



Article Performance Enhancement of PEM Fuel Cells with an Additional Outlet in the Parallel Flow Field

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Abstract: The design of bipolar plates is critical for improving the performance of proton exchange membrane fuel cells (PEMFCs). In this research, a new additional outlet based on a PEMFC's parallel flow field was proposed, and three different positions of outlet were designed on the target side of gas flowing in parallel channels. The results revealed that the additional outlets are able to increase the gas speed through channels near the additional outlets, which results in a lower water saturation and a more uniform distribution of oxygen concentration at the interface between the catalyst layer (CL) and gas diffusion layer (GDL). With the variation of the outlet position in the target side, it was found that the additional outlet set in the middle of the target side exhibits the highest increase of peak power density, namely, 13%. Furthermore, the optimal position of the additional outlet was proved to be suitable for PEMFCs with various active surface areas, indicating the universality of the present results in the study.

Keywords: PEMFC; parallel flow field; the additional outlet; water saturation; oxygen concentration; peak power density

Highlights

An additional outlet in parallel flow field is recommended to enhance the performance of PEMFC.

The additional outlet can meliorate oxygen concentration distribution in the flow field and increase the gas velocity in the flow channels near it.

The best position of the additional outlet is in the middle of the target side in the parallel flow fields with different areas.

1. Introduction

PEMFCs have attracted worldwide attention, because of their high energy conversion efficiency, environmental friendliness, and fast start—up. The design of bipolar plates has an important influence on the reactant gas distribution of fuel cells. Not only can a suitable flow field improve fuel cell performance, but it can also reduce water flooding and improve fuel efficiency [1–6].

There are many studies related to the flow field design of PEMFCs by virtue of both experiments and numerical simulations. By raising the gas flow rate in the channel, Kuo et al. [7] devised a waveform gas flow channel for PEMFC to improve the catalytic reaction performance in the catalyst layer. Thitakamol et al. [8] experimentally investigated a new



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Copyright: © 2021 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (https:// creativecommons.org/licenses/by/ 4.0/). mid-baffle interdigitated flow field. They found that when the cathode reactant was air, the cell power output with the intermediate baffle staggered flow field was approximately 1.2 to 1.3 times higher than that of the conventional cell. Shen et al. [9] analyzed the performance of PEMFC in the flow channel under different blocking conditions via simulation and experiment. It was found that the effective mass transfer coefficient of the flow field was clearly improved by adding a baffle block; thus, the performance of the PEMFC was improved. Previous studies discussed the improvement of mass transfer of the gas in a single channel. Nevertheless, the assumption that the mass flow rates in every channel are equal is prescribed, which is not consistent with the cases in reality.

The uniform distribution of reactants is an important element to be considered in the design of fuel cell parallel channel structure [10–18]. Researchers have mainly divided parallel pattern into four types: consecutive [19], cascade [20,21], ladder [22,23], and baffled–type [24] distributors. Bejan et al. [25] developed the cascade structure of the flow channel to attain uniform flow distribution. Soroush Dabiri et al. [26] designed a new distributor (small cylindrical obstacles) that is capable of being utilized in PEMFCs to make the channel flow more uniform. In [27], the authors achieved a uniform flow distribution through a bifurcation cascade of the flow channels and gave a good design of the bifurcation zone. However, the structures of proposed distributors are generally complex. Utilizing this approach also makes the bipolar plate processing more difficult and has a higher cost.

At present, few studies have focused on the design of flow field inlet and outlet structure. In order to study the oxygen concentration distribution of the cathode, Xiong et al. [28] analyzed the different widths of the inlet distribution channel and the outlet manifold of a Z-type flow field. The results showed that the oxygen distribution in the cathode is more uniform with an increase of the outlet manifold width. Moreover, the uniformity of the oxygen distribution can be enhanced with the help of the oblique inlet manifold and proper distribution of the flow channel. However, the aforementioned research did not study the distribution of liquid water in the flow field, and it is not clear whether the water flooding problem can be solved [29–31].

Although many of the new kinds of flow fields above have achieved a sufficient supply of reactant, uniform distribution of reactant, and excellent distribution of liquid water, their manufacturing processes are so complicated that they cost too much. Therefore, a much more easily realized additional outlet is proposed in the study. Furthermore, it could improve the velocity and concentration distributions through the whole flow field, which is beneficial to enhancing the performance of fuel cells. Thus, this study investigates the influence of an additional outlet position on the performance of a PEMFC, so as to acquire the optimized position of the additional outlet. Moreover, in order to verify the universality of the result, the optimized position of the additional outlet is tested in PEMFCs with various activation areas.

2. Fuel Cell Model Development

2.1. Computed Field and Assumptions

The computed field of PEMFC 3D models includes anode and cathode bipolar plates (BPs), a flow channel, anode and cathode gas diffusion layers (GDLs), catalyst layers (CLs), and a membrane, as shown in Figure 1.



Figure 1. Schematics of (A) PEMFC, (B) the conventional outlet pattern, (C,D) the additional outlet pattern at the flow field plate.

Table 1 shows the geometric parameters of PEMFC.

Table 1. The geometric parameters of each geometric component.

Parameters	eters Values	
BP length, width, height (mm)	30, 30, 1.5	
Rib length, width (mm)	30, 1	
Channel length, width, height (mm)	30, 1, 1	
GDL thickness (m)	$3 imes 10^{-4}$	
CL thickness (m)	$1.29 imes 10^{-5}$	
Membrane thickness (m)	$1.08 imes 10^{-4}$	
The additional location h (mm)	0/7/15/23	

In order to simplify the PEMFC model, the following assumptions were made:

- (1) The PEMFC operation is stable;
- (2) Gravity is ignored;
- (3) The physical property of GDLs and CLs can be considered as isotropic;
- (4) The flow is considered laminar and the gas is assumed to be an ideal gas;
- (5) Neither anode nor cathode reaction gas can penetrate the membrane.

2.2. Governing Equations

For the PEMFC module, we used the Fuel Cell and Electrolysis Model in ANSYS Fluent 2019R2. Figure 2 shows the computational grids in the simulation. Table 2 lists the operational conditions and Table 3 lists the solving zones of the governing equations.



Figure 2. Computational grids in the simulation.

Parameters	Values	Ref.
Cell temperature(K)	338	[9]
Anode inlet temperature(K)	338	[9]
Cathode inlet temperature (K)	338	[9]
Operating pressure (Pa)	101,325	[9]
Stoichiometric proportion at the anode	1.5	[9]
Stoichiometric proportion at the cathode	2.5	[9]
Faraday's constant (C mol ^{-1})	96,487.0	
Porosity of GDL	0.4	Assumed
Porosity of CL	0.5	Assumed
Open circuit voltage (V)	0.95	[9]
Contact angle (°) of CL and GDL	135	Assumed

Conservation Equations	nservation Equations Solved Zones	
Mass conservation equation	Channels, GDLs, CLs	
Momentum conservation equation	Channels, GDLs, CLs	
Gas species equation	Channels, GDLs, CLs	
Liquid water equation	GDLs, CLs	
Electronic charge equation	BPs, GDLs, CLs	
Ionic charge equation	CLs, Membrane	
Energy conservation equation	BPs, Channels, GDLs, CLs, Membrane	

Table 3. The solving zones of the governing equations.

The governing equations are as follows (related symbols can be referred to in the ANSYS Fluent[®] software manual [32]).

Mass conservation equation

$$\frac{\partial(\epsilon\rho)}{\partial t} + \nabla\left(\epsilon\rho \overrightarrow{\mathbf{u}}\right) = S_m \tag{1}$$

Momentum conservation equation

$$\frac{\partial \left(\varepsilon \rho \overrightarrow{u}\right)}{\partial t} + \nabla \left(\varepsilon \rho \overrightarrow{u} u\right) = -\varepsilon \nabla p + \nabla \left(\varepsilon \mu \nabla \overrightarrow{u}\right) + S_u \tag{2}$$

Energy conservation equation

$$\frac{\partial(\epsilon\rho c_p T)}{\partial t} + \nabla \left(\epsilon\rho c_p \vec{u} T\right) = \nabla \cdot \left(k^{eff} \nabla T\right) + S_Q \tag{3}$$

Species conservation equation

$$\frac{\partial(\varepsilon c_k)}{\partial t} + \nabla \left(\varepsilon \overrightarrow{u} c_k\right) = \nabla \cdot \left(D_k^{eff} \nabla c_k\right) + S_k \tag{4}$$

2.3. Numerical Procedures

Figure 3 shows the grids used for simulation. Due to the simplicity of physical geometry, structural grids were adopted.



Figure 3. Grid independence testing result.

The grid independence was tested with five different meshes: the number of elements were 176,889, 353,778, 707,556, 1,415,112, and 2,830,224, respectively. As shown in Figure 3, the relative error of the simulation results of the grids with 707,556 and 2,830,224 elements was less than 2%. Therefore, the grids with 707,556 elements were used for PEMFC simulation [33].

2.4. Model Validation

In order to verify the correctness of the model, the simulation consequences were compared with the experimental results in [34]. The comparison between numerical results and experimental results is demonstrated in Figure 4. As we can see from Figure 4, the simulation data is close to the experimental data, the relative error between the experimental and numerical results is 3–5%, and the simulation results have credibility.



Figure 4. Comparison between the predicted and measured I–V curves and I-P curves of a PEMFC with parallel flow field.

3. Results and Discussion

A 3D multiphase fuel cell model was established, the effect of an additional outlet position on the distribution of the parallel flow field was calculated, and the double outlet model and single outlet model were compared.

3.1. Overall Cell Performance

The polarization and power density curves for the conventional parallel flow field (CPFF) pattern and various additional outlet flow field (AOFF) patterns are shown in Figure 5, respectively. The performance of the AOFF patterns was better than that of the CPFF pattern when the voltage was between 0.65 V and 0.4 V. However, with the further increase of current density, the AOFF patterns showed a significantly better performance. In short, the cell performance follows the order h-15 mm > h-23 mm > h-7 mm > Base. The maximum power density occurred for the cell of the AOFF-h = 15 mm, which increased by about 13% in comparison with that of the CPFF pattern. These differences in the cell performance are explained below



Figure 5. Performance comparison between the CPFF pattern and AOFF patterns: polarization curves and power density curves.

3.2. Mass Fraction of Oxygen and Water Saturation

Figures 6 and 7 show the mass fraction of oxygen and the saturation of water at the cathode CL–GDL interface for the CPFF pattern and AOFF patterns at Vcell = 0.5 V, respectively. The oxygen distributions in the AOFF patterns were more uniform than that in the CPFF pattern, and the water saturations were lower, especially under the additional outlet which was set in the middle of the target side (as shown in Figure 1). By including the additional outlet, the oxygen concentration in the flow passage near the additional outlet could be improved, so that a more uniform concentration distribution of oxygen could be obtained. Furthermore, the water saturation in the inlet area was also reduced. It is worth noting that these trends changed with the variation of the additional outlet location. This will be further discussed in Section 3.3. Moreover, as shown in Figure 6, the concentration distribution of oxygen in the middle part of the CPFF flow field is low. When adding the additional outlet, the oxygen concentration of the flow field was significantly raised, especially in the flow channels near the additional outlet. In conclusion, the AOFF patterns are more beneficial to improving local oxygen concentration than the CPFF pattern.



Figure 6. Oxygen mass fraction on the cathode CL–GDL interface for the CPFF pattern and AOFF patterns at Vcell = 0.5 V.



Figure 7. Water saturation on the cathode CL–GDL interface for the CPFF pattern and AOFF patterns at Vcell = 0.5 V.

3.3. Gas Flow Rate in Each Channel

Figure 8 shows the gas flow rate in each channel with voltage equal to 0.5 V for the case of the CPFF and the AOFF with h = 15 mm. The gas flow rate in the channels near the additional outlet was significantly increased. The average gas flow rate of the CPFF was 0.66 m/s. The average gas flow rate of the AOFF (h = 15 mm) was 0.95 m/s. Compared with CPFF, the gas flow rate in the AOFF flow field increased by about 43.9%. Since the standard deviation can reflect the fluctuation of the value, we measured the flow distribution in each channel in the flow field through standard deviation. The standard deviation of the gas flow rate in all channels in the CPFF was 0.79, and that in thee AOFF was 0.45. The standard deviation of the latter was smaller than that of the former, so the flow distribution in the AOFF was more uniform.



Figure 8. The chart of gas flow rate in each cathode channel for the CPFF pattern and the AOFF pattern at Vcell = 0.5 V.

3.4. Application in Different Areas of Parallel Flow Fields

To verify the universality of the application of the additional outlet, different areas of parallel flow fields were considered. The simulation took 4.5 cm² (3 cm \times 1.5 cm) and 18 cm² (3 cm \times 6 cm) fuel cell parallel flow fields into consideration, and the height, width, and length of the rib and channel were 1 mm, 1 mm, and 30 mm, respectively. The additional outlet was added in AOFF2 and AOFF3, as shown in Figure 9. The h2 was 3, 7.5, or 12 mm and the h3 was 15, 30, or 45 mm.



Figure 9. Schematics of (a,b) the additional outlet pattern at the flow field plate.

Figure 10 shows the performance comparison between the CPFF2 pattern and AOFF3 patterns. The performance of the AOFF patterns was better than that of the CPFF patterns. Furthermore, by comparing AOFF2 with AOFF3, when the number of channels was small, the performance of the additional outlet flow field showed only a trivial change.



Figure 10. Performance comparison between the CPFF2 pattern and AOFF3 patterns: polarization curves and power density curves. (a) The proportion is 4.5 cm² (b) The proportion is 18 cm².

Figures 11 and 12 show the mass fraction of oxygen and the saturation of water at the cathode CL–GDL interface for the CPFF2/CPFF3 pattern and AOFF2/CPFF3 patterns at Vcell = 0.5 V, respectively. The results are the same as those in Section 3.2 (Mass Fraction of Oxygen and Saturation of Water): the additional outlet can increase oxygen concentration and decrease water saturation in the flow field. The influence of the additional outlet flow field on fuel cell performance was changed with different additional outlet positions. Figure 11 shows that the oxygen concentration at the cathode CL–GDL interface near the additional outlet was increased. The oxygen concentration of AOFF3 increased

most significantly. Figure 12 shows that the water saturations in AOFF2/AOFF3 were generally reduced.

Compared with the AOFF2 flow field with less flow channels, the change of the additional outlet position in the AOFF3 flow field had a more obvious influence on the fuel cell performance. The oxygen concentration and current density were improved the most when the additional outlet was set in the middle of the target side. In AOFF2, when the h2 was 7.5 mm, the peak power density increased by about 20%. In AOFF3, when the h3 was 30 mm, the peak power density increased by about 18.6%.



Figure 11. Oxygen mass fraction on the cathode CL–GDL interface at Vcell = 0.5 V. (**a**)The proportion is 4.5 cm² (**b**) The proportion is 18 cm².







Figure 12. Water saturation on the cathode CL–GDL interface at Vcell = 0.5 V. (**a**)The proportion is 4.5 cm² (**b**) The proportion is 18 cm².

Table 4 shows the comparison of specific performance parameters of AOFF2, AOFF3, and CPFF.

Patterns	Current Density (0.4 V)(A/cm ²)	Mean Oxygen Mass Fraction	Mean Water Saturation
CPFF2-Base	0.97	0.028	0.292
AOFF2-h2 = 12	1.18	0.039	0.265
AOFF2 - h2 = 7.5	1.2	0.042	0.264
AOFF2-h2 = 3	1.21	0.041	0.263
CPFF3–Base	1.01	0.032	0.292
AOFF3-h3 = 45	1.12	0.038	0.264
AOFF3 - h3 = 30	1.19	0.043	0.272
AOFF3-h3 = 15	1.17	0.042	0.283

4. Conclusions

This work proposed an additional outlet flow field to enhance the gas velocity in the channels and the concentration of oxygen under ribs in PEMFCs. Influences of the location of the additional outlet on oxygen distribution, saturation, and velocity distribution were numerically investigated via a 3D multiphase PEMFC model. Influences of the additional outlet's position in different flow fields' areas were considered in the model. The main conclusions are as follows:

- (1) Adding the additional outlet in the flow field is an effective way to improve the mass transfer and performance of the PEMFC, because the additional outlet can improve the distribution of oxygen concentration in the flow field and increase the gas velocity in the flow channels near it. In the 9 cm^2 ($3 \text{ cm} \times 3 \text{ cm}$) parallel flow field, the best choice is to set the additional outlet in the middle of the target side, which results in an increase of the peak power density of about 13%.
- (2) In addition, this study proved that the best position of the additional outlet is in the middle of the target side through testing in the parallel flow fields with different areas. Moreover, the peak power density increased by about 20% in the 4.5 cm² ($3 \text{ cm} \times 1.5 \text{ cm}$) parallel flow field and 18.6% in the 18 cm² ($3 \text{ cm} \times 6 \text{ cm}$) parallel flow field.

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