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RESEARCH ARTICLE

Testing Study of Different Flow Direction and Structure for Air-Cooled Proton Exchange Membrane Fuel Cell

QINGTIAN GENG[1], YARU HAN[1], BAOZHU LI[2], (Member, IEEE), ZHIJUN DENG[3], AND CHEN ZHAO[4]

[1]College of Computer Science and Technology, Changchun Normal University, Changchun, Jilin 130031, China
[2]Zhuhai Fudan Innovation Institute, Zhuhai 518057, China
[3]Department of Automotive and Transportation Engineering, Shenzhen Polytechnic University, Shenzhen 518055, China
[4]Shenzhen Institute of Advanced Research, University of Electronic Science and Technology of China, Shenzhen 518038, China

Corresponding authors: Chen Zhao (zhaochen913@163.com) and Zhijun Deng (dengzhijun@szpt.edu.cn)

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ABSTRACT The air-cooled proton exchange membrane fuel cell is widely used in unmanned aerial vehicle since its small size and high efficiency. The bipolar plate structure is an important factor affecting the performance of fuel cells. This article conducts experimental research on the impact of different channel structures on performance based on the annular bipolar plate designed by the team. A single air-cooled fuel cell with $50cm^2$ is used in the experiment to investigate the dynamic response under different current loading rates of 0–40 A. The test results show that the hydrogen and oxygen in different flow directions have a significant impact on the performance of the fuel cell, with a performance improvement of 8.1% by the hydrogen and oxygen in vertical and staggered flow directions for the enhancement of heat and mass transfer ability, and a decrease of about 3.5° compared with the hot spot temperature. In addition, this study further demonstrated the applicability of the annular bipolar plate structure, and verified the impact of different channels on cathode side and ridge shaped structure on performance, wind speed, temperature distribution, stability and mass power density, of which the performance of the fan channel/linear ridge is the best, which is about 8.5% higher than the output power of the worst fan channel/fan back. These test results provide basic data and technical support for the system design and application of air-cooled fuel cell of open cathode.

INDEX TERMS Air-cooled proton exchange membrane fuel cell, structure, flow direction, bipolar plate, performance.

I. INTRODUCTION

Future aircrafts shall be cleaner and quieter; the aeronautics sector's contribution to a sustainable environment is nowadays widely understood. With the development of multi-/all-electric aircraft, the use of fuel cell systems in high-altitude Unmanned Aerial Vehicle(UAV) continues to be investigated [1], [2]. During the past few decades, proton exchange membrane fuel cell (PEMFC) have attracted much attention as efficient and clean alternatives to existing power supplies. PEMFCs boast zero pollution, low operating temperatures, fast response to load change, no limitation by the Carnot cycle, and outstanding energy conversion efficiency [3]. PEMFC continues to gain credibility as an alternative power supply in many applications, including portable power supplies for personal electronic devices,

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commercial aircraft auxiliary power units (APUs) and even aircraft and orbiting platforms [4], [5], and UAV [6], [7]. Alkaline Fuel Cells (AFC) and PEMFC have been used as primary power sources for spacecraft since the 1960s, on the Gemini manned spacecraft, the Apollo moon spacecraft and the Space Shuttle, as well as on the Russian Lunar Orbiter and the Space Shuttle Tempest [8], [9], [10], [11].

The PEMFC fuel cell stack can be designed and constructed in various ways. One option is dependent on the type of cooling medium. It was found that effective cooling is necessary for the safety and operational efficiency of high-powered PEMFC stacks [12]. In terms of cooling methods of PEMFC stacks, PEMFCs can be categorized into circulating liquid-cooled and air-cooled PEMFC stacks. The air-cooling option is also attractive for PEMFC designed for drones or light aircraft, as they require less space and weight. The usage of fuel cells in small to medium-sized UAVs has been investigated since the 2000s and successful examples have been made. The first attempts to develop a fuel cell-based power system for UAVs were carried out in the United States. UAV with hybrid fuel cell and polymer power system by Renau J et al. completes 10,000m high altitude flight test in 2017 [13]. Herwerth et al. applied a PEMFC in a small UAV to show the capabilities of the endurance of PEMFC for flight [14]. They employed the air-cooled PEMFC for thermal management and applied self-humidification at an operating. Domestic fuel cell drone technology started later than foreign development, but now it has also achieved independent development and successful test flights of fuel cell UAV. Air-cooled fuel cell systems are characterized by their light weight, simple design, easy operation, low cost and increased gross efficiency which makes them a suitable technology for unmanned aerial vehicle and aerospace applications [15], [16], [17], [39]. However, the structure of open cathode for the air-cooled PEMFC and the characteristics of air for the limitation of humidity, pressure, and heat transfer coefficient induce the limitation of efficiency for the heat and mass transfer. Therefore, there is an important significance of research to improve the heat and mass transfer capacity of air-cooled PEMFC.

The optimization of heat transfer in the reaction process is one of the main ways of heat transfer in air-cooled PEMFC stack. The flow channel which is carved on the air-cooled PEMFC bipolar plate provides a channel for the reactant gas and products to flow. The main heat transfer mode in the solid part of the air-cooled PEMFC bipolar plate is solid heat conduction, and the main heat transfer mode in the hollow channel part is air heat convection. Therefore, the structure of flow channel can be modified to improve the ability of air thermal convection for heat transfer. In the past decade, some scholars have done some research on the flow channel of the air cooled PEMFC with open cathode. By shortening the channel for the basic structure of the cathode channel, it may help reduce the pressure drop of the air, and the accumulation of heat along the flow direction, which enhances the heat transfer, cools the cell, and improves the working current density [18], [19], [20]. Similarly, there is also an impact from the width of the channel on the pressure drop of the channel. Narrow flow channels with smaller hydraulic diameters will lead to faster pressure drop and temperature difference [21]. Narrow cathode channel design improves the hydration of the proton exchange membrane and achieves uniformity for the current density distribution [22]. However, cells with narrow channel are easy to cause Gas Diffusion Layer (GDL) flooding under the condition of low temperature [23]. By the enlargement of width for the channel, it is easy to remove the water in the channel and GDL by the decrease of flow resistance and the increase of flow rate. However, the larger width for the channel is easy to break the balance between relative humidity and oxygen concentration [24]. Hence, different channel structure models have been studied by some researchers to optimize the performance of fuel cells. Baik et al. introduce a porous structure design in the rib area of the bipolar plate, which avoided the oxygen shortage in the catalytic layer under the rib, and improved the oxygen mass transfer ability, water removal ability and the uniformity of oxygen distribution [25], [26]. Diankai Qiu [24], [27], [28] and others analyzed the impacts from the width of the cathode channel, the rib to groove ratio, and the channel section parameters on the temperature, relative humidity, and oxygen concentration of the channel. The results showed that the rib to groove ratio was about 3, which was reasonable, and under the same rib to groove ratio, the narrower the channel width is, the better the fuel cell performance will be. Henriques [29], Matian [30] and Spiege [31] found that the increase of the channel height can reduce the pressure drop of the channel, which leads to the need to provide higher fan speed to ensure the uniformity of the heat dissipation of the stack. In addition, our team also found that the proper increase for the curvature of the flow channel can also improve the performance [32]. Zhengkai Tu et al have also been conducted on the flow channel design and water heat transfer of air-cooled fuel cells by some experimental and simulation studies [33], [34], [35], [36], [37], [38], they found that series configuration provides higher power output at the expense of lower fuel utilization in comparison with parallel configuration. They also studied the effect of ultra-thin steel bipolar plates on fuel cell performance.

The design and structure of the flow channel in the bipolar plate are important factors that affect the overall performance of the PEMFC. Although some scientific studies have been carried out on the bipolar plate and the flow channel, there is few reports on the impact of oxygen and hydrogen in different flow directions and different flow channel structures under the annular bipolar plate on the performance of the air-cooled PEMFC. Therefore, in order to study the impact of hydrogen and oxygen of the bipolar plate in different flow directions and different flow channel structures under the annular bipolar plate on the overall performance of the air-cooled PEMFC, the experimental study was carried out under the same active area. During the test, the hydrogen and oxygen were set in two flow directions respectively, one is vertical staggered flow direction, the other is parallel with the same direction; In addition, two flow channels are designed for the annular bipolar plate which are straight flow channel and sector flow channel. In order to characterize the impact of the two different design structures on the performance, the polarization curve, Electrochemical Impedance Spectroscopy (EIS), cathode side outlet temperature, wind speed and operation stability were tested during the test, and the mass power density was calculated. The research in this paper provides basic data and technical support for the unmanned aerial vehicles application and system design.

II. DESCRIPTION OF PEMFC EXPERIMENTAL SYSTEM

A. EXPERIMENTAL SETUP

The single fuel cell with a reaction active area of 50 cm^2 was used for testing. However, there was a layer of polyethylene terephthalate (PET) film around the outer frame of membrane electrode assemble(MEA) as the frame to seal which plays the role of isolating bipolar plate and insulation. The commercial catalyst coated membrane (CCM) (Gore USA) and the GDL (Avcarb USA) were applied for the (MEA). The detailed parameters of CCM and GDL were listed in Table 1. The structure straight flow field was used in the cathode and the four serpentine flow fields were designed in the anode.

A schematic of the experimental setup was shown in Fig.1. Dry and non-heated hydrogen with a purity of 99.99% was supplied to the PEMFC anode, and the inlet pressure and flow rate of hydrogen were adjusted by the regulator. The fan (San Ace), which offered cooling and air to the cathode, was regulated by a self-made controller. The anode hydrogen used in this experimental study is flow-by anode mode. A computer-controlled system of an experimental platform dominated the hydrogen and electrical valves to achieve the recording and presenting data simultaneously. Moreover, the EIS could be tested by the experimental setup.

TABLE 1. Parameters of the CCM and GDL.

Parameter	Value
Thickness of CCM	30um
Loading of Pt electro-catalyst on the anode	0.1mg/cm^2
Loading of Pt electro-catalyst on the cathode	0.4mg/cm^2
GDL thickness	200um
GDL area weight	55g/m^2
GDL electrical resistivity	8mΩ/cm^2
GDL density	0.27g/ccm
Thickness of graphite bipolar	2 mm

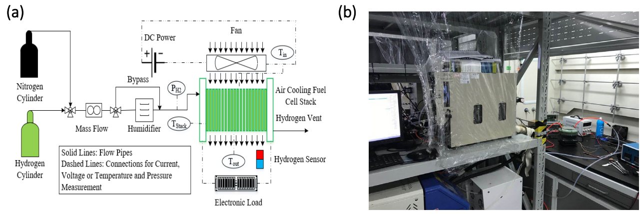

FIGURE 1. Test system diagram (b) Test equipment.

B. EXPERIMENTAL PROCEDURE

All self-designed cathode and anode channels of bipolar plates were machined by Computer Numerical Control (CNC) engraving machine, and the bipolar plates were made of hard graphite plates. While, the collector plate was made of copper plate. It was plated with gold of 1um thick after the process. All experimental tests were performed in the commercial fuel cell test bench (BAITE, China). In the test process, the temperature and humidity of ambient air were between 18°∼25° and 30%∼45% respectively. And, we fixed the hydrogen temperatures at 30°, the pressure at 50kPa, the stoichiometric of hydrogen at 1.8 which could make the hydrogen enough to engage in the reaction.

A tube-axial fan (San Ace (90) Jap) was installed on the cathode side of the stack, forming forced convection of air to supply sufficient air for oxygen reduction reaction and remove the heat. During the test, the wind from the fan is drawn to the fuel cell.

The cathode outlet surface temperature distribution was measured to quantify the impact with different parameters. The thermography shown in this paper have been made with a TESTO® 865 camera (temperature range: −20° to 280°, accuracy: ±2%), with a matrix of 320 × 240 sensors and a thermal resolution < 120 mK.

The MEA needs to be activated in advance of the experiment. In the active process, the RH value for the anode side was set 100% since it could make the MEA activated thoroughly. The different current conditions were 5A-50A, 5A per point and each step requires 2min.

The experimental cases were conducted three times to verify the data values and to ensure that the figures in the final data was the average values. The detailed experimental setup and flow channel design were listed in Fig.2. Additionally, Table 2 summarizes the PEMFC experimental parameters.

In this test, the active reaction area is 50 cm^2, and the bipolar plate structure is annular bipolar plate, of which the outer diameter is 144 mm and the inner diameter is 90 mm. Among them, the hydrogen flow passage adopts four serpents, and the oxygen flow passage adopts straight flow passage with fan-shaped back. With the regard to the flow direction of hydrogen and oxygen, two flow directions were designed in this study, one is vertical staggered flow direction, the other is parallel and in the same direction, and the flow direction is shown in Figure 2e. Secondly, three channel structures are

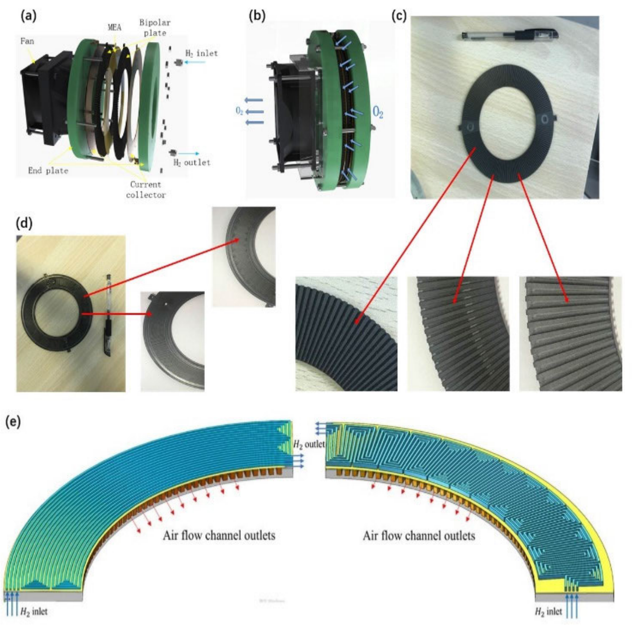

FIGURE 2. **(a) Explosion diagram (b) Oxygen inlet flow direction (c) Bipolar plates with different channel structures (d) Different hydrogen and oxygen flow direction bipolar plate structure (e) Schematic diagram of different hydrogen and oxygen flow directions.**

TABLE 2. **Test parameters.**

Parameter	Definition	Value
V_{cell}	Cell Voltage	0.3-1.0V
i_{cell}	Cell Current Density	0~1.0 A/cm^2
P_{cell}	Cell Power	0~25W
Q_{cell}	Heat Generated by Cell	0~46.2W
T_{H2}	Inlet Hydrogen Temperature	30℃
T_{Air}	Inlet Air Temperature	18℃～25℃
λ_{H2}	Inlet Hydrogen/Consumed Hydrogen	1.8
F_{H2}	Flow rate Hydrogen	0~0.63L/min
λ_{Air}	Wind Ratio of Fan	5%
n_{cell}	Numbers of Cell	1
RH_{H2}	Relative Humidity of Hydrogen	0%
RH_{Air}	Relative Humidity of Air	30%～45%
P_{H2}	Inlet Hydrogen Pressure	50kPa
V_{cell}	Cell Voltage	0.3-1.0V
i_{cell}	Cell Current Density	0~1.0 A/cm^2
$depth_c$	The depth of cathode channel	1.3mm
$width_c$	The width of straight cathode channel	1.1mm

designed respectively for the optimization of cathode channel structure, which are straight channel/sector back, sector channel/sector back, sector channel/sector back. The specific channel size parameters are as follows: the depth and width of the channel on the anode side are 0.3mm and 0.45mm, the depth and the width of the channel on the cathode side are 1.3mm and 1.1mm. And the inner and outer arc length of the sector channel are about 0.56mm, and 1.56mm. There will be some errors in the process but can be ignored. There are four channels for all the anode flow channels with vertical and staggered flow directions. The structure is shown in Fig.2c.

III. RESULTS AND DISCUSSION

A. EFFECT OF OXYGEN AND HYDROGEN FLOW MODE

Generally speaking, there are two ways for the flow of hydrogen and oxygen on both sides of the membrane electrode inside the air cooled PEMFC of open cathode. One is the parallel flow of hydrogen and oxygen on both sides of the membrane electrode, and the other is vertical staggered flow. This flow mode of hydrogen and oxygen is a key factor that impacts the performance of air-cooled PEMFC. The details are shown in Figure.2e. In order to deeply study the impact of oxygen and hydrogen in different flow modes on the performance of open-cathode air-cooled PEMFC with annular bipolar plate structure, two flow modes of annular bipolar plate were designed in this study. The flow channel at the cathode side is a long rectangular flow channel with a fan-shaped back, and the anode side is serpentine channel of which the flow direction is parallel and perpendicular to the flow channels at the cathode side. The structures can be seen in Figure.2d. The polarization curve, electrochemical impedance spectroscopy, cathode side outlet temperature and stable operation conditions were tested respectively during the test, and the fan ratio was 5% (4.5W). Figure.3 shows the polarization curve and EIS for the hydrogen and oxygen in two different flow directions. It can be seen from Fig.3a there is a significant impact of hydrogen and oxygen in two flow modes on the performance of the PEMFC. The voltage of the vertical staggered mode under different current densities is higher than that of the parallel co-directional mode. When the current densities are 0.2 A/cm^2, 0.4 A/cm^2, 0.6 A/cm^2 and 0.8 A/cm^2 respectively, the voltage differences are 15 mV, 22 mV, 31 V and 46 V and increases with the increase of the current density. Since when the flow directions of hydrogen and oxygen are intersected and perpendicular, the number of turns in the flow channel at the hydrogen side is significantly less than that in the parallel flow direction. This design also reduces the pressure loss when hydrogen flows in the flow channel, and relatively increases the pressure and flow rate of hydrogen, resulting in the enhancement of mass and heat transfer of hydrogen in the reaction process. When the current density is 0.8A/cm^2, the power density of the vertical staggered flow is 8.1% higher than that of the parallel flow. This phenomenon is consistent with the test phenomenon for the hydrogen and oxygen of traditional strip bipolar plate in different flow directions conducted by our team before [40], which means that no matter what kind of bipolar plate structure in the air-cooled PEMFC of open cathode is, the optimal design for the flow directions of hydrogen and oxygen on both sides of the MEA is vertical staggered flow direction which improves the performance of the PEMFC well.

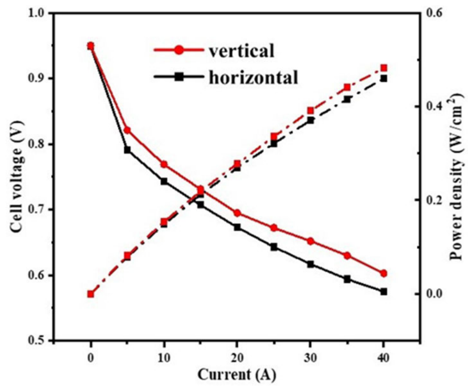

FIGURE 3. Polarization and power density curves of the cell with different design.

Electrochemical impedance spectroscopy is a technique that can be used to distinguish various loss mechanisms that dominate the corresponding region of the polarization curve at a specific current density. The electrochemical impedance is mainly composed of ohmic resistance and mass transfer resistance. Figure.4 shows the ohmic resistance and the total polarization resistance of air-cooled open channel PEMFC at 0.8A/cm^2 under two different flow modes. It can be clearly seen from Figure. 4a that hydrogen and oxygen in different flow directions have little impact on contact resistance, with the difference of only 0.007 Ω cm^2 which can be ignored. Moreover, there is no significant change for the opening rate at the anode side by the change of direction, and the difference of opening rate is only 0.0081. Since the contact resistance is mainly determined by the contact area between the bipolar plate and the GDL while the contact area is determined by the opening rate, the change of the flow direction for hydrogen and oxygen will not induce the contact area between the bipolar plate and the MEA to change the contact resistance.

The PEMFC will generate water in the reaction process. For the air cooled PEMFC, most of the water generated will be eliminated by the wind generated by the fan, but still a small amount of water will be diffused to the anode side in reverse. For the vertically staggered anode flow channel design mode, the number of right-angle bends in the flow channel is smaller, and the flow resistance of hydrogen and water in the flow channel will become weaker, resulting in easier drainage of water that avoids flooding. It can also be seen from Figure.4a that the impacts from different flow directions are different on the mass transfer resistance. The mass transfer resistance of the vertical staggered flow mode decreases about 0.21 Ω cm^2 (27.6%) compared with the parallel and the same flow mode. It is the reduction of mass transfer resistance that promotes the improvement of PEMFC performance. For further data analysis, Figure.4b shows the electrochemical impedance of the annular air-cooled PEMFC at 0.8 A/cm^2. The ohmic impedance of the vertical staggered flow mode and the parallel co-flow mode are 0.1070 Ω cm^2 and 0.1175 Ω cm^2 respectively, and the ohmic impedance of the parallel co-flow mode is 9.81% higher. The ohmic impedance of the vertical cross-flow mode and the parallel co-flow mode are 0.5832 Ω cm^2 and 0.7884 Ω cm^2 respectively. Compared with the parallel co-flow mode, the charge transfer impedance of the vertical cross-flow mode is reduced by 26.03%. The ohmic impedance of the vertical staggered flow mode and the parallel co-flow mode are 0.1036 Ω cm^2 and 0.1343 Ω cm^2 respectively. The mass transfer impedance of the parallel co-flow mode has increased by 29.63% due to the existence of more right angles, larger pressure drop and smaller gas pressure. Since the charge transfer impedance and mass transfer impedance of the vertical staggered flow mode are smaller, better performance can be achieved.

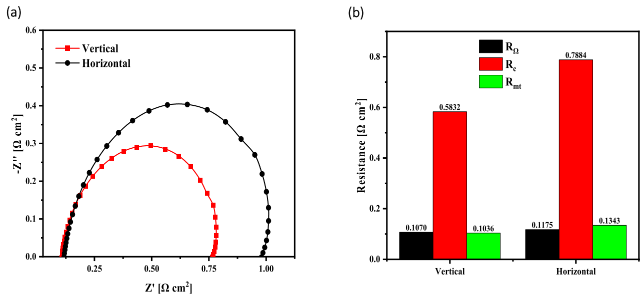

FIGURE 4. (a)EIS at 0.8A/cm^2 (b) curves of various impedances at 0.8 A/cm^2.

Many scholars and our team have conducted a large number of experiments and simulation studies on the air-cooled PEMFC, and found that temperature is an important factor that impacts the performance of the PEMFC. The temperature of the PEMFC is mainly decided by the heat generated in the reaction process and the heat dissipation capacity of the cell. Figure.5 shows the cathode side outlet temperature distribution for hydrogen and oxygen in two different directions at the current density of 0.8 A/cm^2. It can be seen from the figure that the outlet temperature at the cathode side under the two flow directions shows good uniformity, and the temperature difference is within 1.5° for the PEMFC composed of annular structure bipolar plates. In addition, the hot spot temperature at the outlet of cathode side in the design mode of vertically staggered anode flow channel is higher than that in the parallel flow direction mode, with a difference of about 3.5°. The result is consistent with the output performance of PEMFC. According to the law for the conservation of energy, when the electrical performance of the PEMFC is better, the less waste heat will be generated and the corresponding temperature will be lower [40]. Besides, attributed to the vertically staggered anode channel design, the resistance of hydrogen flow in the channel is weaker and the flow rate is faster, which reduces the reaction heat to a certain extent. It shows that the vertically staggered anode channel design mode is an excellent flow direction design mode as it can not only improve the reaction efficiency, reduce waste heat generation, but also improve the overall heat dissipation capacity.

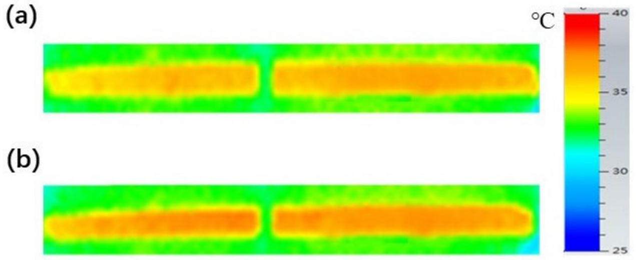

FIGURE 5. **Cathode outlet temperature of the cell with different flow direction at 0.8A/cm^2.**

The operation curves of fuel cell voltage with time for different hydrogen and oxygen flow modes are measured, and the results are shown in Figure 6a. The test time for stable operation is set to 30min, and the fan power is 4.5W. It can be seen from Figure 6a that the air cooled PEMFC of open cathode with two air flow interleaving modes can operate stably under the condition of current density of 0.8 A/cm^2, and the deviation is basically within 0.02V, which indicates that they both have good working stability. Besides, we can learn that there is no impact of different air flow operation modes on the stable operation of the fuel cell. Figure.6b shows the porosity and mass power density of the anode plate under two different flow directions of hydrogen and oxygen. During the calculation of the mass power density, only the anode plate, membrane electrode and cathode plate are included in the mass of this study, because it is the same for the end plate, collector plate, screw, etc. It can be seen from Figure. 6b that the opening rate of the anode plate under the design of two different hydrogen flow directions are 52% and 51.19% respectively, with a difference of only 0.81, showing that changing the flow direction of hydrogen, whether horizontal or vertical, will not have too much impact on the opening rate of anode side. In addition, although the difference in the opening rate is little, it still causes the difference in the quality of the anode plate. It can be seen from Fig.6b that the mass power of the vertical staggered flow direction is higher than that of the parallel co-flow direction, with a difference of 0.011w/g. The reason is that the quality of the anode plate in the vertical staggered flow direction (the transverse flow of hydrogen) is poorer, and the quality of the anode plate in the parallel co-flow direction (the longitudinal flow of hydrogen) is better. In combination with the output power measured in the test in Figure. 3, the output power of the vertical staggered flow is higher than that of the parallel flow, as it is obtained from the above results. Through the integration of the performance parameters such as polarization curve, EIS data and mass power density, it can be concluded that there is a significant impact of oxygen and hydrogen in different flow directions on the performance of the air-cooled PEMFC of open cathode, and whether the structure of the bipolar plate is conventional rectangular or annular, the vertical staggered flow direction is the best design method.

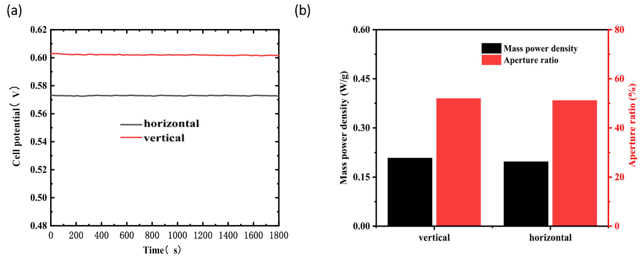

FIGURE 6. **(a) Single-cell potential against time for different flow direction at 0.8A/cm^2 (b) Mass power density and aperture ratio for different flow direction.**

B. INFLUENCE OF CATHODE CHANNEL STRUCTURE

In order to study the impact of different cathode side channel structures on the performance, three channel structures are designed for the annular bipolar plate, which are straight channel/fan ridge(design1), fan channel/straight ridge(design2) and fan channel/fan ridge(design3). Figure. 2c shows the detailed structure shape and design parameters. Different channel structures impose an impact on the speed of air entering the channel, change the mass transfer and heat transfer, and lead to different reaction rates and heat dissipation capabilities. The fan power during the test is 4.5W. Figure.7 shows the polarization curve and cathode side outlet temperature under three different cathode side channel structures. It can be seen from Figure.7a that there is a significant impact of different cathode side channel structures on the performance of the fuel cell. Among them, the voltage of fan channel/straight ridge channel shows good output performance from low current density to high current density. When the current density is 0.8A/cm^2, the voltage is 0.625V, which is 0.007V and 0.049V higher than that of straight channel/fan ridge, fan channel/fan ridge, respectively. It is worth noting that from the structure of the back, the two fuel cell ridge structures with poor performance are both fan ridges. Combined with the porosity, the linear spine has better conductivity and mass transfer capacity than the fan-shaped spine. Meanwhile, the straight channel structure with the fan-shaped channel structure is compared under the condition of the same fan-shaped back. It can be seen from Figure.7a that the straight channel shows better performance output, with a difference of 0.042V. And the output difference between the two channel structure design models of linear channel/fan-shaped ridge and fan-shaped channel/linear ridge is very small under different current densities, but the fan channel/linear ridge still shows better performance compared with the straight channel/fan ridge, which is about 1.1% higher under different current densities. This is due to the cross-sectional area of the fan shaped flow channel gradually decreases from the inlet to the outlet, the diameter of the air column decreases, and the air flow rate gradually increases. The pressure of the air decreases in areas with high flow rates, and the pressure difference inside the channel increases, resulting in an enhanced mass and heat transfer effect of the air in GDL. For the entire annular bipolar plate, the fan-shaped spine reduces the overall number of flow channels, leading to a decrease in fuel cell performance.

Figure.7b to 7d shows the outlet temperature distribution of three different cathode side channel structures at current density of 0.8A/cm^2. It can be seen from Figure.7b that the hot spot temperature of the cathode side channel outlet section of the three cathode channel structures is 36.6°, 36.3° and 37.8°, respectively. Among them, the difference for the hot spot temperature of the sector channel/straight ridge back cathode side channel outlet section is the smallest, while the fan channel/sector ridge back-channel outlet section is the largest which is 1.5°C. Compared with Figure.7a, the hot spot temperature at the outlet section of the cathode side channel is related to the current density. The better the output performance is, the lower the hot spot temperature at the outlet section of the cathode side channel will be. Since the better the performance is, the more intense the chemical reaction will be, and the less waste heat will be generated. At the same time, since the structure of the fan channel/straight back bipolar plate cathode channel is characterized by the gradual reduction of the cross-sectional area from the inlet to the outlet, the pressure of the air in the internal flow decreases, the flow rate increases, and the heat eliminated increases.

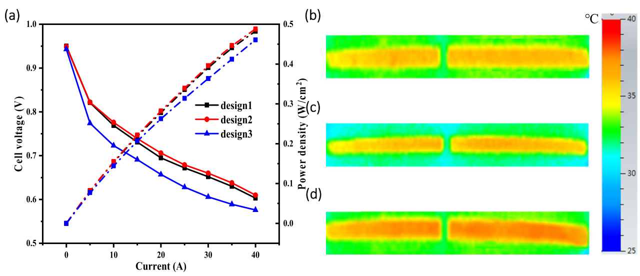

FIGURE 7. (a) Polarization and power density curves of the cell with different design (b) Cathode outlet temperature of the cell with design1 at 0.8A/cm^2 (c) Cathode outlet temperature of the cell with design2 at 0.8A/cm^2 (d) Cathode outlet temperature of the cell with design3 at 0.8A/cm^2.

For the bipolar plates with three different cathode side structure models, the air flow rate will be measured transversely along the cathode side outlet. The measuring points will be set every 2 cm along the cathode side outlet. The fan is in suction mode, and the fan power is 4.5W. The test range of the wind speed sensor is 0.2-30m/s. During the test, each point is tested three times with a duration of 30s, and the average value is the same with the final value. The corresponding standard deviation value of wind speed is calculated using the following formula. The calculation results are shown in Table 3.

$$\sigma_{abs} = \sqrt{\frac{1}{N-1}\sum\nolimits_{i=1}^{N}(v_i - \bar{v})^2} \tag{1}$$

$$\bar{v} = \frac{1}{N}\sum\nolimits_{i=1}^{N} v_i \tag{2}$$

$$\sigma_{relative} = \frac{\sigma_{abs}}{\bar{v}} \tag{3}$$

In the formular: v_i is the wind speed at position i; σ_{abs} and $\sigma_{relative}$ are the absolute and relative standard deviation of wind speed; v^{-} and N represent the average value of the speed and the number of observations.

The bipolar plate structure of the open cathode air cooled PEMFC optimized and designed in this study is an annular bipolar plate. Although the fan still uses the traditional axial flow fan, the annular bipolar plate does not have the disadvantages of the axial flow fan. The axial flow fan's axis is no longer directly oriented towards the bipolar plate, but towards the space between the annular bipolar plates. This completely solves the uneven phenomenon of M-type wind speed distribution in the suction or blowing of the axial flow fan to the traditional rectangular bipolar plate [40]. Through the test, the wind speed distribution uniformity of the three channel structures under the annular bipolar plate is better than that of the traditional rectangular bipolar plate. The maximum difference of the measured wind speed of the three cathode side channel structures is very little, which are 0.09m/s and 0.1m/s respectively. This is because after the optimization of the annular bipolar plate, the distance between the fan and each flow channel of the bipolar plate is the same, and there is no influence from the fan shaft. However, there is a significant difference of the average wind speed among the three. The average wind speed of straight channel/fan ridge, fan channel/straight ridge and fan channel/fan ridge are 0.75m/s, 0.72m/s and 0.91m/s respectively. This shows that there is an important impact of different channel structures on the wind speed and flow field in the annular bipolar plate channel, resulting in different performance.

TABLE 3. Consistency of wind speed distribution.

Parameter	Value		
	design1	design2	design3
Maximum difference(m/s)	0.09	0.09	0.1
Standard deviation(m/s)	0.025	0.026	0.027
Average value(m/s)	0.75	0.72	0.91
Relative difference(%)	3.37	3.59	3.00

The operation stability of PEMFC is another important indicator to evaluate the impact of different cathode channel structures on the performance of the cell, because the stability directly determines the redundancy factors in the engineering application design of PEMFC, and the application feasibility of this channel structure. Fig. 8a shows the stable operation test of three different cathode side channel structures at a current density of 0.8 A/cm^2, and the stable operation time is set to 30 min. It can be seen from Fig. 8a that the channel/fan-shaped ridge, fan-shaped channel/straight ridge and fan-shaped channel/fan-shaped ridge operate stably at about 0.618V, 0.625V and 0.576V, and the difference during stable operation is within 0.002V, 0.001 and 0.001 which shows good working stability with negligible difference.

The mass power density is also an important factor to evaluate the optimization of the cathode side channel structure. Because the mass of the end plate, the collector plate and the sealing ring are the same, during the calculation of the mass power density, the mass components of the PEMFC only the bipolar plate and the membrane electrode are included in this study for the mass components of the PEMFC to simplify the calculation. Fig. 8b shows the mass power density and porosity of three different cathode side channel structures. It can be seen from Figure. 8b that the opening rate of fan channel/fan ridge is the highest, followed by straight channel/fan ridge, and finally by fan channel/fan ridge, with the maximum difference of 10.57%. From the quality point of view, the larger the porosity is, the poorer the cathode plate quality will be. Combined with the output power, although the weight of the fan channel/fan back and the output power are both the smallest, the difference with the other two channel structures is large, resulting in the smallest mass power density of the three channel structures. While the difference between the opening rate of the straight channel/fan ridge and the fan channel/straight ridge is very small which is less than 1%. Combined with the performance of output power, in this situation, the increase of output power has a greater impact on the mass power density than the mass of the bipolar plate, so the mass power density of the fan channel is slightly better than the linear channel model. This result shows that we can further reduce the mass of the fan channel/straight back structure model for optimization to improve its overall mass power density.

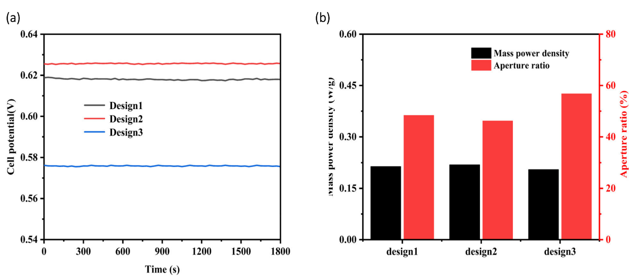

FIGURE 8. Single-cell potential against time for different design at 0.8A/cm2 (b) Mass power density and aperture ratio for different design.

IV. CONCLUSION

At present, in both commercial and extensive research on the bipolar plate structure of fuel cells, rectangular bipolar plates are used. This bipolar plate structure is combined with an axial flow fan, and an M-shaped airflow is formed in the stack formed by the rectangular bipolar plate structure, resulting in uneven distribution of airflow and inconsistent velocity in the bipolar plate channel. To solve this problem, our team proposed an annular bipolar plate structure, which corresponds the axis of the axial flow fan to the hollow part of the annular bipolar plate, The distance between each flow channel of each layer of annular bipolar plate corresponding to the fan is the same, which improves the wind speed and distribution uniformity. In order to further investigate the impact of different channel structures on performance based on annular bipolar plates, this study proposes three different channel structure combinations, namely straight channel/fan ridge(design1), fan channel/straight ridge(design2) and fan channel/fan ridge(design3). In addition, comparative analysis and research were conducted on the cross direction of oxygen and hydrogen within the annular bipolar plate structure to find a more suitable cross direction.

So, in this paper, the purpose is to find out the impact of different channel structures on the performance of the PEMFC to obtain the best corresponding relationship of hydrogen and oxygen flow channel, and get the best flow channel structure.

The different channel structures and flow direction characteristics of the air-cooled PEMFC of open cathode with the active area of 50 cm^2 are studied. Polarization curve, EIS distribution, temperature distribution, operation stability and mass power density are also be measured. The detail conclusion is follow:

1. The test results show that different flow directions of hydrogen and oxygen can effectively affect the performance, temperature distribution, EIS and mass power density of the PEMFC.
2. For annular bipolar plates, different cathode side channel structure shapes will also affect the performance, temperature distribution, wind speed and mass power density of the PEMFC.
3. The hydrogen and oxygen on both sides of the membrane electrode show better performance in the vertically staggered flow mode, with an increase of about 8.1% compared with the parallel and the same direction, and a decrease of about 3.5 ° compared with the hot spot temperature.
4. Different flow channels can change the air velocity entering the cathode side channel, thus changing the output performance of the PEMFC.
5. The fan channel/straight back has the best output performance and mass power density among the three different structures, which is about 8.5% higher than the output power of the worst fan channel/fan back.

It shows that the optimization of the cathode side channel shape structure can play a leading role. The fan-shaped flow channel structure can effectively improve the performance of cathode open air cooled fuel cells. The experimental results of this study provide data support for the heat and mass transfer mechanism of internal multi-physical field coupling, and also provide design ideas for the future channel design.

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QINGTIAN GENG received the B.S. degree in computer science and technology from the Jilin University of Technology, in 1996, and the M.S. and Ph.D. degrees in computer science and technology from Jilin University, in 2005 and 2016, respectively. He is currently a Professor with the College of Computer Science and Technology, Changchun Normal University, Changchun, China. His current research interests include image processing and pattern recognition.

YARU HAN received the Graduate degree from Changchun Normal University and the master's degree. During the school period, she won the third class scholarship at the university level, published three academic papers, and participated in two scientific research projects. She is simple and upright, has a positive enterprising spirit, has good comprehensive quality, has strong willpower, and is willing to communicate with others. Her research interest includes fuel cell of CFD.

BAOZHU LI (Member, IEEE) received the Ph.D. degree in computer science and technology from the Beijing University of Posts and Telecommunications, Beijing, China, in 2017. From 2013 to 2014, he was a Visiting Student with the Broadband Communications Research (BBCR) Laboratory, Department of Electrical and Computer Engineering, University of Waterloo, Waterloo, ON, Canada. He is currently with the Internet of Things & Smart City Innovation Platform, Zhuhai Fudan Innovation Institute. His research interests include vehicular networks, mobile edge computing, machine learning, and resource management.

ZHIJUN DENG received the master's degree in vehicle engineering from the South China University of Technology. He was with the South China University of Technology, from 2002 to 2004. He is currently an Associate Professor with the School of Automobile and Transportation, Shenzhen Polytechnic University, China. His research interests include fuel cell systems, suspension design of electric vehicles, and structural optimization design.

CHEN ZHAO received the Ph.D. degree from Beihang University, Beijing, China, in 2013. He is currently a Senior Fellow with the University of Electronic Science and Technology of China. He has published more than 30 relevant academic papers. His current research interests include control, detection techniques, fuel cell, and data mining.