1. Introduction

Developing clean energy and reducing environmental pollution are inevitable trends in human society [1]. The proton exchange membrane fuel cells (PEMFCs), which have the advantages of zero-emission, high energy efficiency, quick start-up, and so on, are expected to be an ideal energy conversion device in the future [2, 3]. However, the commercialization of PEMFCs is limited by some technical problems, such as reactants’ mass transfer and drainage capacity at high current density [4, 5]. Bipolar plates which are crucial components of PEMFCs provide flow fields to distribute reactants, remove water, and manage heat [6]. Therefore, the design of flow fields attracts more and more attention [7–9].

Many studies have focused on the optimization of traditional flow fields including parallel, serpentine, and wavy flow fields with the aim of improving power density [10–12]. Chen et al. [13] have proposed a stepped flow field to solve the nonuniform distribution of reactant gas. They observed that the net power of stepped flow field model was increased by 21.5% compared to parallel flow field model. Wang et al. [14] added serial baffles into triserpentine channels and studied the influence of arrangement and height of baffles on PEMFC performance. They found that the presence of baffles could promote diffusion of reactant gas into GDL compared to conventional channel. Yin et al. [15] developed a wavy flow field with opposite cathode and anode inlet directions. The experimental and simulation results show that the distributions of current density, water, and reactant concentration follow the geometry of cathodic rather than anodic wave flow field.

Except for traditional flow fields, novel flow field structures with high efficiency are applied in fuel cells, such as bionic, 3D fine mesh, metal foam, and dot flow fields [16–18]. Xia et al. [19] designed an improved vein biomimetic flow field according to the characteristics of vein network structure. It was found that the flow field has the advantages of lower pressure drop, more uniform distribution of reactive gas, and better output performance. Shen
et al. [20] established a 3D structure as the flow field of PEMFC to investigate water transport and cell operating characteristics. The result indicated that 3D flow field could enhance the mass transfer ability and improve PEMFC output performance compared with conventional flow field. Choi et al. [21] experimental studied about the nonuniform arrangement of metallic structures in cathode flow field on PEMFC conducted. And then, the results showed that maximum power density of the channel with nonuniform width arrangement and tapered structure is 12.8% higher than parallel channel. Azarafza et al. [22] compared conventional flow fields (i.e., parallel, serpentine, and interlaced) with metal foam flow field, which demonstrated that the metal foam flow field can provide the most uniform current density and temperature distribution, as well as acceptable pressure drop, so as to obtain the best fuel cell performance. Karthikeyan et al. [23] inserted porous carbon inserts into serpentine flow channel with staggered arrangement which improved power density by 42.56%. He et al. [24] developed a trapezoidal dot block flow field to investigate the effect of block tilt angle on PEMFC performance through experiments and simulations. The study showed that the PEMFC enhanced net output power by 15% when the tilt angle was 15° compared with parallel flow field. Atyabi et al. [25] proposed a hexagonal prismatic dot flow field and analyzed its influence on oxygen mass fractions, pressure distribution, and local current density. One of the highlighted results was that the hexagonal prismatic dot flow field increased the rate of oxygen diffusion in gas diffusion layer (GDL) by ten times.

In this paper, we designed a streamline dot block and applied it to flow field of PEMFC in order to compare it with parallel flow field and conventional dot flow field (rectangular and rhombic dot flow fields). We used tail length as a geometrical structure parameter to study streamline dot blocks and analyzed the effect of streamlined dot flow fields with different tail lengths on the fuel cell performance. The distributions of flow velocity, oxygen pressure, oxygen molar fraction, and membrane current in different flow fields are analyzed by numerical calculation methods. Therefore, the research in this paper provides the theoretical basis and technical reserve for the future optimization of the PEMFC flow field.

2. Model Development

2.1. Geometric Geometry. The three-dimensional PEMFC model containing anode/cathode parallel flow field, anode/cathode GDL, anode/cathode catalytic layer (CL), and proton exchange membrane (PEM) was developed, as shown in Figure 1(a). The baffle structure with streamline cross-section can be developed based on the variation of gas flow rate formed by adding rectangular baffles in flow channels. The application of streamline baffles enhances the reactants supplied to CL, thus further improving performance [26, 27]. In this paper, a streamline dot block is proposed based on the gas flow velocity after adding $1 \times 1$ mm rectangular dot block in flow field. The proposed streamline dot block with tail length ($L_T$) of $1$ mm is illustrated in Figure 2, which can be divided into three parts, including the windward part (pink), middle part (grey), and leeward part (orange). Furthermore, by changing $L_T$ of streamline dot block to develop PEMFC model with difference streamline dot flow field, as shown in Figure 3, the streamline flow field model consists of short straight flow channel (SSFC) and dot flow field. The dot flow field is obtained by interdigitating streamline dot blocks and setting the blockage rate to 100%. And the PEMFC model with streamline flow fields ($L_T = 1.0$ mm)
for the cathode and anode is shown in Figure 1(b). And the reactant gas of cathode and anode is flowing in a congruent direction. The geometric parameters of streamline dot blocks with different LT are listed in Table 1. In addition, the rectangular and rhombic dot flow fields are developed to compare and analyze with the streamline dot flow field, which is shown in Figure 3. The size of all PEMFC models is 10 × 2.7338 × 23 mm. The geometric and simulation parameters of PEMFC models are shown in Tables 2 and 3, respectively.

2.2. Mathematical Model. The main model assumptions of this study are listed below [28]:

(i) The PEMFC is in stable working condition
(ii) The ideal gas law is used
(iii) The reactant gas flow state is laminar flow
(iv) The liquid water in flow field is neglected
(v) The porous media material is isotropic

In order to more accurately model the redox reactions, mass transfer, current, and voltage changes occurring inside the fuel cell, the following equations have been used.

Mass conservation equation [29]:

\[ \nabla \cdot (\rho \vec{u}) = S_{\text{mass}}. \tag{1} \]

Momentum conservation equation:

\[ \nabla \cdot (\rho \vec{u} \vec{u}) = -\nabla p + \nabla \cdot (\mu \nabla \vec{u}) + S_{\text{mom}}. \tag{2} \]

Species conservation equation:

\[ \nabla \cdot (\rho \vec{u} c_k) = \nabla \cdot (\rho D \nabla c_k) + S_i. \tag{3} \]**

<table>
<thead>
<tr>
<th>Table 1: Geometric parameters of streamline dot block.</th>
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<tbody>
<tr>
<td>Dot block</td>
</tr>
<tr>
<td>Case 1</td>
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<tr>
<td>Case 2</td>
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<tr>
<td>Case 3</td>
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<table>
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<th>Table 2: Geometric parameters.</th>
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<tbody>
<tr>
<td>Parameters (unit)</td>
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<tr>
<td>Channel height (mm)</td>
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<tr>
<td>Channel width (mm)</td>
</tr>
<tr>
<td>Channel length (mm)</td>
</tr>
<tr>
<td>SSFC length (mm)</td>
</tr>
<tr>
<td>Rib width (mm)</td>
</tr>
<tr>
<td>GDL thickness (mm)</td>
</tr>
<tr>
<td>CI thickness (mm)</td>
</tr>
<tr>
<td>PEM thickness (mm)</td>
</tr>
<tr>
<td>Cell reaction area (mm²)</td>
</tr>
<tr>
<td>Rectangular dot block length (mm)</td>
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<tr>
<td>Rhombic dot block width (mm)</td>
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<tr>
<td>Blockage percentage</td>
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</table>

Figure 3: PEMFC flow field models: (a) parallel flow field, (b) rectangular dot flow field, (c) rhombic dot flow field, (d) streamline dot flow field \((L_T = 1 \text{ mm})\), (e) streamline dot flow field \((L_T = 1.5 \text{ mm})\), and (f) streamline dot flow field \((L_T = 2 \text{ mm})\).
Energy conservation equation [30]:

\[
\nabla \cdot (\rho \, c_p \, u^*) = \nabla \cdot (k_{\text{eff}} \nabla T) + S_Q. \tag{4}
\]

Electric charge conservation equation [31]:

\[
\nabla \cdot (\sigma_s \nabla \phi_s) + S_s = 0, \\
\nabla \cdot (\sigma_m \nabla \phi_m) + S_m = 0. \tag{5}
\]

Butler-Volmer equation [29]:

\[
\begin{align*}
\dot{j}_a &= a_i^{\text{ref}} \theta_a \left( \frac{C_{i_\text{H}_2}}{C_{i_\text{H}_2}^{\text{ref}}} \right)^{0.5} \left( e^{\alpha_e F \eta_a / RT} - e^{-\alpha_e F \eta_c / RT} \right), \\
\dot{j}_c &= a_i^{\text{ref}} \theta_c \left( \frac{C_{i_\text{O}_2}}{C_{i_\text{O}_2}^{\text{ref}}} \right) \left( -e^{\alpha_c F \eta_c / RT} + e^{-\alpha_c F \eta_c / RT} \right). \tag{6}
\end{align*}
\]

The local activation losses are solved as [32]

\[
\begin{align*}
\eta_a &= \phi_s - \phi_m, \\
\eta_c &= \phi_s - \phi_m - U_a. \tag{7}
\end{align*}
\]

2.3. Boundary Conditions. The inlet of PEMFC flow channel is set to velocity boundary. The inlet velocities of anode and cathode are [33]

\[
\begin{align*}
U_{\text{in},a} &= \zeta_a I_{\text{sto}} x_{\text{H}_2} RT / (p_{\text{ref}} \cdot A_{\text{ch}} \cdot n_{\text{ch}}), \\
U_{\text{in},c} &= \zeta_c I_{\text{sto}} x_{\text{O}_2} RT / (p_{\text{ref}} \cdot A_{\text{ch}} \cdot n_{\text{ch}}), \tag{8}
\end{align*}
\]

where \( U_{\text{in},a} \) and \( U_{\text{in},c} \) are average inlet velocities of anode and cathode flow fields, respectively, \( \zeta_a \) and \( \zeta_c \) are anode and cathode stoichiometric ratios, respectively, \( I_{\text{sto}} \) is current operating density used for gas flow calculation, \( x_{i_\text{H}_2} \) is hydrogen molar fraction, \( x_{i_\text{O}_2} \) is oxygen molar fraction, \( A_{\text{ch}} \) is cross-sectional area of flow channel, and \( n_{\text{ch}} \) is the channel number, which is 5 for the parallel and dot flow fields.

The outlet of PEMFC flow field is set to pressure boundary, and the outlet pressures of anode and cathode are

\[
\begin{align*}
p_{\text{out},a} &= 0, \\
p_{\text{out},c} &= 0. \tag{9}
\end{align*}
\]

2.4. Numerical Procedures. In order to investigate the effect of flow field structure on the output performance, reactant transport, and other characteristics of fuel cells, the

<table>
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<tr>
<th>Table 3: Model simulation parameters.</th>
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<tr>
<td>Parameters (unit)</td>
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<tr>
<td>Operating temperature (K)</td>
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<tr>
<td>Operating pressure (atm)</td>
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<tr>
<td>GDL porosity</td>
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<tr>
<td>GDL permeability (m²)</td>
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<tr>
<td>CL porosity</td>
</tr>
<tr>
<td>CL permeability (m²)</td>
</tr>
<tr>
<td>Open circuit voltage (V)</td>
</tr>
<tr>
<td>Anode charge transfer coefficient</td>
</tr>
<tr>
<td>Cathode charge transfer coefficient</td>
</tr>
<tr>
<td>Anode stoichiometry ratio</td>
</tr>
<tr>
<td>Cathode stoichiometry ratio</td>
</tr>
<tr>
<td>Molar fraction of inlet hydrogen</td>
</tr>
<tr>
<td>Molar fraction of inlet oxygen</td>
</tr>
<tr>
<td>Molar fraction of inlet nitrogen</td>
</tr>
<tr>
<td>Relative humidity (%)</td>
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Figure 4: The current density and mesh number.

Figure 5: Model validation.
commercial software COMSOL Multiphysics was used for 3D geometric modeling of PEMFC, and the numerical model was solved based on the finite element method. The computer processor is an AMD Ryzen 5 5600H with Radeon Graphics @3.30 GHz. The polarization curve of the fuel cell is obtained by an iterative process to calculate the current density, and the convergence criterion of the equation residuals is set to $10^{-6}$. The average computation time for all fuel cell models is 3 h.

2.5. Mesh Generation. In this study, a mesh-independent analysis of PEMFC model with parallel flow field was carried out by increasing the number of cells. The mesh number and current density at 0.4 V are shown in Figure 4. Meanwhile, the relative difference of current density for different meshing schemes is calculated. The relative difference of all meshing schemes is within 2.5%, which meets the requirements of calculation accuracy. The relative difference between mesh 4 and mesh 3 is 0.25%. And the relative difference between mesh 5 and mesh 4 is 0.04%. Therefore, in order to ensure the accuracy of calculation results while reducing computational effort, mesh 4 is used for the PEMFC geometric models.

2.6. Model Validation. To verify the validity of numerical model developed in this paper, the model used the same parameters as [34], and the result was compared with experimental data, as shown in Figure 5. From this figure, it can be observed that the simulation results correspond well to experimental data at low current density, and the simulation performance is significantly better than experimental performance at high current density. That is because the liquid water produced in experiment obstructs the mass transfer of reactant gas which causes voltage loss.

3. Results and Discussion

3.1. Comparison of Flow Velocity Distribution. Figure 6 illustrates the flow velocity distribution of reactant gas on different cathode flow fields at 0.6 V: (a) model A, (b) model B, (c) model C, (d) model D, (e) model E, and (f) model F.
Figure 7: Local flow velocity distribution in different cathode flow fields at 0.6 V: (a) model A, (b) model B, (c) model C, (d) model D, (e) model E, and (f) model F.

Figure 8: Oxygen pressure distribution in different cathode flow fields at 0.6 V: (a) model A, (b) model B, (c) model C, (d) model D, (e) model E, and (f) model F.
PLANE 1 and PLANE 2 within cathode flow fields at 0.6 V. PLANE 1 is the horizontal plane at the height of 0.5 \(H_{ch}\) in cathodic flow fields. PLANE 2 includes five vertical cross sections, and the distance between two adjacent cross sections is 2 \(W_{ch}\). The flow velocity in parallel flow field is obviously higher compared to dot flow fields, which can be obtained from Figure 6(a). That is because the average inlet velocity is the same for six flow fields, but the larger flow region in dot flow fields leads to the lower overall flow velocity. As observed in Figure 6, the flow velocity of SSFC in dot flow fields remains the same with the corresponding region of parallel flow field, which also verifies that the lower flow velocity in dot flow fields is associated with larger flow regions. Furthermore, the lower flow velocity in dot flow fields facilitates the diffusion of reactant gas into GDL.

In order to compare the effect of dot blocks on flow velocities more clearly, we compared the local flow velocities in six cathode flow fields on PLANE 1 at 0.6 V. As shown in Figure 7, in parallel flow fields, the flow velocity is uniformly distributed. The vortices are produced behind dot blocks because of low pressure in dot flow field. Among them, the vortices behind rectangular dot blocks are the largest, followed by rhombic dot blocks, and the vortices behind streamline dot blocks are the smallest. Therefore, streamline dot blocks can effectively eliminate vortices by increasing the length of tail since streamline dot blocks are helpful to reduce the flow resistance. Besides, with the increase of tail length, the uniformity of flow velocity distribution is improved.

### 3.2. Comparison of Oxygen Pressure Distribution.

The pressure drop and uniformity of reactants are essential concerns in the design of flow field. To maintain a constant gas stoichiometry, especially near outlet, the inflow mass flow rate is scaled resulting in additional parasitic power losses (pumping losses). In other words, higher-pressure drops require more power to pump the reactants. Figure 8 shows the comparison of oxygen pressure distribution in different cathode flow fields when operating voltage is 0.6 V. From Figure 8(a), the oxygen pressure gradually decreases from inlet to outlet in parallel flow field, which is due to partial oxygen consumption by electrochemical reaction. From Figure 8, the oxygen pressure in dot flow field is significantly lower near outlet region compared with parallel flow field.
The average oxygen pressure drops ($\Delta p$) between inlet and outlet from model A to model F are 1459 Pa, 2077 Pa, 1896 Pa, 1863 Pa, 1819 Pa, and 1794 Pa, respectively. Compared with parallel flow field, the pressure drop ($\Delta p_{\text{dot-par}}$) of dot flow fields increases by 618 Pa, 437 Pa, 404 Pa, 360 Pa, and 335 Pa, respectively. From this, the rectangular dot flow field has the highest $\Delta p_{\text{dot-par}}$ among all dot flow fields, with an increase of 84.48% compared to streamline dot flow field with $L_T = 2.0$ mm.

As shown in Figures 8(d)–8(f), as the increase of streamline dot blocks tail length, the oxygen pressure drop in flow field decreases, and the overall oxygen pressure distribution is more uniform.

3.3. Comparison of Oxygen Molar Fraction Distribution. Oxygen starvation leads to significant concentration polarization, especially in high currents. Figure 9 shows the comparison of oxygen molar fraction in cathode CL-GDL under different flow fields at 0.6 V. The distribution of oxygen molar fraction in parallel flow field is seriously uneven since the oxygen molar fraction is nearly zero in CL-GDL under the rib shown in Figure 9(a). The oxygen molar fraction distribution in CL-GDL with dot flow field is more uniformly and higher than in parallel flow field since the convection around dot blocks enhances oxygen diffusion into GDL, as shown in Figures 9(b)–9(d). However, the insufficient supply of oxygen still exists especially downstream of flow field. According to fluid dynamics, increasing the streamline dot block tail length can decrease mass transfer resistance and improve the distribution of local reactants. The increase of streamline dot block tail length from 1 mm to 2 mm results in oxygen supply improving significantly.

3.4. Comparison of Membrane Current Density Distribution. The current density distribution in different flow fields over the PEM-CL cross section on cathode side at 0.6 V is illustrated in Figure 10. It observed that the most nonuniform distribution of current density appears in parallel flow field since the rib plate obstructs reactant mass transfer. The dot block of dot flow field can change the flow direction of reactants to GDL and CL which enhances the reactant mass transfer, so the current density in the membrane is increased obviously.

For better analysis of the uniformity of current density distribution over the PEM-CL cross section on cathode side, the Index of Uniformity Current Density (IUCD) is introduced in this paper as follows [35, 36]:

$$IUCD = \frac{\int_A |I - \overline{I}| \, dA}{\int_A \overline{I} \, dA},$$  \hspace{1cm} (10)

where $I$ is the surface current density at PEM-CL on cathode side and $\overline{I}$ is the average surface current density at PEM-CL on cathode side.

IUCD represents the deviation of surface current density from surface average current density. In other words, if the current density is equal over the entire surface, the index is zero. Table 4 lists the IUCD, the maximum current density (MAXCD), and the minimum current density (MINCD) of six models for the PEM-CL cross section at 0.6 V.

As shown in Table 4, the streamline dot flow field with $L_T = 2.0$ mm has advantages in terms of membrane current density distribution. The results show that the lowest IUCD is 0.012991, and the best performance is obtained for model F with the maximum MAXCD and MINCD. In parallel flow field, IUCD is the largest with the value of 0.031946, and both MAXCD and MINCD are the lowest. Although model B has a lower IUCD, its MAXCD and MINCD are smaller than model F.

![Figure 10: Membrane current density distribution in different cathode PEM-CLs at 0.6 V: (a) model A, (b) model B, (c) model C, (d) model D, (e) model E, and (f) model F.](attachment:image10.png)
3.5. Comparison of Polarization Curves and Pumping Power Density. Comparison of the output performance of different PEMFC models at 0.6 V is shown in Figure 11. The polarization curves of parallel flow field model and five dot flow field models are plotted in Figure 11(a). According to this figure, the output performance of PEMFC with dot flow fields is significantly improved compared to applying parallel flow field. However, the performance of dot flow field with different dot block shapes differed less. To further analyze the effect of different dot block shapes on fuel cell performance, the current density of different models and average oxygen molar fraction over the PEM-CL cross section on cathode side at 0.6 V was compared in Figure 11(b). The lowest current density at 0.6 V appears in parallel flow field which is 1.2928 A/cm². Among three flow fields, the average oxygen molar fraction as well as current density increases continuously with increasing \( L_T \). And the highest current density is 1.3559 A/cm² appeared in streamline dot flow field with 2 mm tail which increased by 4.9%.

Furthermore, the average oxygen molar fraction value in rectangular dot flow field is second only to the streamline dot flow field with \( L_T = 2.0 \) mm. That is due to the higher resistance of rectangular dot blocks to gas at inlet, forcing more oxygen to diffuse into GDL below the dot blocks, which results in a higher oxygen molar fraction near inlet, as can be observed in Figure 9(b). However, the current density of rectangular dot flow field model is lower than that of three streamline dot flow fields. That is, since although the rectangular dot block forces gas into GDL, the larger vortex region is generated behind dot blocks, which can be observed in Figure 7. The larger vortex region is not conducive to improving the overall oxygen concentration distribution in the PEMFC.

The larger pressure drop in the fuel cell means that more power is required to pump reactants. The increase in this pressure drop is undesirable because it increases the pumping power.

The net power is calculated as follows [37]:

\[
P_{\text{net}} = VI - P_{\text{pump}}.
\]  

(11)

The relationship between cathode pressure drop and pumping power density is given below [38]:

\[
P_{\text{pump}} = \frac{\Delta p A_{\text{th}} U_{\text{in}}}{A_{\text{tot}}},
\]  

(12)

where \( A_{\text{tot}} \) is the reaction area.

In Table 5, the values of net output power density and pumping power are also given.

From Table 5, we can conclude that the pumping power compared to net power has lower values in all models. The net power density of dot flow field model is higher than that of parallel flow field model, and the streamline flow field model with \( L_T = 2.0 \) mm has the highest net power density.

4. Conclusions

A 3D PEMFC model with streamline dot flow field is developed in this study. The performances of PEMFC with parallel, rectangular dot, rhombic dot, and streamline dot flow
fields are analyzed by numerical simulation, including the flow velocity, oxygen pressure distribution, oxygen molar distribution in CL-GDL, membrane current density in PEM-CL, and polarization curves. Further, to enhance the performance of PEMFC with streamline flow field, streamline dot blocks with different length tails are compared. The main conclusions of this study are as follows:

(i) In dot flow fields, vortices produced by the reactant gas behind dot blocks increase the flow resistance and pressure drop. Compared with the conventional rectangular dot flow field, the proposed streamline dot flow field can effectively reduce the generation of vortices behind dot blocks. And when $L_T = 2.0$ mm, the vortices behind the point block are the least $P_{dot-par}$ of rectangular flow field is increased by 84%

(ii) In dot flow fields, the oxygen pressure drop of rectangular dot flow field is the largest which increases parasitic losses. Besides, the oxygen pressure drop in streamline dot flow field can be decreased by optimizing block tail length. Compared with streamline dot flow field with $L_T = 2.0$ mm, the $\Delta$ of oxygen pressure drop is increased by 84%

(iii) Compared to parallel flow field, dot flow fields can promote diffusion rate of reactant gas to GDL and CL. Therefore, oxygen pressure distribution in dot flow field is more uniform compared to parallel flow field, and the oxygen molar fraction in GDL and membrane current density are significantly increased

(iv) Streamline dot flow field with $L_T = 2.0$ mm has advantages in terms of membrane current density distribution, and the lowest IUCD is 0.012991

(v) The current density in streamline dot flow field with 2 mm tail at 0.6 V is 1.3559 A/cm$^2$ which increased by 4.9% compared to parallel flow field. Different shapes of dot blocks have limited effects on fuel cell current density, but streamline dot blocks significantly reduce vorticity and voltage drop. Among all dot flow field models, the streamline model with $L_T = 2.0$ mm has the highest net power density with the value of 804.50 mW/cm$^2$

Data Availability

The data that support the findings of this study are available from the corresponding author upon reasonable request.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

Acknowledgments

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