Experimental and Numerical Study of Proton Exchange Membrane Fuel Cells with a Novel Compound Flow Field

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ABSTRACT: Excess water seriously affects the performance and lifetime of proton exchange membrane fuel cells (PEMFCs). This study proposes a novel compound flow field, which is named the active drainage flow field (ADFF). The new design enhances the drainage performance by under-ribs flow, while the output performance is very close to that of the conventional serpentine flow field (CSFF). Additionally, the ADFF bipolar plate has been taken as a cathode while retaining CSFF as an anode; the combination shows a good output performance under high relative humidity. The peak power density has reached to 0.59 W/cm², which is 13% higher than that of the CSFF.

1. INTRODUCTION

Proton exchange membrane fuel cells (PEMFCs) are significant for solving the energy crisis and environmental pollution. The transport of uncharged matter in its interior predominantly depends on diffusion and convection. In the case of the interdigitated flow field, because of the nonconnected design, the reaction gas in the inlet channels can only reach the outlet channels under the rib by forced convection, so does the draining of liquid water. Therefore, forced convection once was a research hotspot because of its unique mass transfer mode, which is more conducive to water management within PEMFCs.1−5 There are a number of studies in which the blocks and baffles were added in the flow field.6−11 The results showed that the blocks improved the current density and heat and mass transfer efficiency, and the shape and layout of the blocks significantly influenced performance. Wang et al.12 studied the effect of obstruction and tapering angles at the inlet and outlet of the conventional serpentine flow field (CSFF) on the performance of PEMFCs. The results showed that the design of the flow field under the condition of low operating voltage predominantly determined cell performance. In recent years, many scholars13−19 designed and evaluated various enhanced convective flow fields, and the results showed that enhanced convective flow fields could effectively drain liquid water from porous electrodes and improve the current density, especially in three-dimensional (3D) flow fields. Vijayakrishnan, Limjeerajaru, and Zhang et al.20−22 designed novel serpentine flow fields, which all showed that using novel serpentine flow fields at the cathode side while retaining CSFF at the anode can enhance the performance of power density.

In summary, forced convection is conducive to water management within the proton exchange membrane fuel cell (PEMFC), and the large local current density region is concentrated on the edge of channels. Because of forced convection, mass and heat transfer efficiency is improved, and shortening the inlet channel length is conducive for improving the performance of the cell. Simultaneously, the pressure loss will increase.

By considering the characteristics that forced convection enhances local heat and mass transfer and the characteristics of the distribution of reaction gases in flow fields, an improved model of interdigitated flow fields was proposed, which is named the active drainage flow field (ADFF). This study analyzed various characteristics of the ADFF. To verify its feasibility, a 25 cm² ADFF bipolar plate was designed and manufactured, and the single cell was assembled and tested.

2. NUMERICAL SIMULATION OF THE ELEMENT MODEL

2.1. Element Model Description. The novel interdigitated flow field element model, as shown in Figure 1, is established based on the conventional interdigitated flow field (CIFF). The starting surface of the outlet channel was changed from the...
closure of the interdigitated flow field to the active drainage (AD) inlet. To ensure the flow characteristics, the length of the model was set to 50 mm, and the width was bounded by the midline of two adjacent interdigitated channels. Similar elements were taken, with symmetrical boundaries of two sides, i.e., the width of the rib was 1.0 mm, the depth of the left and right channels was 1.0 mm, and the width was 0.5 mm.

Table 1 shows the remaining geometric parameters. The calculation domain includes bipolar plates, channels, gas diffusion layers (GDLs), microporous layers (MPLs), catalyst layers (CLs), and the membrane (MEM). The total number of grids in this research model is 530 000, and the grid type is a regular hexahedral structural grid, which is divided by GAMBIT software.

### 2.1. Assumptions

1. The fuel-cell operates under a steady-state condition.
2. The gases in the PEMFC are ideal, and H₂, O₂, and N₂ cannot dissolve in water.
3. The porous electrodes are isotropic and homogeneous, with the same characteristic parameters in the same layer.
4. Constant temperature boundary conditions are applied in the PEMFC outer surfaces.
5. Contact resistance is ignored.
6. The effects of gravity are ignored in multicomponent transfer and reaction processes.
7. The fluid flow is laminar.

### 2.2. Parameters

The key in numerically calculating PEMFC is the electrochemical calculation, and the electrochemical parameters involved successively are important in the calculation process. Table 2 shows the electrochemical parameters.

| parameters                          | value     | units  |
|-------------------------------------|-----------|--------|
| anode exchange current density      | 10 000    | A/m²   |
| anode reference molality            | 1         | kmol/m³|
| anode concentration index           | 0.5       |        |
| anode exchange coefficient          | 0.5       |        |
| cathode exchange current density    | 0.5       | A/m²   |
| cathode reference molality          | 1         | kmol/m³|
| cathode concentration index         | 1         |        |
| cathode exchange coefficient        | 1.5       |        |
| open-circuit voltage                | 0.95      | V      |
| porosity of GDLs                    | 0.4       |        |
| viscous resistance of GDLs          | 1 × 10⁻¹² | 1/m²   |
| contact angle of GDLs               | 110       | deg    |
| porosity of CLs                     | 0.112     |        |
| viscous resistance of CLs           | 1 × 10⁻¹² | 1/m²   |
| contact angle of CLs                | 95        | deg    |
| molar mass of MEM                   | 1100      | kg/mol |
| proton conductivity in MEM          | 1         |        |
| proton transfer coefficient in MEM  | 1         |        |

Table 3 shows the operating parameters. When the PEMFC operates under the conditions of oxygen as an oxidant and high current density, more reaction water is generated in the cathode flow field, and the drainage performance testing of the flow field is more essential. Therefore, the operating voltage is set to 0.3 V. The active drain inlet pressure is set to a tentative 100 Pa.

2.3. Numerical Simulation Results. Figure 2a shows the current density distribution at the interface between the cathode catalyst layer (CL) and cathode microporous layer (MPL) for the ADFF and CIFF at 0.3 V. Figure 2a shows that the current density of the ADFF is only lower than that of the CIFF at the drainage inlet because the increase in the pressure at the
drainage inlet reduces the pressure difference between the adjacent channels, i.e., the convection phenomenon in this region is weakened. In other regions, the ADFF is superior to the CIFF, with an average current density of 1364.87 mA/cm², which is 10.83% higher than that of the CIFF (1273.50 mA/cm²).

Figure 2b shows the contours of H₂O molar concentration at the interface between the cathode gas diffusion layer (GDL) and the cathode plate for the ADFF and the CIFF. The difference in water distribution in the inlet channel is small. The liquid water retention in the ADFF is less than that in the CIFF because the smooth drainage of liquid water in the channels accelerates the convection in the diffusion layer, increases the output performance of the cell, and reduces the retention of liquid water in the inlet channels. The effect is more obvious in the outlet channels. The water content in the outlet channels of the ADFF is less than that of the CIFF. Therefore, after setting the AD channel, the liquid water in the cathode is easier to discharge (Figure 2b). It promotes the reaction gases to the outlet channels through GDLs, increases the output power of the cell, and reduces the reverse diffusion phenomena. Thus, the water content in the anode channels is reduced, thereby significantly decreasing the pressure loss of the anode.

The ADFF is superior to the CIFF regarding both the output current density and water retention in the channels. Therefore, the design of the ADFF improves the performance and stability of the cell.

### 3. NUMERICAL SIMULATION OF SINGLE CELL

#### 3.1. Single Cell Model Description

Figure 3a,b shows the three-dimensional models of the CSFF and ADFF. In the ADFF, two staggered interdigitated inlet channels are set at both sides of the flow field, and a serpentine channel is set between adjacent interdigitated channels. Based on the 50×50 mm² conventional interdigitated flow field, a new standard size ADFF model was established (Figure 3c). The ADFF is provided with two reaction gas inlets (1), left and right inlet channels (2), AD inlet (3), serpentine drainage channel (4), and outlet (5). The inlet channels are an interdigitated structure distributed on both sides, and the outlet channel is a serpentine structure distributed between the two sides of the inlet channels as the reaction gas outlet channel. The cross section of the channel is square. The width, depth, height, and rib’s width are all 1.0 mm. The schematic diagram of the ADFF is shown in Figure 3d. Simultaneously, the CSFF is taken as a reference (Figure 3b). By considering the calculation accuracy and resources, the grid of the flow field and bipolar plates were uniformly divided into each side by 0.25 mm, establishing regular hexahedral grid units with the same number of grids, both of which were 2 080 000.

#### 3.2. Parameters

The basic assumptions and boundary conditions are the same as that of the previous section. Table 4 shows the operating parameters, and Table 2 shows the other electrochemical parameters.

The high current density was selected as the principal object of study, and the operating voltage was set to 0.3 V. According to the conditions in the previous section, within the effective area of 25 cm², the friction and local pressure losses are proportional to the square of the density and flow velocity, whereas the density and flow velocity in the drainage channel are small in the calculation process. Therefore, the pressure loss in the channel is smaller than the inlet pressure and can be ignored. During the simulation, the cathode oxidizer was set as pure oxygen, with 100% humidification, and the constant mass flow rate was 2.1 × 10⁻⁷ kg/s. The mass flow rate of hydrogen at the anode was 7 × 10⁻⁸ kg/s, with 100% humidification.

#### 3.3. Numerical Simulation Results

Figure 4 shows the polarization curve simulated by the standard size CSFF and ADFF. The overall performance of the two is similar, but in the ohmic loss region, the voltage drop rate of the ADFF is slower than that of the CIFF, with an average current density of 1364.87 mA/cm², which is 10.83% higher than that of the CIFF (1273.50 mA/cm²). Therefore, after setting the AD channel, the water content in the outlet channels of the ADFF is less than that in the CIFF (1273.50 mA/cm²).

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**Table 3. Operating Parameters**

| parameters           | values | units |
|----------------------|--------|-------|
| operating pressure   | 101 325| Pa    |
| operating temperature| 343    | K     |
| anode mass flow rate  | 2.8 × 10⁻⁷| kg/s |
| anode humidity       | 100    | %     |
| anode drainage pressure| 100  | Pa    |
| cathode mass flow rate| 5.72 × 10⁻⁷| kg/s |
| cathode humidity     | 100    | %     |
| cathode drainage pressure| 100  | Pa    |
| operating voltage    | 0.3    | V     |

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Figure 2. Contours in the ADFF and CIFF: (a) current density and (b) H₂O molar concentration.
than that of the CSFF because the ADFF has better drainage performance and timely drainage of the excess liquid water.

Figure 3. Flow field models: (a) structure of the ADFF and (b) CSFF. (c) Two-dimensional schematic diagram of the ADFF and (d) three-dimensional schematic diagram of (1) ADFF reactant gas inlets, (2) interdigitated inlet channels, (3) drainage inlet, (4) serpentine drainage channel, and (5) outlet.

Table 4. Operating Parameters

| parameters             | values     | units |
|------------------------|------------|-------|
| operating pressure     | 101 325    | Pa    |
| operating temperature  | 343        | K     |
| anode mass flow rate   | $7 \times 10^{-6}$ | kg/s |
| anode humidity         | 100        | %     |
| cathode mass flow rate | $2.1 \times 10^{-5}$ | kg/s |
| cathode humidity       | 100        | %     |
| operating voltage      | 0.3        | V     |

Figure 4. Polarization curves of the standard size CSFF and ADFF.
channels, but the overall drainage performance of the ADFF is far better than that of the CSFF.
4. EXPERIMENT OF SINGLE CELL MODEL

4.1. Experimental Setup. In the present study, three combinations of two forms of flow fields were studied, and the CSFF and ADFF were designed and processed on flexible graphite plates (Figure 6a,b). The combination that the ADFF is taken as the anode while retaining the CSFF at the cathode (S-AD configuration) is taken into consideration too. The active area of the PEMFC is 25 cm² (50 × 50 mm²), and the membrane electrode assembly for all flow fields was from Nekson Power Technology Co., Ltd. The contact resistance between the bipolar and collector plates was reduced by treating the collector plates with a gold plating process.

After the PEMFC was assembled (Figure 6c), the FCT-6KW fuel-cell testing system (Nekson Power Technology Co., Ltd.) was used to monitor and control the mass flow rate, temperature, humidity, and load of the PEMFC (Figure 6d). Tables 5 and 6 show the operating parameters. The polarization curve of the cell was evaluated after all operating parameters remained stable. The current controlled the polarization curve; the current was increased by 2.5 A for each step and held for 2 min.

4.2. Results and Discussions. Figure 7a shows the polarization curves of the simulation and experimental results. The experimental data’s tendency of PEMFC current density is consistent with the numerical simulation results. The experimental results are slightly smaller than the numerical simulation results, especially in the ohmic polarization region, because the contact resistance between the graphite bipolar and current collector plates in the experiment and the additional contact resistance between the electronic load and cell’s connection cannot be ignored. Consequently, the resistance in the experiment enhanced the ohmic polarization effect. Experimental data cannot meet the numerical output with a high current density. The insufficient reactant concentration of CLs prevents electrochemical reactions to produce electronic numbers that reach the setting current. The assumptions of numerical calculation are incompressible gases, a given reaction gas inlet for the constant mass flow rate, and an insufficient catalyst layer concentration. The phenomenon of concentration polarization is not obvious. Therefore, the experimental data of the ADFF are consistent with numerical results. Figure 7b shows the comparison of the polarization curves of the CSFF, ADFF, and S-AD; it can be seen that the performance of the CSFF and ADFF is very close at operating voltages below 0.6 V. With the increase of current density and liquid water, the advantages of the ADFF are more significant. Since the cathode is more prone to water flooding than the anode, the S-AD configuration combines the advantages of the CSFF and ADFF, while the performance of the S-AD configuration is integrally better than those of other configurations. The peak power density of the S-AD configuration is 0.59 W/cm², which is 13% higher than that of the CSFF.

5. CONCLUSIONS

In the present research, a novel compound flow field was proposed and a single cell was assembled and tested. The results revealed that the drainage performance of the ADFF is better than that of the CSFF because of the under-ribs flow and active drainage pressure, while the output performances of the two are very close. However, the S-AD configuration has better drainage performance and output performance than others. The peak power density of the S-AD configuration is 0.59 W/cm², which is 13% higher than that of the CSFF.
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Notes
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