | 1              | 1             | 0.75           |
| height ratio 0.5 and increased length | 1.5            | 1             | 0.5            |

4.1. Smooth straight flow channel
The dimensions of smooth straight flow channel and grid system is shown as case 1 of table 1. The hydrogen gas enters at an inlet velocity of 4 m/s (Reynolds number: \( \text{Re} = \frac{\rho u H}{\mu} = 200 \)). Initially, there is no hydrogen gas in the flow channel. With the increase of time, due to the fast inlet speed and the small geometric shape length, the flow field inside the flow channel has been developed about 0.3 ms. Figure 4a-4c are streamlines diagram of hydrogen gas at different times. Because the geometric shape is a smooth straight flow channel, the internal streamlines represent straight flow pattern. By the result of pressure distribution in flow channel from 0.1ms to 0.3ms (Figure 5a-5c), pressure at the inlet is the maximum, and pressure gradually decreases along the flow channel downstream. After the time 0.3ms, pressure distribution of the flow channel has no difference. Further, in order to clearly distinguish the completion time of the flow field development in the flow
channel, the variation of surface friction coefficient ($cf$) along electrode plate (XY plane) at $Y=0.5$ mm position is shown in Figure 6. At the beginning, the flow field in the flow channel has not been developed yet, and the value has changed. With time increase until 0.3 ms later, no change of value indicates that the flow field inside the flow channel has been completely developed.

![Streamlines diagram of smooth straight flow channel at different times.](image)

**Figure 4.** Streamlines diagram of smooth straight flow channel at different times.

![Pressure distribution diagram of smooth straight flow channel.](image)

**Figure 5.** Pressure distribution diagram of smooth straight flow channel.

![The coefficient of skin friction with time along the electrode plate at $Y=0.5$ mm.](image)

**Figure 6.** The coefficient of skin friction with time along the electrode plate at $Y=0.5$ mm.

4.2. **Straight flow channel with bump height**

All dimension and grid system of straight flow channel with bump height are obtained from Table 1 and Table 2. In straight flow channel with 0.25 height ratio of bump, similarly, hydrogen gas has an inlet velocity of 4 m/s ($Re=200$). At the beginning, there is no hydrogen gas in the flow channel. During simulation time, the calculation results are known that the backflow effect between the bumps is not obvious due to the lower height of bumps (Figure 7a-7c).
The pressure distribution in flow channel at different times is shown in Figure 8a-8c. These results can be discovered that pressure variation between the bumps is not very strong. So, the backflow effect is not obvious.

As the height ratio of bump is 0.5 and 0.75, in initial time, the recirculation area between the bumps has appeared. With increasing time, the recirculation effect between the bumps becomes more obvious as Figure 9a-9c and Figure 11a-11c. In further comparison of Fig.9a-9c and Figure 11a-11c, when the height of the bumps in flow channel increases, the recirculation effect between the bumps becomes stronger. From the pressure distribution diagrams at different times (Figure 10a-10c and Figure 12a-12c), there is the obvious low pressure area between the bumps in flow channel. The recirculation can be produced in the low pressure area.

Figure 7. Streamlines diagram of straight flow channel with 0.25 height ratio of bump.

Figure 8. Pressure distribution diagram of straight flow channel with 0.25 height ratio of bump.

Figure 9. Streamlines diagram of straight flow channel with 0.5 height ratio of bump.

Figure 10. Pressure distribution diagram of straight flow channel with 0.5 height ratio of bump.

Figure 11. Streamlines diagram of straight flow channel with 0.75 height ratio of bump.

Figure 12. Pressure distribution diagram of straight flow channel with 0.75 height ratio of bump.
As for the increased length to 1.5 mm with height ratio 0.5 of bump, the distance between the bumps in the flow channel becomes smaller. The calculated results are obtained that the backflow effect is obvious with increased length with the height ratio 0.5 of bump. (Figure 13a-13c)

![Streamlines diagram of straight flow channel for length 1.5 mm and height ratio 0.5 of bump.](image)

**Figure 13.** Streamlines diagram of straight flow channel for length 1.5 mm and height ratio 0.5 of bump.

### 4.3. The coefficient of skin friction

According to the study Chen et al. [10], Nusselt number is directly proportional to current density (I). Where non-dimensional parameters are defined as follows:

- Nusselt number: \( Nu = hD/k \)
- Prandtl number: \( Pr = \mu C_p/\kappa \)
- Stanton number: \( St = Nu/(Pr Re) \)

So, Nusselt number is as follows:

\[
Nu = St \times Pr \times Re
\]

(3)

By the way of Reynolds analogy, the relationship between Stanton number (\( St \)) and the coefficient of skin friction (\( cf \)) is obtained.

\[
St = \frac{cf}{2}
\]

(4)

The relationship between \( Nu \) and \( cf \) are derived as follows:

\[
Nu = \left( \frac{cf \times Re \times Pr}{2} \right)
\]

(5)

From above the relationship, Nusselt number is proportional to the coefficient of skin friction (\( cf \)). Similarly, current density (I) is proportional to the coefficient of skin friction (\( cf \)). Of course, for gas flow in the anode channel, the result can be concluded that the greater value of the coefficient of skin friction can obtain the greater current density. At different times, in comparison of the smooth straight flow channel and straight flow channel with different height and length of bump, the variation of \( cf \) value along the electrode plate plane (XY plane) at the position \( Y=0.5 \text{ mm} \) are shown in Figure 14a-14c.

In addition to the smooth straight flow channel, the \( cf \) value has the periodic variation due to the same interval distance between the bumps with different heights or lengths in straight flow channel. Under the same length of bump, the \( cf \) value of bump with height ratio 0.75 is the largest, and \( cf \) value of bump with height ratio 0.25 is the smallest. The \( cf \) value of bump with height ratio 0.5 is almost the same regardless of whether the bump length is increased. So, the height of the bump in flow channel increases, the current density increases too. The bump length of flow channel hardly affects the current density.
Figure 14. The coefficient of skin friction along the electrode plate plane at the Y=0.5 mm.

5. Conclusions
Numerical method is used to calculate the hydrogen gas transmission characteristics in the anode flow channel. In order to discuss the influence of surface structure of the anode flow channel, two shape designs of three-dimensional smooth straight flow channel and three-dimensional bump straight flow channel are adopted. In the simulation results of this study, for the increased height ratio under same length of bump, the backflow effect becomes more obvious, and the $cf$ value also increases, which means the current density increases. For the increased length under same height ratio of bump, the $cf$ value changes little, which means the variation of bump length of flow channel hardly affects the current density.
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