ABSTRACT: The proton exchange membrane fuel cell (PEMFC) is a type of efficient and environmentally friendly battery. The structure of its bipolar plate directly affects reactant transport and liquid water removal and thereby affects the fuel cell performance. An improved three-partition trapezoidal baffle flow field based on the conventional trapezoidal baffle flow field design is proposed in this paper. A three-dimensional multiphase PEMFC model was established by considering the Forchheimer inertial effect. The mass-transfer characteristics and fuel cell performance of the improved three-partition baffle flow field were compared with those of the conventional parallel flow field and ordinary trapezoidal baffle flow field. It was observed that both improved three-partition baffle flow field and ordinary trapezoidal baffle flow field reduced the flow velocity near the baffle to enhance the inertial effect and mass transfer. In addition, improving the three-partition baffle flow field by further optimizing the baffle heights in different regions of the ordinary trapezoidal baffle flow field improved the transverse flow transmission and the inertial effect near the three-partition baffles. The water removal capability of the porous electrode and the PEMFC performance also improved. The net power of the improved three-partition baffle flow field increased by 4.8% compared with that of the conventional parallel flow field. This study provides an effective reference for the study of the PEMFC bipolar plate structure.

1. INTRODUCTION

The proton exchange membrane fuel cell (PEMFC) is an electrochemical device with high energy-conversion efficiency. It can directly convert chemical energy into electrical energy. Its thermal efficiency is not limited by the Carnot cycle. It has high energy-conversion efficiency, high operational reliability, fewer moving parts, and low noise, and is environmentally friendly. It has been widely used in many applications. As an important part of the PEMFC, the bipolar plate plays a key role through the following functions: (1) separate the oxidizer and reducing agent, (2) separate each cell in the fuel cell stack, (3) collect and transport the current, (4) discharge the generated water smoothly, and (5) uniformly distribute the reactants. Therefore, the flow field design of the bipolar plate is highly important in the water and thermal management of PEMFCs.

The conventional bipolar flow field can be parallel, a serpentine flow field, and an intersecting finger flow field. The conventional parallel flow field has the advantages of simplicity of manufacturing, a marginal pressure drop, and a simple structure. However, its flow channel is vulnerable to blockage, which affects the distribution of the reactants in the flow channel. Moreover, water aggregation occurs in the flow channel, which hinders the water generated by the reaction from flowing out. The distribution of the reaction gas is not uniform.

The water generated in the serpentine flow field can be discharged more conveniently, and the reactants are more uniformly distributed. However, a larger pressure drop is generated. The intersecting finger flow field has a better drainage performance and more uniform reactant distribution. However, its pressure drop is larger than that of the parallel flow field or serpentine flow field. Considering these advantages and disadvantages of the three flow channels, previous scholars studied their detailed designs. The studies indicated that the flow channel size should be set at less than 1 mm. Furthermore, reducing the flow channel size to within an appropriate range can improve the performance of fuel cells. Lin et al. designed a flow field with a progressively reducing flow passage height. They obtained an optimal height at each bend of the flow passage. Their design strengthened the subrib convection and effectively removed the liquid water in the
porous diffusion layer to improve the transfer rate of the reaction gas. Considering the advantages of the parallel flow field and serpentine flow field, Belcor et al. designed a parallel serpentine flow field to maintain the membrane wet under the condition of low humidification. This substantially improved the fuel cell performance. In addition, a variety of flow field cross-sectional shapes is available, including parallelogram, wave, rhombus, triangle, rectangle, and U shape. A good flow channel cross-sectional shape can reduce the pressure drop of the PEMFC, enhance the diffusion of the reactants, and improve the comprehensive performance of the fuel cell.

In recent years, the addition of baffles to obstruct the gas flow in a flow field has been demonstrated to be an effective means of improving PEMFC performance. The baffle improves the transfer of the reactants by forcing these into the gas diffusion layer. Meanwhile, the flow caused by the baffle removes the excess liquid water. Compared with a completely blocked channel, a partially blocked channel results in a relatively uniform distribution of the reactants and alleviates the problem of a large pressure drop. Previous researchers carried out detailed studies on the height, number, plugging level, inclination, and operating conditions of baffles to improve the uniformity of reactant distribution and water distribution. The baffle shape is also a key factor because different shapes affect the channel flow. Chen et al. studied the impacts of triangular, circular, trapezoidal, and rectangular baffle shapes on the PEMFC performance using a two-digit nonisothermal correction model. Their results show that an increase in the baffle volume can increase the reactant flow to the gas diffusion layer. Based on this study, they designed a streamlined baffle plate to facilitate the discharge of the liquid water. However, most of the present designs for baffles are based on two-dimensional designs along the flow path direction. Furthermore, most of the three-dimensional (3D) designs for baffles are more complex in structure and not conveniently machinable. In addition, excessive pressure drop remains a key problem in flow fields with baffles having large heights. The excessive pressure drop would increase the pumping power, which would neutralize the performance improvement yielded by the high-grade fast. This would reduce the overall performance of the cell. Therefore, it is important to reduce the pressure drop of the flow field with baffles and thereby reduce the pumping power to increase the net output power of the PEMFC.

Considering the aforementioned issues, this study addresses the Forchheimer inertial effect in a porous electrode to establish a three-dimensional (3D) multiphase PEMFC simulation model. It analyses trapezoidal baffle layouts with different partition ratios. The objective is to improve the mass-transfer efficiency and water removal capacity of the PEMFC while reducing the large pressure drop caused by the baffles and increasing the net output power. This study can guide the flow channel design of the PEMFC.

### 2. NUMERICAL SIMULATION

#### 2.1. Geometric Models and Initial Conditions

A 3D multiphase PEMFC model was established in this study as shown in Figure 1a. Owing to the symmetry about the z-axis, a channel and two rib regions were used as a repeating unit in the computation. The computational domain included the flow channels, gas diffusion layer (GDL), catalyst layer (CL) on both sides of the anode and cathode, and proton exchange membrane. The geometric parameters are shown in Table 1. Three baffle areas with different heights from left to right along the entrance direction were defined as zones A, B, and C. As shown in Figure 1b, the partition ratio $\zeta$ is defined as $R_2/(R_1 + R_2 + R_3)$. Here, $R_1 + R_2 + R_3 = 1$ mm. The block height in zones A and C was $h$.

![Illustration of geometric layout.](image)

**Table 1. PEMFC Model and Operation Parameters**

| parameter                  | unit  | value  |
|----------------------------|-------|--------|
| membrane thickness         | mm    | 0.0508 |
| CL thickness               | mm    | 0.01   |
| GDL thickness              | mm    | 0.2    |
| floor width                | mm    | 1      |
| flow channel height        | mm    | 1      |
| flow channel width         | mm    | 1      |
| flow channel length        | mm    | 50     |
| baffle spacing             | mm    | 10     |
| flow channel cross-sectional area | mm$^2$ | 1     |
| reaction area              | cm$^3$| 1.5    |
| inlet temperature at the anode or cathode | K | 348.15 |
| anode stoichiometric ratio |       | 1.5    |
| cathode stoichiometric ratio|      | 3      |
| anode humidification ratio |       | 100%   |
| cathode humidification ratio|      | 100%   |
= 0.9 mm, and that in zone B was h = 0.7 mm. The fuel cell temperature was set at 348.15 K. The humidification of both the anode and cathode was assumed to be 100%. The stoichiometric ratios of the anode and cathode were set as 1.5 and 3.0, respectively.

2.2. Hypotheses and Governing Equations. The 3D multiphase PEMFC model of a single cell was used to study the impacts of different baffle designs on the fuel cell performance. Table 2 lists the required physical parameters in the 3D multiphase simulation. The following assumptions were made to eliminate the interference factors:

1. The PEMFC is operated under steady-state conditions.
2. The gas phase is in an ideal gas condition.
3. The GDL and CL are uniform and isotropic.
4. The thermal contact resistance and electrical contact resistance are omitted.

It is generally considered that the fluid flowing at a low speed in the PEMFC conforms to the continuum hypothesis. Thus, the gas mass conservation equation can be expressed by eq 1. The momentum conservation equation of the gas can be described by eq 2. The energy conservation can be expressed as eq 3 if the heat consumption caused by the viscosity in the fluid flow process in the PEMFC is omitted. Eq 4 is the composition conservation equation.

\[
\nabla \cdot (\rho_g \dot{u}_g) = S_m \quad (1)
\]

\[
\nabla \cdot \left( \frac{\rho_g \dot{u}_g}{\epsilon^2 (1 - \phi_i)^2} \right) = -\nabla P_g + \mu_g \nabla \cdot \nabla \left( \frac{\dot{u}_g}{\epsilon (1 - \phi_i)} \right) + \mu_g \nabla \left( \frac{\dot{u}_g}{\epsilon (1 - \phi_i)} \right) \quad (2)
\]

\[
\nabla \cdot \left( \rho_i C_p \dot{T} \right) = \nabla \cdot \left( \rho_i \dot{Y} \nabla \phi_i \right) + S_T \quad (3)
\]

\[
\nabla \cdot (\rho_g \dot{u}_g \dot{Y}) = \nabla \cdot (\rho_i \dot{D}_i \nabla \phi_i) + S_i \quad (4)
\]

The conservation equation of the liquid water is derived from Darcy’s Law \(^{24}\) and can be expressed as eq 5. Here, f is the interface resistance coefficient. It is defined in eq 6. \(\mu_g\) and \(\mu_l\) represent the dynamic viscosities of the gas phase and liquid phase, respectively. \(K_g\) and \(K_l\) represent the permeability coefficients of the gas phase and liquid phase, respectively. Permeability can be calculated by the volume fraction of the liquid water in eq 7.

\[
\nabla \cdot \left( \rho_i \dot{D}_i \nabla \phi_i \right) = \nabla \cdot \left( \rho_i \dot{D}_i \nabla \phi_i \right) + S_i \quad (5)
\]

\[
f = \frac{K_g \mu_g}{K_l \mu_l} \quad (6)
\]

\[
K_g = K_0 (1 - \phi_i)^4 \quad (7)
\]

The pore diameter of the polymer electrolyte is approximately 10 nm. The clusters of water molecules tend to be localized and less connected in pores of this size. Therefore, it is generally assumed that the water is in a “dissolved” phase in the electrolyte region, rather than being in a liquid phase. \(^{25}\) The dissolved water can be analyzed by eq 8. Here, \(\lambda_d\) is the water content of the membrane. It is defined in eq 9.

\[
\frac{\rho_n}{\rho_m} \nabla \cdot \left( \dot{D}_d \nabla \lambda_d \right) = S_d = 0 \quad (8)
\]

\[
\lambda_d = \frac{\rho_n}{\rho_m} \frac{C_d}{\lambda_d} \quad (9)
\]

The solid-phase potential and membrane-phase potential of the PEMFC provide the driving force for the chemical reaction. The solid-phase potential is related to the transport of electrons through a solid conducting material. The membrane-phase potential is related to the transport of ions. The electron conservation equation can be obtained as follows according to the principle of charge conservation

\[
\nabla \cdot (\kappa_g \nabla \phi) + S_e = 0 \quad (10)
\]

The ion conservation equation is given by

\[
\nabla \cdot (\kappa_{ion} \nabla \phi_{ion}) + S_{ion} = 0 \quad (11)
\]

where \(\kappa_g\) and \(\kappa_{ion}\) represent the electrical conductivity coefficients of electrons and ions, respectively. These can be calculated by the Bruggeman equation.
The source terms in eqs 10 and 11 represent the current density generated in the catalytic layer. It is expressed by the following Butler–Volmer equations

\begin{equation}
\dot{i}_a = (1 - \phi_a)_{ref}^{act} \left( \frac{C_{H_2}^{ref}}{C_{H_2}} \right)^{0.5} \exp \left( \frac{2F\alpha_i}{RT} \eta_{act} \right) - \exp \left( -\frac{2F\alpha_i}{RT} \eta_{act} \right)
\end{equation}

(12)

\begin{equation}
\dot{i}_c = (1 - \phi_c)_{ref}^{act} \left( \frac{C_{O_2}^{ref}}{C_{O_2}} \right) \exp \left( \frac{4F\alpha_i}{RT} \eta_{act} \right) - \exp \left( -\frac{4F\alpha_i}{RT} \eta_{act} \right)
\end{equation}

(13)

where \(C_{H_2}^{ref}\) and \(C_{O_2}^{ref}\) are the reference concentrations of the anode and cathode, respectively. \(\alpha_n\) and \(\alpha_c\) are the transfer coefficients of the anode and cathode, respectively. \(\phi_{ref}^{act}\) and \(\phi_{act}\) are the reference exchange current densities of the anode and cathode, respectively, and are calculated as follows

\begin{equation}
\dot{i}_{0,a}^{ref} = 10^9 \exp \left( -1400 \left( \frac{1}{T} - \frac{1}{353.15} \right) \right)
\end{equation}

(14)

\begin{equation}
\dot{i}_{0,c}^{ref} = 10^4 \exp \left( -7900 \left( \frac{1}{T} - \frac{1}{353.15} \right) \right)
\end{equation}

(15)

The PEMFC is generally operated at relatively low temperatures. Therefore, the water vapor is converted to liquid water. However, the liquid water prevents the gas from reaching the membrane. This reduces the reaction efficiency. The calculations for the phase change of water and transport of dissolved water as well as the source terms in other conservation equations were based on previous studies.25–27

Moreover, the Forchheimer inertial effect was considered in the proposed model. Hence, the source term in the momentum conservation equation is given by

\begin{equation}
S_a = \frac{1}{2} \sum_{j=1}^{3} D_{ij} \mu_{ij} + \sum_{j=1}^{3} C_{ij} \frac{1}{2} \rho u_i u_j
\end{equation}

(16)

where \(S_a\) is the source term and \(D_{ij}\) is the Darcy coefficient. \(C_{ij}\) is the Forchheimer coefficient and is given by

\begin{equation}
D_{ij} = \frac{d_i^2}{150 (1 - \varepsilon)^3}
\end{equation}

(17)

\begin{equation}
C_{ij} = \frac{3.5 (1 - \varepsilon)}{d_i \varepsilon^3}
\end{equation}

where \(d_i\) represents the effective hydraulic diameter of the porous media.

2.3. Boundary Conditions. The molar fraction of the reactants at the inlet of the flow channel is determined by the relative humidity and pressure. It can be calculated as follows

\begin{equation}
P_a^0 = 1 \text{ atm } x_{H_2O,a}^0 = \frac{P_{sat} RH_a}{P_a} \quad x_{H_2,a}^0 = 1 - x_{H_2O,a,\text{in}}
\end{equation}

(18)

\begin{equation}
\quad p^0_a = 1 \text{ atm } x_{H_2O,c}^0 = \frac{P_{sat} RH_c}{P_a} \quad x_{O_2,c}^0 = 0.21(1 - x_{H_2O,c,\text{in}})
\end{equation}

(19)

where \(P_a^0\) and \(p^0_a\) are the inlet absolute pressures; \(x_{H_2O,a}^0\) and \(x_{H_2O,c}^0\) are the mole fractions of the inlet water of the anode and cathode, respectively; \(x_{H_2,a}^0\) and \(x_{O_2,c}^0\) are the mole fractions of hydrogen and oxygen, respectively; and RH_a and RH_c are the humidification degrees of the anode and cathode, respectively.

The inlet velocities of the anode and the cathode are expressed as follows

\begin{equation}
u_{a,in} = \frac{\xi_a RT i A_{act}}{2FP_a x_{H_2} A_{ch}}
\end{equation}

(20)

\begin{equation}
u_{c,in} = \frac{\xi_c RT i A_{act}}{4FP_c x_{O_2} A_{ch}}
\end{equation}

(21)

where \(\xi\) represents the reference current density; \(\xi_a\) and \(\xi_c\) are the stoichiometric ratios at the inlets of the anode and cathode, respectively; and \(A_{act}\) and \(A_{ch}\) are the effective area of the membrane electrode assembly (MEA) and cross-sectional area of the flow channel’s inlet, respectively. A pressure boundary condition was applied at the outlet of the flow channel, and the pressure was set to zero. The inlet gas temperature and wall temperatures were consistent with the internal temperature of the PEMFC. The overpotential was calculated based on the electronic potential \(\Phi\) and ionic potential \(\Phi_s\) as follows

\begin{equation}
\eta = \Phi - \Phi_s - E^0
\end{equation}

(22)

where \(E^0\) is the equilibrium potential according to the Nernst equation

\begin{equation}E_s^0 = 0
\end{equation}

(23)

\begin{equation}E_i^0 = 1.23 - 0.9 \times 10^{-3}(T - 298.15) + \frac{RT}{2F} \ln \frac{C_{O_2}}{C_{H_2}}
\end{equation}

(24)

2.4. Grid Independence Verification. In this study, COMSOL multiphysics field simulation software was used to realize the physical fields by combining the porous medium reaction flow, secondary current distribution, dense and dilute matter transfer, and porous medium phase transfer using the finite element method. The PARDISO steady-state solver (provided with the software program) was used in the calculation process. The relative tolerance was set to 10^{-4}. The grid independence was tested to demonstrate the accuracy of grid generation. Seven grids with gradually increasing sizes were tested. The results are shown in Figure 2. The computed polarization curves are significantly close (average error < 1.1%) when the numbers of grids are 139,332 and 200,510. Therefore, a further increase in the number of grids had a negligible effect on the simulation result. The subsequent computational analysis was based on the simulation model with 139,332 grids. It has sufficient accuracy and computational efficiency.

2.5. Model Validation. The simulated polarization curve obtained was compared with the experimental data to verify the simulation model. The experimental equipment included a fuel supply system, a flow control system, a temperature control system, a humidification system, and an electronic load system. The experimental operation parameters were consistent with those used in the simulation. The polarization curve was tested...
by current control with increments of 3 A and 26 test data points. Each data point was measured until it attained a steady state for over 3 min. The inlet and outlet pressures of each test point were recorded to determine the pressure drop. The average values of three independent tests were obtained. The comparison between the simulation and test is shown in Figure 3. The simulation was essentially consistent with the test with an average error of at most 2%. Therefore, the numerical simulation results in this paper are sufficiently accurate.

3. RESULTS AND DISCUSSION

The flow channel design of PEMFCs needs to resolve the problems of reactant transport, water management, and reactant heterogeneity. This study addresses these design problems through the following analysis.

3.1. Reactant Transport Characteristics. The flow field velocity distributions of the improved three-partition baffle flow field, ordinary trapezoidal baffle flow field, and conventional parallel flow field were compared as shown in Figure 4.

The average flow velocity in the catalyst layer was $1.48 \times 10^{-5}$ m/s owing to the simple structure of the conventional parallel flow field. The overall velocity in the flow channel improved substantially after the baffle was installed, particularly the flow velocity around the baffle. The local space for the flow near the baffle was small, whereby over-baffle convection was generated. The average flow velocity on the surface of the catalyst layer in the ordinary trapezoidal baffle flow field attained $2.03 \times 10^{-4}$ m/s. The velocity near the baffle in the improved three-partition baffle flow field was higher than that in the parallel trapezoidal baffle flow field. The local flow space near the baffle reduced as the heights of the baffles in zones A and C increased. The volume under baffle B was larger so that most of the reactants passed under the baffle in zone B. The flow rate near the baffle in zone B and the over-baffle flow velocity increased. This resulted in an overall increase in the flow channel velocity. Thereby, the height increase of the baffle in zone C affected the flow to a lesser extent. This caused the flow velocity under the baffle in zone C to be less than that in the ordinary trapezoidal baffle flow field. The flow velocity in the three-partition baffle flow field attained $2.73 \times 10^{-4}$ m/s. This was 34.5% higher than that in the ordinary trapezoidal flow field.

The overall flow velocity in the flow channel at the location of $Z = 1$ mm (it is close to the flow channel wall) decreased compared with that at $Z = 1.5$ mm. The higher flow velocity in zone B of the improved three-partition flow field affected the flow velocity in the areas outside zone A. Thereby, the flow velocity in the area without baffle in the improved three-partition flow field was still higher than that in the ordinary trapezoidal flow field. An increase in the flow rate increased the Forchheimer inertial force owing to the Forchheimer effect. Thereby, more reactants were supplied to the porous region. This resulted in lateral diffusion in the flow direction of the channel. Although the flow velocity under the baffle in zone C of the improved three-partition flow field was relatively low, the increase in baffle height forced more reactants to enter the GDL.

Figure 5 shows the oxygen distributions at the junction between the GDL and CL in the conventional parallel flow field, ordinary trapezoidal flow field, and improved three-partition flow field. Overall, the oxygen concentrations in the different flow fields are in the following order: three-partition flow field > ordinary trapezoidal flow field > conventional parallel flow field. The oxygen distribution trend of the three-partition flow field is approximately identical to that of the ordinary trapezoidal flow field. However, it is more uniform. The velocity increase caused an increase in the gas inertial force owing to the Forchheimer effect. This forced the reaction gas to enter the GDL. The use of baffles caused the local flow area of the reactants to reduce. Consequently, the reactants were forced to enter and diffuse in the porous region under the influence of pressure. Compared with the conventional parallel flow field, the baffles increased the local concentrations of the reactants and caused the oxygen distribution in the entire flow channel to be more uniform. The increase in the oxygen concentration along the three-partition flow field was significant.
Figure 4. Velocity distributions at the junction between GDL and CL with a fuel cell voltage of 0.6 V. (a) Conventional parallel flow field, (b) ordinary trapezoidal baffle flow field, and (c) three-partition baffle flow field.

Figure 5. Oxygen distributions at the junction between the GDL and CL with a fuel cell voltage of 0.6 V. (a) Conventional parallel flow field, (b) ordinary trapezoidal flow field, and (c) three-partition baffle flow field.

Figure 6. Performance comparison under different flow fields. (a) Oxygen concentration curves at the junction between the GDL and CL at $Z = 1.5$, 1, and 0 mm with a fuel cell voltage of 0.6 V. (b) Liquid water saturation curves at the junction between the GDL and CL at $Z = 1.5$ and 0 mm with a fuel cell voltage of 0.6 V. (c) Polarization curves and power density curves of different flow fields of PEMFC.
flow channel attained 3.6 and 2.8% compared with the conventional parallel flow field and conventional trapezoidal flow field, respectively.

The oxygen concentration distributions at the junction between the GDL and CL at different positions in the flow direction of the reaction gas are shown in Figure 6a. At \( Z = 1.5 \) mm, the improved three-partition baffle flow field and ordinary trapezoidal baffle flow field had oxygen concentrations higher than those of the conventional parallel flow field. The oxygen concentration of the improved three-partition baffle flow field was higher than that of the ordinary trapezoidal flow field. In the first half of the flow channel, the oxygen concentration difference near the baffles between the two flow fields was highly marginal.

Near the baffles in the two flow fields in the second part of the flow channel, the inertial force caused by the Forchheimer effect in the improved three-partition flow field was higher, and the enhanced effect on the local diffusion of the reactants appeared gradually. At \( Z = 1 \) mm, near the baffle area in the first half of the flow channel, the oxygen concentration of the ordinary trapezoidal flow field was marginally higher than that of the improved three-partition flow field. Because the flow velocities near the baffles in zones A and C were marginally less than that in the ordinary trapezoidal flow field, the oxygen concentration was marginally lower. However, the overall flow velocity in the flow channel was higher than that in the ordinary trapezoidal flow field. Furthermore, the oxygen concentration in the three-partition flow field was overall higher than that in the ordinary trapezoidal flow field. A higher baffle was installed at \( Z = 0 \) mm in the improved three-partition flow field. Consequently, the flow velocity was higher, and the lateral diffusion was enhanced. To facilitate comparison, linear curve fitting was carried out to use the slope of the curve to evaluate the oxygen content in the flow channel. The oxygen concentrations of the improved three-partition trapezoidal baffle flow field increased by 4.31, 3.82, and 3.71% at \( Z = 1.5, 1, \) and 0 mm, respectively, compared with the ordinary trapezoidal baffle flow field. Thus, the improved three-partition baffle flow field provided a more uniform oxygen concentration distribution, a reduced concentration polarization, and an increased fuel cell performance, compared with the ordinary baffle flow field.

3.2. Cathode Water Distribution. Water management of the PEMFC is important for fuel cell performance. The proton exchange membrane needs to be maintained wet permanently. Excessive water can cause “waterlogging” to obstruct the porous electrode and prevent the transfer of the reactants to the catalyst layer. Figure 6b shows the liquid water distribution curves of the improved three-partition baffle flow field and ordinary baffle flow field at different positions at the junction between the GDL and CL.

As the reaction progresses, the water generated increases gradually, and it flows to the outlet with the reaction gas. The water gradually accumulates, which causes a gradual increase in the water content along the flow channel. The overall water content increases from the inlet to the outlet. It is noteworthy that the water content near the baffle area was reduced significantly owing to the inertial force effect on the liquid water. The liquid water distributed between the GDL and CL was swept away. The improved three-partition flow field had a higher flow velocity and stronger inertial force at \( Z = 1.5 \) mm with more water being swept away in the entire flow channel. The negative effect of the baffle height and the positive effect of the flow velocity offset each other. This caused a marginal difference in water saturation in the area near the baffle in the first half of the flow channel. The inertial force caused by the flow velocity in the second half of the flow channel increased gradually. The improved three-partition baffle flow field has a stronger water removal capability than the ordinary baffle flow field. At \( Z = 0 \) mm, the transverse flow movement in the improved three-partition flow field was marginally higher owing to the influence of the transverse gas movement around the baffle and thereby more water was removed. As shown in Figure 6b, the saturation gradient of the liquid water decreased because the position of \( Z = 0 \) mm was farthest from the baffle and the flow velocity gradually decreased along the flow direction with a reduced gradient.

3.3. Fuel Cell Performance Analysis. The polarization curve and power density curve are important indicators for evaluating fuel cell performance. Figure 6c shows the polarization curves and power density curves of the three flow channels. It can be observed that the current density was improved after the baffle was installed in the flow channel. With a higher current density, the transport of the reactants and the enhanced sweeping of the liquid water improved the performance of the baffle flow fields. Therefore, the differences among the three flow fields increased. The improved three-partition flow field caused the oxygen distribution in the flow channel to be more uniform. As a result, the concentration polarization in the second half of the polarization curve decreased and the current density increased. The power density was proportional to the current density. Thus, the power density showed a trend similar to that of the current density. The maximum power density of the improved three-partition baffle flow field increased by 1.11 and 4.3% compared with the ordinary trapezoidal baffle flow field and conventional parallel flow field, respectively. These data demonstrate that the improved three-partition baffle flow field has a better fuel cell performance than the ordinary trapezoidal baffle flow field.
### 3.4. Analysis of Impact of Partition Ratio on PEMFC Performance

The partition ratio has a significant impact on the fuel cell performance. The following partition ratios were investigated in this study: 0.8, 0.6, 0.4, and 0.2 (denoted as cases A, B, C, and D, respectively). As shown in Figure 7. The baffle widths of zone B were 1, 2, 3, and 4 mm. Figure 8a shows the oxygen concentrations at the junction between the GDL and CL in the improved three-partition baffle flow field with different partition ratios at $Z = 1.5$ mm. It is observed that the initial values of the oxygen concentration in the different flow fields could be ranked as follows: case D $>$ case C $>$ case B $>$ case A. Case D had the smallest partition ratio and highest average baffle height. Furthermore, its flow resistance was higher than those of the other cases. The reactants tended to accumulate in the front end of the flow channel. This results in a higher initial value of oxygen concentration. The oxygen consumption increased with the increase in average baffle height. Accordingly, the oxygen concentration at the outlet of the flow channel decreased. This resulted in an essentially identical oxygen concentration at the outlet of the four flow fields specified by the four partition ratios. To summarize, the oxygen concentration at $Z = 1.5$ mm increased when the partition ratio decreased. Case D had the highest slope, and its oxygen concentration increased by 4.82% compared with case A.

Figure 8b shows the mass fractions of water at the junction between the GDL and CL at the position $Z = 1.5$ mm in the improved three-partition baffle flow field with different partition ratios. The liquid water saturation could be ranked as follows: case A $>$ case B $>$ case C $>$ case D. The oxygen concentration increased with a decrease in the partition ratio and thereby the water generated increased. When the partition ratio decreased, the average height of the baffle in the flow channel increased, and the over-baffle convection was enhanced and thereby the water removal capacity increased.

A comparison of the polarization curves of the gas channels with different partition ratios revealed that the current density and power density increased as the partition ratio decreased (see Figure 8c). The mass transfer in the improved three-partition baffle flow field was affected by the partition ratio. Furthermore, the concentration of the reactants flowing to the catalyst layer increased. Case D had the highest partition ratio, power density, and current density. The power density of the fuel cell increased by 4.8% compared with that of the conventional parallel flow field.

### 3.5. Pressure Loss

Pumping power is a key indicator of fuel cell performance. Previous studies showed that a baffled flow channel could increase the pumping power during reactant transport owing to the increase in the pressure drop caused by the increase in reactant consumption. The pumping power can be calculated as follows

$$P_{\text{pump}} = A_{\text{in}} P_{\text{in}} - A_{\text{out}} P_{\text{out}}$$

Figure 8. Performance comparison under different partition ratios. (a) Oxygen concentration curves at the junction between the GDL and CL at $Z = 1.5$ mm with a fuel cell voltage of 0.6 V. (b) Liquid water saturation curves at the junction between the GDL and CL at $Z = 1.5$ mm with a fuel cell voltage of 0.6 V. (c) Polarization curve and power density curve of PEMFC. (d) Power loss and net power.
The different partition ratios of the various designs of the improved three-partition baffle flow field also affected the pumping power of the flow channel. A smaller partition ratio causes the flow resistance and the pressure drop in the flow channel to increase. This yields an increased pumping power. A higher partition ratio results in reduced convection effect and flow velocity. Figure 8d shows that the pumping power of case D was the highest and that of the conventional parallel flow field was the lowest (which yielded the lowest fuel cell power). Case C had less pumping power and a higher fuel cell power. The net power of the different flow fields is shown in Table 3. The net power of the improved three-partition flow fields is superior for improving the net power of a fuel cell.

4. CONCLUSIONS

This study proposed an improved three-partition baffle flow field and analyzed the impact of the partition ratio on transport characteristics and PEMFC performance. The main conclusions drawn are as follows:

1. The baffled flow channel can induce a stronger Forchheimer inertial force to improve the reactant transport and remove the liquid water. The reaction gas can diffuse better, and the fuel cell current density can be increased.

2. The improved three-partition baffle flow field can achieve good performance by optimizing the baffle height. When the baffle height varies, the inertial force effect becomes more significant, and the reactants display stronger transverse transmission. This results in a higher and more uniform oxygen concentration in the rib region. An increased over-baffle flow rate can increase the liquid water removal rate in the porous electrode. The average anodic oxygen concentration in the three-partition baffle flow field can be increased by 5.5 and 1.2% compared with the conventional parallel flow field and ordinary trapezoidal baffle flow field, respectively.

3. The improved three-partition baffle flow field shows the best fuel cell performance when the partition ratio is 0.4. The maximum net power of the improved three-partition baffle flow field can increase by 4.8 and 1.8% compared with the conventional parallel flow field and ordinary trapezoidal baffle flow field, respectively. The fuel cell output power can also increase. Thus, the improved three-partition baffle flow field is superior for improving the net power of a fuel cell.

AUTHOR INFORMATION

Corresponding Authors

Jilin Lei — Yunnan Key Laboratory of Internal Combustion Engines, Kunming University of Science and Technology Kunming, Kunming 650500, P. R. China; Email: leijilin@sina.com

Dewen Jia — Yunnan Key Laboratory of Internal Combustion Engines, Kunming University of Science and Technology Kunming, Kunming 650500, P. R. China; Email: 27546658@qq.com

Authors

Xiwen Deng — Yunnan Key Laboratory of Internal Combustion Engines, Kunming University of Science and Technology Kunming, Kunming 650500, P. R. China; orcid.org/0000-0002-1579-6019

Enming Zhang — Yunnan Key Laboratory of Internal Combustion Engines, Kunming University of Science and Technology Kunming, Kunming 650500, P. R. China

Yi Liu — Yunnan Key Laboratory of Internal Combustion Engines, Kunming University of Science and Technology Kunming, Kunming 650500, P. R. China

H. E. Shuchao — Kunming Yunnai Power Co., Ltd., Kunming 650200, P. R. China

Complete contact information is available at: https://pubs.acs.org/10.1021/acsomega.2c04949

Notes

The authors declare no competing financial interest.

ACKNOWLEDGMENTS

This work was supported by the Yunnan Science and Technology Plan Project (Grant No.202202AB008011) and Yunnan Fundamental Research Projects (Grant Nos. 202101BE070001-059, 202101AT070266)

 NOMENCLATURE

A  active area of fuel cell (m²)
C  molar concentration (mol/m³) or Forchheimer’s coefficient (m⁻¹)
Cₚ  specific heat [J/(kg·K)]
dₑ  effective hydraulic diameter of porous media (m)
D  mass diffusivity (m²/s) or Darcy’s coefficient (m⁻²)
EW  equivalent weight of membrane (g/mol)
f  interfacial drag coefficient
F  Faraday’s constant (C/mol)
h  channel height (mm)
I  current density (A/cm²)
Iₒ  volumetric exchange current density(A/m³)
K  permeability (m²)
Kᵦ  intrinsic permeability (m²)
P  pressure (Pa)
R  universal gas constant [J/(mol·K)]
RH  relative humidity (%)  
S  source term
T  temperature (K)
Tₒ  volume-average cell temperature (K)
u  velocity (m/s)
V  electrical potential (V)
$W$  power (W)
$Y$  mass fraction
$C$  molar concentration (mol/m$^3$) or Forchheimer’s coefficient (m$^{-1}$)
$A$  active area of fuel cell (m$^2$)

**Greek symbols**

$\alpha$  transfer coefficient
$\varepsilon$  porosity
$\eta$  over potential (V) or pump efficiency
$\kappa$  electrical conductivity (S/m)
$\lambda$  water content in ionomer
$\mu$  dynamic viscosity [kg/(m·s)]
$\xi$  stoichiometric ratio
$\rho$  density (kg/m$^3$)
$\phi$  electrical potential (V) or liquid water volume fraction
$\xi$  stoichiometric ratio
$\rho$  density (kg/m$^3$)
$\phi$  electrical potential (V) or liquid water volume fraction

**Subscripts**

$a$  anode
$act$  activation
$atm$  atmospheric
$c$  cathode
$cell$  fuel cell
$d$  dissolved water
$eff$  effective
$e$  electronic
$end$  bipolar plate end surface
$fl$  fluid phase
$g$  gas phase
$H_2$  hydrogen
$in$  inlet
$ion$  ionic
$l$  liquid water
$m$  mass (in source term)
$mem$  membrane
$O_2$  oxygen
$out$  outlet
$pump$  pumping power
$ref$  reference state
$rev$  reversible
$sat$  saturation
$sl$  solid phase
$T$  energy (in source term)
$u$  momentum (in source term)

### REFERENCES

(1) Manso, A. P.; Marzo, F. F.; Barranco, J.; Garikano, X.; Mujika, G. M. Influence of geometric parameters of the flow fields on the performance of a PEM fuel cell. A review. *Int. J. Hydrogen Energy* **2012**, *37*, 15256–15287.

(2) Aiyejina, A.; Sastry, M.K.S. PEMFC Flow Channel Geometry Optimization: A Review. *J. Fuel Cell Sci. Technol.* **2012**, *9*, No. 011011.

(3) Chowdhury, M. Z.; Gene, O.; Toros, S. Numerical optimization of channel to land width ratio for PEM fuel cell. *Int. J. Hydrogen Energy* **2018**, 43, 10798–10809.

(4) Yoon, Y. Z.; Lee, W. Y.; Park, G. G.; Yang, T. H.; Kim, C. S. Effects of channel and rib widths of flow field plates on the performance of a PEMFC. *Int. J. Hydrogen Energy* **2005**, *30*, 1363–1366.

(5) Elena, C.; Mihai, V.; Derek, B. L.; Mohammed, S. L.; Laurentiu, P.; Adriana, M.; Dorin, S. The effects of cathode flow channel size and operating conditions on PEM fuel performance: A CFD modelling study and experimental demonstration. *Int. J. Hydrogen Energy* **2018**, 42, 2789–2804.

(6) Zhang, H. F.; Yi, B. L.; Hou, M.; Zhang, H. M. Effect of dimension of flow field on performance of PEMFC. *Chin. J. Power Sources* **2004**, *28*, 494–497.

(7) Cooper, N. J.; Smith, T.; Santamaria, A. D.; Park, J. W. Experimental optimization of parallel and interdigitated PEMFC flow-field channel geometry. *Int. J. Hydrogen Energy* **2016**, *41*, 1213–1223.

(8) Lin, L.; Feng, D. L.; Wang, X. D.; Zeng, X. X. Inverse problem method applied to flow field optimization of proton exchange membrane fuel cells. *J. Univ. Sci. Technol. Beijing* **2010**, *32*, 105–111.

(9) Belchor, P. M.; Forte, M. M. C.; Carpenter, D. E. O. S. Parallel serpentine-baffle flow field design for water management in a proton exchange membrane fuel cell. *Int. J. Hydrogen Energy* **2012**, *37*, 11904–11911.

(10) Ma, L. J.; Lin, C. S.; Xue, F. Q.; Han, L. H.; Wang, X. D. Investigation on Section Design and 3D Simulation of Flow Field in PEMFC. *Hydrometall. China* **2008**, *27*, 52–55.

(11) Jiang, B. K. The Mode Experiment Studies of Flow Flied in Bipolar Plates of PEMFC. *Ship Ocean Eng.* **2009**, *38*, 85–87.

(12) Jabbarly, A.; Sadra, R. A.; Hossein, S.; Nima, A. Numerical investigation of 3D rhombus designed PEMFC on the cell performance. *Int. J. Green Energy* **2021**, *18*, 425–442.

(13) Xiong, S. J.; Xiao, J. S.; Pan, M. Modeling of PEM Fuel Cell with Different Kind of Section Channels. *J. Wuhan Univ. Technol.* **2006**, *28*, 553–557.

(14) Wawde, P.; Limtrakul, S.; Vatanatham, T.; Fowler, M. W. Water transport in a PEM fuel cell with slanted channel flow field plates. *Int. J. Hydrogen Energy* **2015**, *40*, 3739–3748.

(15) Kahraman, H.; Hasimoglu, C.; Cevik, I.; Murcak, A. A Different Flow Field Design Approach for Performance Improvement of a PEMFC. *Acta Phys. Pol., A* **2017**, *131*, 484–486.

(16) Tiss, F.; Chouikhi, R.; Guizani, A. A numerical investigation of reactant transport in a PEM fuel cell with partially blocked gas channels. *Energy Convers. Manage.* **2014**, *80*, 32–38.

(17) Soong, C. Y.; Yan, W. M.; Tseng, C. Y.; Liu, H. C.; Chen, F.; Chu, H. S. Analysis of reactant gas transport in a PEM fuel cell with partially blocked fuel flow channels. *J. Power Sources* **2005**, *143*, 36–47.

(18) Peng, S. W.; Wu, H. W. Effects of internal flow modification on the cell performance enhancement of a PEM fuel cell. *J. Power Sources* **2008**, *175*, 806–816.

(19) Heidary, H.; Kermain, M. J.; Dabir, B. Influences of bipolar plate channel blockages on PEM fuel cell performances. *Energy Convers. Manage.* **2016**, *124*, 51–60.

(20) Yin, Y.; Wang, X. F.; Xiang, S. G.; Zhang, J. F.; Qin, Y. Z. Numerical investigation on the characteristics of mass transport and performance of PEMFC with baffle plates installed in the flow channel. *Int. J. Hydrogen Energy* **2018**, *43*, 8048–8062.

(21) Peng, S. W.; Wu, H. W. A three-dimensional numerical investigation of trapezoid baffles effect on non-isothermal reactant transport and cell net power in a PEMFC. *Appl. Energy* **2015**, *143*, 81–95.

(22) Bilgili, M.; Bosomoiu, M.; Tsotridis, G. Gas flow field with obstacles for PEM fuel cells at different operating condition. *Int. J. Hydrogen Energy* **2015**, *40*, 2303–2311.

(23) Chen, H.; Guo, H.; Ye, F.; Ma, C. F. Forchheimer’s inertial effect on liquid water removal in proton exchange membrane fuel cells with baffled flow channels. *Int. J. Hydrogen Energy* **2020**, *46*, 2990–3007.

(24) Sui, P. C.; Kumar, S.; Djilali, N. Advanced computational tools for PEM fuel cell design: Part I. Development and base case simulations. *J. Power Sources* **2008**, *180*, 410–422.

(25) Wu, H.; Li, X. G.; Peter, B. On the modeling of water transport in polymeric electrolyte membrane fuel cells. *Electrochim. Acta* **2009**, *54*, 6913–6927.

(26) Wang, X. F.; Qin, Y. Z.; Wu, S. Y.; Xiang, S. G.; Zhang, J. F.; Yin, Y. Numerical and experimental investigation of baffle plate arrangement on proton exchange membrane fuel cell performance. *J. Power Sources* **2020**, *457*, No. 228034.

(27) Yin, Y.; Wang, X. F.; Xiang, S. G.; Zhang, J.; Qin, Y. Z. Numerical investigation on the characteristics of mass transport and performance
of PEMFC with baffle plates installed in the flow channel. *Int. J. Hydrogen Energy* 2018, 43, 8048–8062.

(28) Li, X. G.; Jiao, K.; Du, O.; Yin, Y.; Qin, Y. Z. Effective removal and transport of water in a PEM fuel cell flow channel having a hydrophilic plate. *Appl. Energy* 2014, 113, 116–126.

(29) Ahmadi, N.; Taraghi, H.; Sadeghiazad, M. A numerical study of a three-dimensional proton exchange membrane fuel cell (PEMFC) with parallel and counter flow gas channels. *Iran. J. Sci. Technol., Trans. Mech. Eng* 2015, 39, 309–323.