ENHANCEMENT OF THE GAS TRANSPORT AND THE PERFORMANCE IN THE PEMFC BY THE IRREGULAR FLOW CHANNELS

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ABSTRACT

The purpose of this study is to evaluate the gas transport and the performance of the flow channel design in the Proton Exchange Membrane Fuel Cells (PEMFCs). The numerical simulation is restricted to 2-D incompressible flow, laminar. The types of the flow channels in the bipolar plates embrace the blocked, wavelet, triangular flow channels etc. The results show the more gas flow into the gas diffusion layer and the performance increases compared to the straight flow channel. These structures increase the gas flow velocity in the longitudinally, and improve the performance in the catalyst layer. That is due to the forced convection mechanism caused by the irregular flow channels. Therefore, the irregular flow channel can enhance the gas transport into the catalyst layer, and improve the performance of the PEMFC.

Keywords: PEMFCs, numerical simulation, the irregular flow channel.

1. INTRODUCTION

The proton exchange membrane (PEM) fuel cell is considered to be a promising power source. And there is interest in the use of fuel cells for both mobile and stationary applications as an environmentally friendly power source. In order to satisfy the requirements for compactness, low cost, high power density, and performance and stability, the optimization for the PEMFC is necessary. The channel design is one of the important parts in the PEMFC. The section geometry and the pattern of the fuel flow channel influence the reactant gas transport, water management, and the efficiency of the fuel.

In the past years, lots of fundamental studies have been directed towards increasing our understanding of PEM fuel cells and their performance. The effects of the several different channel types such as the arrangements of serpentine channels, multiple channels in parallel type, interdigitated channels, etc. have been studied in PEM fuel cells. Dutta et al. [1] performed three-dimensional computations for cell transport in fuel cells of serpentine channels with the electrochemistry modeled by the mass source/sink terms. The electrochemical behaviors of a direct methanol fuel cell with serpentine flow field (SFF) and interdigitated flow field (IFF) at both cathode and anode were investigated by Arico et al. [2]. The experimental results showed that the IFF’s significantly enhanced the mass transport inside a DMFC and allowed achieving higher maximum power outputs compared to the classical serpentine geometry. The larger methanol permeation through the electrolyte determines both lower voltage and fuel efficiencies in the activation-controlled region with respect to the SFF. Tüber et. al. [3] are investigated and compared with common serpentine and parallel flow-fields. For both PEMFCs and DMFCs fractal flow-fields show similar performance to parallel designs. The most stable and highest power output is reached with the serpentine flow-field. Zhukovsky et al. [4] found maximum current limitations come due to oxygen depletion on the cathode. And the results appear strongly dependent on the geometry of the gas diffuser and supply channels. Yan et al. [5] conducted a numerical study of the effects of fuel channel width and GDL porosity on the cross-cell transport of reactant gas and the performance of a PEM fuel cell. Most recently, GDL characteristics with various thickness and porosity fabricated by using different manufacturing methods were studied by numerical simulation and experimental measurements. Soong et al. [6] proposed a novel configuration of partially blocked fuel channels with baffle plates transversely inserted in the channel. The numerical simulation showed that designs with the baffle gap ratio no smaller than 0.1, number of baffle plates N= 3 - 5, and the GDL porosity around 0.7 seems quite appropriate. J.K. Kuo and C.K. Chen [7,8] report on novel composite material for the bipolar of proton exchange membrane fuel cells by wave-like channel design. Yi et al. [9] developed an along-the-channel
model for evaluating the effects of various design and operating parameters on the performance of a PEM fuel cell. The model has been extended to include the convective water transport across the membrane by a pressure gradient, temperature distribution in the solid phase along the flow channel, and heat removal by natural convection and coflow and counterflow heat exchangers. Zhou and Liu [10], Um and Wang [11], and Hwang et al. [12] described a 3D model for PEM fuel cell. Their results agree well with the experimental observations. It is noted that the above-modeled results are based on the adiabatic conditions.

Therefore, the aim of this investigation was to study the flow channel with the different shape by doing simulations. The design in the bipolar plate would raise the force convection to enhance the reaction in the catalysis. Furthermore, the geometry design in the bipolar plate improves the reaction gas transport and the performance in the PEM fuel cell. Finally, the simulation showed the PEMFC performance for the different shape in the bipolar plate.

2. PEMFC MODEL

The simulations performed in this study are based on a steady state, single-phase, multi-species, two-dimensional mass transfer model of a PEMFC. The physical domain is shown as Figure 1. As shown, the fuel cell comprises anode and cathode flow channels with wavelet profiles, two gas diffusion layers made of a porous material (carbon paper), two catalyst layers, and a proton exchange membrane. The operating pressure and temperature are 1 atm and 353 K, respectively. The simulations assume that the anode is supplied with humidified hydrogen with a mass fraction of 0.70/0.30 H2/H2O. The cathode side is fed with saturated air with a mass fraction of 0.21/0.79 O2/N2. The geometry and physical parameters are given as Table 1. The following additional assumptions are also made:

1. The gas mixture is an incompressible, ideal fluid.
2. The Reynolds number of the fluid is less than 200 and the flow is laminar.
3. The gas diffusion layer, the catalyst layer and the membrane are all isotropic and homogeneous, and are characterized by high permeability and a uniform porosity.
4. The electrochemical reaction is governed by Butler-Volmer kinetics.
5. The water byproduct of the electrochemical reaction at the cathode side is in a vapor state.
6. The membrane is impervious to the reactant gases.
7. The fuel cell geometry is periodic in the x-axis direction.

PEMFCs with various gas flow channel configurations have been presented in the literature. In general, the aim of all of these different pathways is to maximize the area of the reaction surface exposed to the oxygen and hydrogen gas streams and to provide a route for the liquid water produced during the catalytic reaction to exit the fuel cell. The wave-like gas flow channel considered in this study has the additional function of enhancing the gas velocity in the vertical direction in order to improve the efficiency of the catalytic process.

The heat and mass transfer in different gas flow channel can be modeled using conventional mass conservation, Navier-Stokes, and energy and species conservation equations.

The basic gas transport equations for a general 2D PEMFC are as follows:

Continuity equation:
\[
\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} = 0 \quad (1)
\]

Momentum equation:
\[
\varepsilon_{\rho} \left( \frac{\partial u}{\partial x} + v \frac{\partial u}{\partial y} \right) = -\varepsilon_{\rho} \frac{\partial P}{\partial x} + \nu \varepsilon_{\rho} \left( \frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 u}{\partial y^2} \right) + S_u \quad (2)
\]

Energy equation:
\[
\varepsilon_{\rho} \frac{\partial T}{\partial x} + \frac{\partial T}{\partial y} = \frac{k \varepsilon_{\rho}}{\rho} \left( \frac{\partial^2 T}{\partial x^2} + \frac{\partial^2 T}{\partial y^2} \right) + S_E \quad (4)
\]

Species conservation equation:
\[
\varepsilon_{\rho} \left( \frac{\partial C_i}{\partial x} + v \frac{\partial C_i}{\partial y} \right) = \frac{D_{i,eff} \varepsilon_{\rho}}{\rho} \left( \frac{\partial^2 C_i}{\partial x^2} + \frac{\partial^2 C_i}{\partial y^2} \right) + S_c \quad (5)
\]

Charge conservation equation:
\[
\varepsilon_{\rho} \left( \frac{\partial \phi}{\partial x} + v \frac{\partial \phi}{\partial y} \right) = -S_\phi \quad (6)
\]

where \( S_{\text{anode}} = -\frac{J_{\text{anode}}}{2F} \), \( S_{\text{cathode}} = -\frac{J_{\text{cathode}}}{2F} \), \( S_{\phi} \) are the source terms in the governing equations. In these formulae, the parameters \( \varepsilon_{\rho}, k, D_{i,eff} = D_i e^\varepsilon \) denote the effective porosity, the permeability and the valence of the species, respectively. Furthermore, \( D_{i,eff} = D_i e^\varepsilon \) represents the effective diffusion coefficient of the \( k_{an} \) component of the reactant fuel.

In the PEMFC, the generation/consumption of the chemical species and the charge transfer are restricted to the catalyst layer. Therefore, the source terms in Eqs. (5) and (6) can be implemented based on electrochemical kinetics, i.e.

\[
S_{\text{anode}} = -\frac{J_{\text{anode}}}{2F} \quad (7)
\]

\[
S_{\phi} = -\frac{J_{\text{cathode}}}{2F} \quad (8)
\]

where \( J \) denotes the transfer current density and is derived from the following Butler-Volmer kinetics expressions:

\[
J_{\phi,act} = \frac{C_{\text{act,anode}}}{C_{\text{act,ref,anode}}} \left[ \frac{\alpha F}{RT} \eta_{\text{act,anode}} - \frac{\alpha F}{RT} \eta_{\text{act,ref,anode}} \right] \quad (10)
\]

\[
J_{\phi,act} = \frac{C_{\text{act,cathode}}}{C_{\text{act,ref,anode}}} \left[ \frac{\alpha F}{RT} \eta_{\text{act,cathode}} - \frac{\alpha F}{RT} \eta_{\text{act,ref,cathode}} \right] \quad (11)
\]

where \( \eta_{\text{act,anode}} \) is the surface over potential and is defined as:

\[
\eta_{\text{act}} = \phi_{anode} - \phi_m - \nu_{OC} \quad (12)
\]

in which \( \phi_{anode} \) and \( \phi_m \) denote the potentials of the carbon phase and the membrane phase, respectively, in the catalyst layer, and \( \nu_{OC} \) is the reference open-circuit potential of the electrode.

The phase potential equation for the potential and current profile is given by:

2


\[
\frac{\partial}{\partial x} \left( \sigma_n \frac{\partial \Phi}{\partial x} \right) + \frac{\partial}{\partial y} \left( \sigma_n \frac{\partial \Phi}{\partial y} \right) = S
\]  

(13)

Where \( \Phi \) is the phase potential function and \( \sigma_n \) is the membrane conductivity, which has the form:

\[
\sigma_n (T) = \sigma_n^{ref} \exp \left[ 1268 \left( \frac{1}{303} - \frac{1}{T} \right) \right]
\]

(14)

where \( \sigma_n^{ref} \) is the reference conductivity of the membrane and is given by:

\[
\sigma_n = 0.005139 \lambda - 0.00326
\]

(15)

\[
\lambda = \begin{cases} 
0.043 + 17.81 \cdot a - 39.85 \cdot a^2 + 36.0 \cdot a^3 & \text{for } 0 < a \leq 1 \\
14 + 1.4 \cdot (a - 1) & \text{for } 1 \leq a \leq 3 
\end{cases}
\]

(16)

in which \( a \) is the water activity and is defined as:

\[
a = \frac{s_{H_2} P}{P_{sat}}
\]

(17)

In Eq. (17), the saturation pressure varies with the temperature and can be determined directly from thermodynamic tables or from the following empirical expression:

\[
P_{sat} = 10^{-2.1794 + 0.029537 \cdot 9.1377 \cdot 10^{-7} T + 1.4454 \cdot 10^{-9} T^2}
\]

(18)

### 3. BOUNDARY CONDITIONS

The governing equations for the current PEMFC model are elliptic, partial differential equations, and hence boundary conditions are required for all of the boundaries in the computational domain. Due to the conjugated nature of the current problem, the gas flow channel surfaces are included within the solution domain and are treated as a particular type of fluid.

The boundary conditions are as follows:

1. **Gas flow channel:**
   - **Anode inlet:**
     \[ u = u_{in}, \quad T = T_{in} \]
     \[ v = 0, \quad C_{N_2} = C_{H_2, in}, \quad C_{N_2} = C_{N_2, in} \]
   - **Cathode inlet:**
     \[ u = u_{in}, \quad T = T_{in} \]
     \[ v = 0, \quad C_{O_2} = C_{O_2, in}, \quad C_{N_2} = C_{N_2, in} \]
   - **Interface between gas flow channel walls and catalyst layer:**
     \[ u = v = \frac{\partial C_i}{\partial x} = 0 \]
   - **2. Gas flow channel outlet:**
     \[ \frac{\partial u}{\partial x} = \frac{\partial v}{\partial x} = \frac{\partial T}{\partial x} = 0 \]
   - **3. Upper surface:**
     - **Anode gas channel:**
       \[ u = v = 0 \]
       \[ T_{surface} = 300K \]
   - **4. Lower surface:**
     - **Cathode gas channel:**
       \[ u = v = 0 \]

### 4. RESULTS AND DISCUSSION

#### 4.1 Velocity field

The transport phenomenon plays an important role for the characteristics in the PEMFC, and the flow velocity is a fundamental effect on the gas transport. Figure 2 (a)-(f) shows the axial velocity profile (x-direction) in the straight, 3-continuous semicircle convex, 3-blocked, 3-semi-elliptic convex, 3-triangle block and 3-continuous wavelet flow channel for laminar flow with an operating potential of 0.6V with the air flow inlet velocity of 0.3 m/s and the hydrogen flow inlet velocity of 0.2 m/s. These flow channels have the minime It is shown that the different flow channels affect the more gas flow into the GDL. The velocity along the axial direction varies acutely in the other channel than in the straight channel. As the gas is extruded by the block in the channel, the velocity is accelerated, ex. Figure (b)-(f). The maximum axial velocity is 0.4583, 4.012, 3.608, 3.507, 4.034 ms/ in figure 2 (a)-(f), respectively. Figure 3 (a)-(f) shows the distribution of the y-direction velocity in the straight, 3-continuous semicircle convex, 3-blocked, 3-semi-elliptic convex, 3-triangle block and 3-continuous wavelet flow channel in the same conditions as figure 2. As the blocks are added in the flow channel, the vertical velocity increases significantly. The vertical velocity is uniform in the straight flow channel. Figure 3(c), 3(d) and 3(e) that these channel put the different block in the flow channel appear that the y-direction velocity increases more in the GDL, and the 3-tri-blocked flow channel has the higher vertical velocity than 3-blocked and 3-semi-elliptic flow channels. Figure 3(b) and 3(f) design continuous semicircle convex and wavelet shape in the flow channel, and the vertical velocity is lower than the others. But the vertical velocity has a very wild distribution in the channel. The phenomenon increases the range that the gas flow into the GDL, and can expect to arise the performance of the PEMFC. Hence, the different flow channel induces a strong convection force along the reaction surface. The mechanism increases the reactant gases to the catalyst layers and drive out the reaction products by the reactant processes. Therefore, the performance of the fuel cell is significantly improved by the different flow channel.

#### 4.2 Concentration distribution

Figures 4(a)-(f) show the oxygen concentrations in the different flow channels. The over potential is 0.6V and the contour indicates the molar concentration of the two gases. The oxygen concentration reduces slightly along the axial direction, as Figure 4(a)-(f). Conspicuously, the oxygen concentration varies rapidly near the reactant surface. The contour in the geometry shape flow channel has a greater variation than that in the straight flow channel. The phenomenon is the result of the forced convection effect caused by the geometry change, and more reactant gases flow into the catalyst layer. The concentration field in the figure 4(b), 4(f) near the catalyst layer varies acutely than the others because of these design flow channel cause the stronger convection flow, and more oxygen react with the hydrogen. By contrast, the different gas flow channel achieves higher oxygen transfer rate in the
reaction surface region since transport is achieved by stronger convection.

4.3 Polarization curve

The polarization characteristics of a PEMFC for the different gas flow channel show the meanings of evaluating the performance of the fuel cell. Figure 5 appears the polarization and power density curves of PEMFCs with the different flow channels. The inlet velocities in the anode and cathode are 0.2 m/s for hydrogen and 0.3 m/s for air. It is showed that the different shape in the flow channel have the different influences. The 3-continuous semicircle convex, 3-blocked and 3-continuous wavelet flow channel design have the conspicuous change for the performance of the fuel cell. That is because the more gas flow into the GDL and catalyst layer, and cause the more reaction happen. The results also shows that the power density of the PEMFC can add 20-30% than the straight flow channel design.

This result demonstrates that the different flow channel affect the reactant gas transport to the catalyst layer by a convection mechanism. And the effect improves electrical performance significantly. Especially, the 3-continuous semicircle convex, 3-blocked and 3-continuous wavelet flow channel design can arise the performance major.

5. CONCLUSION

This study search the effect of the gas transport and the performance of the PEMFCs with the different gas flow channels compared to the straight gas flow channels. The gas flow velocity, the reactant gas concentration, and the performance in the fuel cell have been examined. The results show that the new style channel provides a better transport mechanism, and improves the performance characteristics. Furthermore, the different gas flow channel enhances the transport mechanism and improves the polarization characteristics and power density. Finally, the numerical results show that the better channel design improves the maximum power density by approximately 20-30%.

ACKNOWLEDGMENTS

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REFERENCES


Table 1

<table>
<thead>
<tr>
<th>Quantity</th>
<th>Value</th>
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<tbody>
<tr>
<td>Gas channel width</td>
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</tr>
<tr>
<td>Gas channel length</td>
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</tr>
<tr>
<td>Gas diffusion layer thickness</td>
<td>0.25 mm</td>
</tr>
<tr>
<td>Catalyst thickness</td>
<td>0.025 mm</td>
</tr>
<tr>
<td>Membrane thickness</td>
<td>0.25 mm</td>
</tr>
<tr>
<td>Porosity of gas diffusion layer</td>
<td>0.4</td>
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<tr>
<td>Porosity of catalyst layer</td>
<td>0.28</td>
</tr>
<tr>
<td>Permeability of gas diffusion layer</td>
<td>1.76×10^{-11} m²</td>
</tr>
<tr>
<td>Permeability of catalyst layer</td>
<td>1.76×10^{-11} m²</td>
</tr>
<tr>
<td>Permeability of membrane layer</td>
<td>1.18×10^{-11} m²</td>
</tr>
<tr>
<td>Tortuosity of gas diffusion layer</td>
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<tr>
<td>Tortuosity of catalyst layer</td>
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<tr>
<td>Electronic conductivity of gas diffusion layer</td>
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<tr>
<td>Electronic conductivity of catalyst layer</td>
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<tr>
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<tr>
<td>Operation pressure</td>
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<tr>
<td>Anode fuel</td>
<td>H₂, H₂O</td>
</tr>
<tr>
<td>Cathode fuel</td>
<td>O₂, N₂</td>
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<tr>
<td>Relative humidity of the anode</td>
<td>100 %</td>
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Figure 1. Computational domain of PEMFC gas flow channel.
Figure 2. Velocity field in x-direction of gas flow channels.

Figure 3. Velocity field in y-direction of gas flow channels.
Figure 4. Oxygen concentration distribution in gas flow channels at cell voltage of 0.6 V.

Figure 5. (a) Polarization curve and (b) power density curve in gas flow channels for various channel shape with gap size = 0.1.