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The performance of miniature metallic PEM fuel cells

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Abstract

A prototype of metallic PEM fuel cell with thin stainless steel bipolar plates was tested for their potential applications in portable electronic products. The flow field pattern was grown from the stainless steel plates by the electroforming process. The main flow channel has the dimensions of 300 μm (width) × 300 μm (depth). The dimensions of the micro-features were 100 μm width × 50 μm depth and 50 μm width × 50 μm depth. The material of the electroformed flow field pattern is nickel. A prototype of a single cell with total thickness of 2.6 mm, overall reaction area of 4 cm^2 and bipolar plate area of 16 cm^2 was assembled for this study. In order to improve its corrosion resistance, the bipolar plates were coated with 5 μm thick of multi-layered corrosion resistant material.

In this study, indices of cell performance, with and without micro-features, of flow field concentration distribution, water-draining capability were studied by both numerical simulation and experimental measurement. The results show that the micro-features will provide a more uniform gas concentration environment in the bipolar plate flow field. Also, the bipolar plate with micro-features could greatly improve cell-draining capability. The results of cell performance tests show that the cell average power density reaches 195 mW cm^{-2}. The long-term tests verify their performance are very stable.

Keywords: Electroforming; Micro-features; Metallic bipolar plate; Numerical simulation; Water-draining capability

1. Introduction

Recently, because of the rapid development of green technologies and 3C products, the small fuel cells as portable power sources are gaining more attentions.

The miniaturized fuel cells require thinner and smaller bipolar plates. The current approach in developing miniature fuel cells and its bipolar plates cells is based on adoption of micro-fabrication technologies like MEMS, CMOS, etc. [1,2].

For example, the use of silicon micro-machining and related thin film processes have been employed by several research groups as attractive routes for fabrication. Lee et al. [3], by using sputtering and MEMS processes to create bipolar plates with depth between 50 μm and 200 μm on silicon wafer. The micro-fuel cell performed normally with cell efficiency of 50 mA cm^{-2}. Dry etching process, RIE, could provide at least 200 μm depth of flow channel on silicon wafer [4]. However, the conductivity of silicon-based bipolar plate is merely 0.5 S cm^{-1}. It was 10,000-fold smaller than that of a metallic bipolar plate.

On the other hand, due to smaller dimensions of the bipolar plate, the fuel transport and water-draining capability could be greatly influenced by the channel size and geometry. The pressure distribution in the bipolar plates depends on the Reynolds number and geometric parameters of the small flow channels [5]. Their results indicated that the pressure drop in a fuel cell bipolar plate depends on the plate configurations. And for a given serpentine channel configuration, it depends on geometric factors such as channel hydraulic diameter and bend geometry.

In addition, the cell relative humidity current distributions and water transport depend on the gas temperature, fuel utilization, flow direction and fluid dynamics [6–9]. At lower cell temperature, because of the water transport, the cell relative humidity was not uniform. Also, the cell current distribution could be effected by the gas flow direction. It increases in the gas downstream direction [10].

Therefore, for a miniature fuel cell, it is not easy to perform detailed in situ measurements during cell operation. Yet, such

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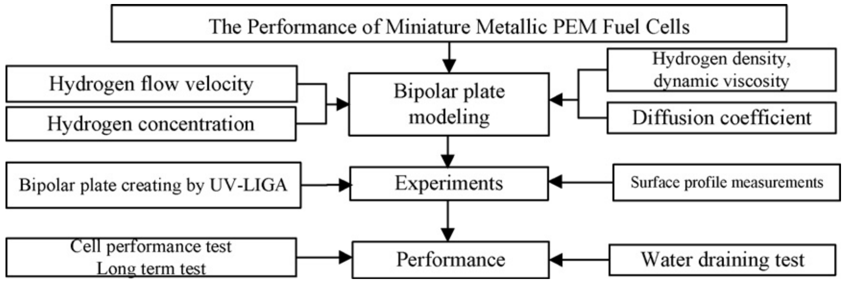


Fig. 1. Research procedures.

detailed information is essential in improving understanding of water and species transport and, hence, cell performance.

2. Research procedures

In this paper, thin metallic bipolar plates with functional micro-features were assembled into single cells for testing. The 2D gas concentration distribution was simulated by commercial software, FEMLAB.

First, given the hydrogen-related coefficients, velocity and concentration condition at the gas inlet and outlet of the bipolar plate, a numerical simulation model is established to simulate the flow field hydrogen concentration distribution for both with and without micro-features. Secondly, using CCD camera and visualization test to demonstrate the water-draining capability of the bipolar plate with and without micro-features. Finally, the cell performance and 300 h long-term test was conducted to verify its performance stability. The research procedure is shown in Fig. 1.

The shape and size of the bipolar plate was 4.0 cm × 4.0 cm with effective area of 2.0 cm × 2.0 cm. The substrate material is 316 L stainless steel. The width of the main flow channel was selected to be 300 μm. The depth of the channel was 250 μm taking pressure drop and flow resistance into consideration. Micro-features are designed with depth of 50 μm and width of 50 μm and 100 μm. Fig. 2 presents the geometrical dimensions of the 2D schematic plot.

2.1. Models for numerical simulation

2D multi-physics models of bipolar plate flow field for hydrogen concentration distributions are established using FEMLAB commercial software. The fuel's mass transportation of an ideal fuel cell system is composed of complex process such as flow of gas into the bipolar plate, diffusion into the MEA and flow in the MEA. However, the focus of the numerical simulation is to analyze the gas mass transportation of the bipolar plate with and without micro-features. The gas flow and diffusion of the MEA is ignored in this study.

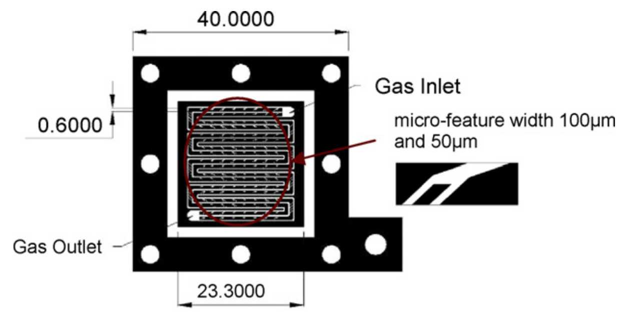


Fig. 2. Schematic picture of the geometry model (mm).

The mass transportation consists mainly of the total sum of the flux of ionic migration under electrical field, the diffusion due to the concentration gradient and the convection of the fluid field. It is represented by Eq. (1). The components on the right hand side of the equation represent: ionic migration, diffusion and convection.

$$Ni = -z_i u_i F C_i \nabla\phi - D_i \nabla C_i + C_i v \quad (1)$$

where i is the i's species, z_i the number of electrons of species i, u_i the coefficient of mobility of species i, $\nabla\phi$ the gradient of the electrical field, C_i the concentration of species i, and F the Faraday's constant. The fuel is hydrogen and it is electrical neutral. Thus, the effects of electron migration are ignored. The overall governing equation is represented by Eq. (2).

$$Ni = -D_i \nabla C_i + C_i v \quad (2)$$

The resulting transport equations governing the flow in the channels of the bipolar plate are the steady version of the well known

Table 1
Variables and their parametric settings

Parameters						
Hydrogen velocity (m s^{-1})		Hydrogen concentration		Density (kg m^{-3}, ρ)	Dynamic viscosity ($\times 10^{-5}$ Ns m^{-2}, η)	Diffusion coefficient ($\times 10^{-4}$ m^2 s^{-1})
Variables				Coefficients		
0.001[a]	0.0005[a]	1 (Inlet)[a]	0 (Outlet)[a]	0.09[a]	0.9[a]	0.7[a]

[a] Setting values.

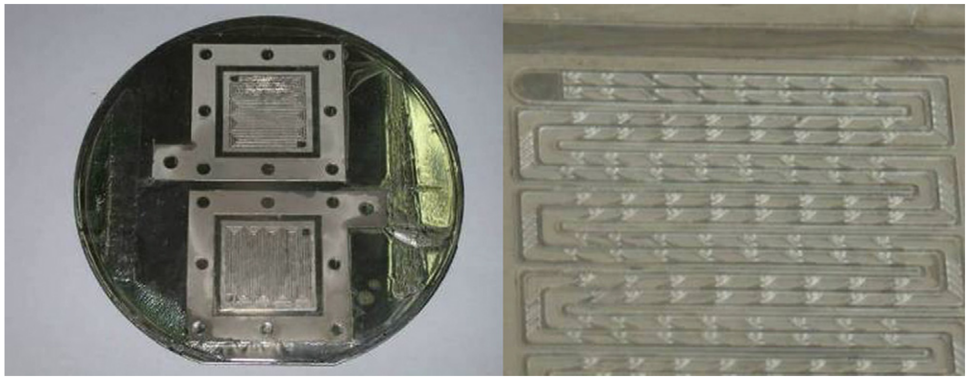


Fig. 3. Main flow channels and micro-features.

Navier–Stokes equations for mass and momentum conservation:

$$\rho\frac{\partial u}{\partial t} - \eta\Delta^2 u + \rho(u\,\nabla)u + \nabla p = F, \qquad \nabla u = 0 \tag{3}$$

where ρ: gas density, η: dynamic viscosity, u: velocity field, p: pressure, F: volume force or gravitation force.

The modeling dimension of 20 mm × 20 mm represents the size of the reaction area. The flow direction is perpendicular to the gravitation direction. Thus, the effect of gravitation force is ignored. Variables in this study include hydrogen velocity and concentration. Their parametric settings and related coefficients such as gas density (kg m^{-3}, ρ), gas dynamic viscosity (Ns m^{-2}, η) and diffusion coefficient (m^2 s^{-1}) are shown in Table 1.

In order to verify the difference between bipolar plates with and without micro-features, all of the boundaries are no-slips except for the gas inlet and outlet, hydrogen flow conditions are set at the gas inlet, $V_i = V_0$, and at the outlet, $V_o = V_1$. The hydrogen concentration conditions are assumed to be at the gas inlet, $C_i = 1$ and at the outlet, $C_o = 0$.

2.2. Micro-fabrication of bipolar plates

The bipolar plates are fabricated by the UV–LIGA and electroforming processes. The thickness of thin stainless steel 304 plates is 0.6 mm. The depth of the flow field is around 250 μm × 300 μm. Therefore, conventional photo resist of the MEMS process is not suitable. After many trials, the SU-8 photo resist is found to meet our research goal of obtaining a 250 μm × 300 μm thickness of photo resist after spin coating.

In order to create the flow field with micro-features, two iterations of the complete UV–LIGA and electroforming processes are conducted. The first iteration is to fabricate the main flow field pattern. The second iteration is to create the micro-features. Fig. 3 shows the results of electroforming of main flow channels and micro-features.

2.3. Cell performance and water-draining tests

A single cell is assembled for cell performance test. The single cell has an overall size of 4 cm × 4 cm square with 2.6 mm in thickness. A five-layered MEA, from Fuel Cell Store, #597010, is used which is composed of Nafion 112, GDL of carbon cloth material and 0.5 mg of Pt loading on both anode and cathode. The effective reaction area is 2 cm × 2 cm. The weight of the single cell without the fuel connectors is 24 g. The single cell design is shown in Fig. 4.

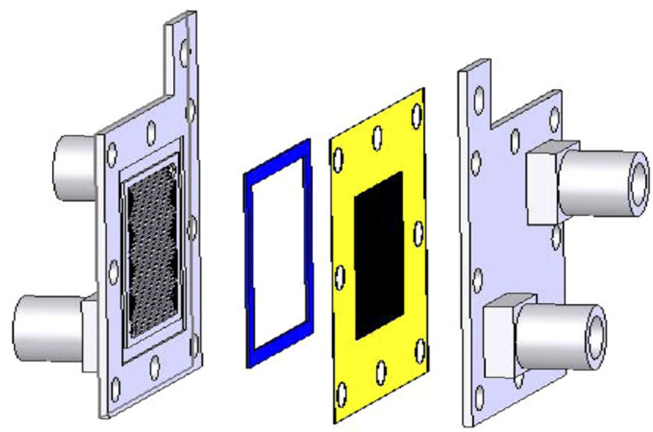


Fig. 4. Single cell design.

In order to verify the water-draining capability of the micro-featured bipolar plates, the water flow visualization test is employed to observe the water-draining situation of the bipolar plate. The bipolar plates, with and without micro-features, are sealed by gasket and acrylic plate. The flow fields are filled with red color stain. The draining tests are conduct with 50 and 100 SCCM (Standard Cubic Centimeter per Minute) hydrogen, respectively.

3. Results and discussion

3.1. Numerical simulation results

Figs. 5 and 6 show the results of the flow field hydrogen concentration distribution, with and without micro-features, at gas flow velocity of 0.001 m s^{-1} and 0.0005 m s^{-1}, respectively. The simulated data output on the dotted line of Figs. 5 and 6 are plotted in Figs. 7 and 8. Figs. 5 and 6 indicate that, regardless of gas flow velocity, both of the flow fields seem to have the same trend in concentration drop.

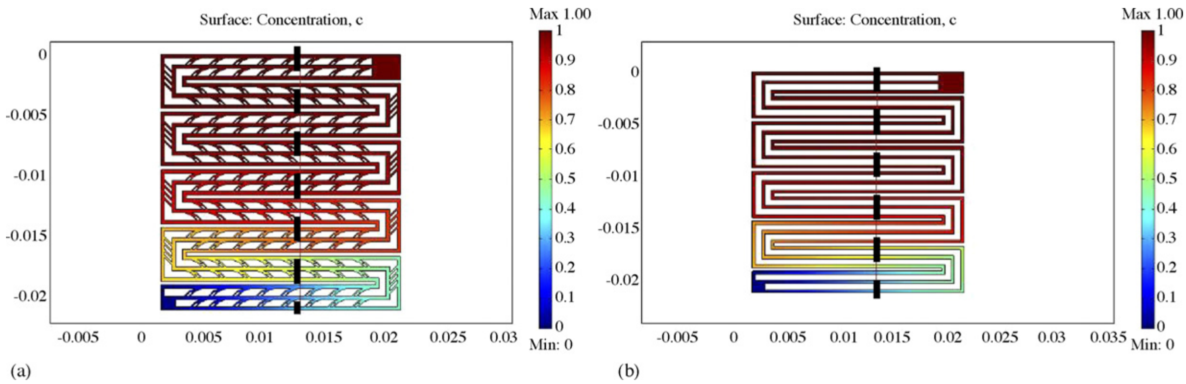


Fig. 5. Hydrogen concentration distribution with $v = 0.001\,\mathrm{m\,s^{-1}}$: (a) with micro-features, (b) without micro-features.

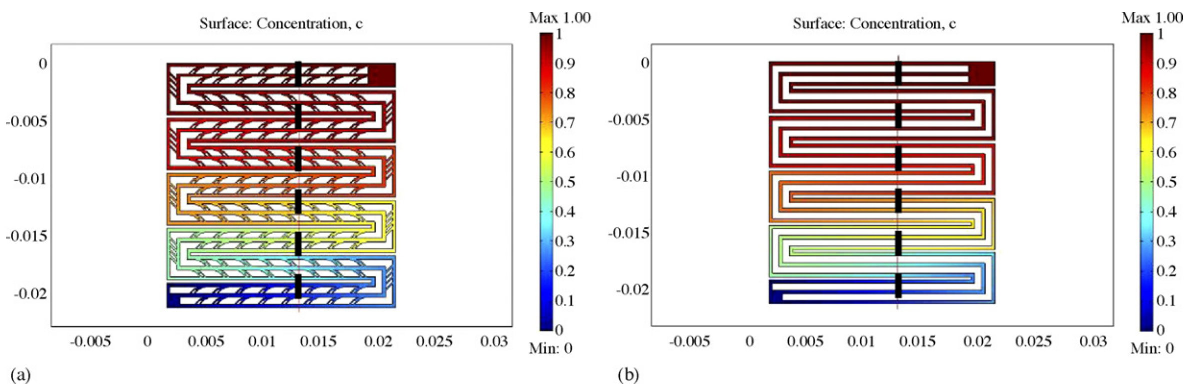


Fig. 6. Hydrogen concentration distribution with $v = 0.005\,\mathrm{m\,s^{-1}}$: (a) with micro-features, (b) without micro-features.

In the beginning, at near the gas inlet, the hydrogen concentration is uniform in the flow channel. Thus, the functions of the micro-features are not obviously. The concentration distribution of the flow field with micro-features is equal to that without micro-features. However, for the bipolar plate without micro-features, the difference in concentration drop of each flow channel is increased from the middle of the flow field. In addition, the differences are getting more serious when the hydrogen flows toward the gas outlet. For example, the flow field without micro-features at the position −0.017 of the Fig. 5(b), the highest concentration channel is around 0.65. But the lowest concentration channel is around 0.55. The difference reaches 0.1.

The problem could be effectively eliminated by micro-features. Figs. 7 and 8 show there are no obvious concentration difference between each channel from the gas inlet to the outlet. These results indicate that the micro-features could help gas diffusion between each channel. Thus, the flow field has more uniform gas concentration and the cell could perform better.

3.2. Single cell and results of water-draining test

The prototype of a single cell and surface profile of a bipolar plate are shown in Fig. 9. The optical microscopy, micrometer and laser displacement profiler are employed to exam the surface profile and depth of the flow field. The results showed that the overall size of the bipolar plate is around 4 cm × 4 cm square. The depth of the flow field is around 250–300 μm. However, the shape is not very sharp which is caused by the chemical residues left on the pattern before electroforming. There is around 20 μm

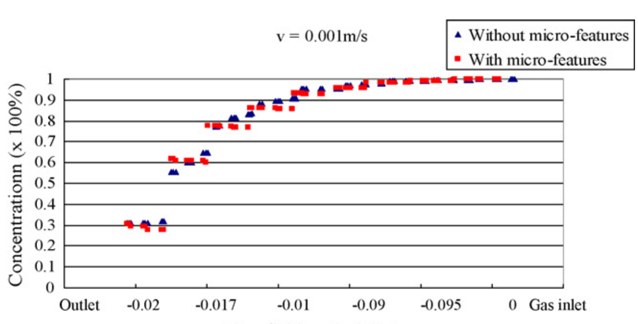


Fig. 7. Values of hydrogen concentration with $v = 0.001\,\mathrm{m\,s^{-1}}$.

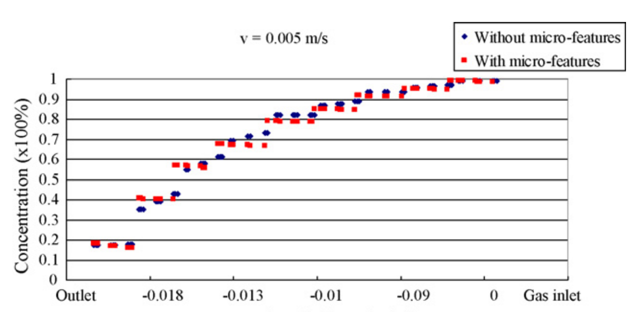
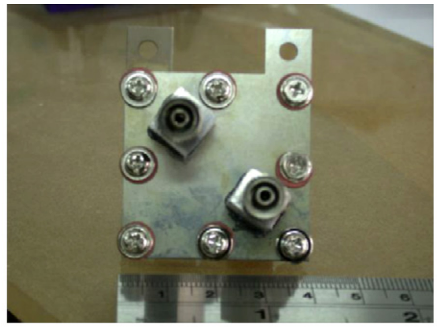
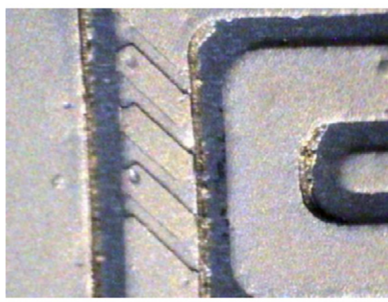
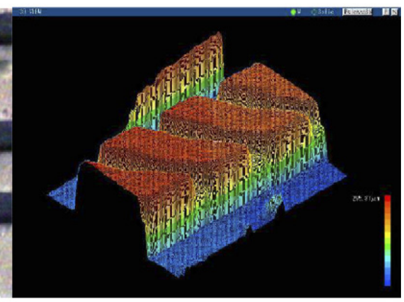


Fig. 8. Values of hydrogen concentration with $v = 0.0005\,\mathrm{m\,s^{-1}}$.



(a) Prototype of a single cell





(b) Flow field and micro-features **(c) The depth and profile of flow field**

Fig. 9. Illustration of single cell and flow field.

difference in depth over the whole bipolar plates. This might be caused by the initial flatness error of the SS304 plate. It could also be resulted from the non-uniformity of the photo resist.

The water-draining tests are conducted with 50 and 100 SCCM of pure oxygen and the flow field is full of red color stain. The water-draining time is 3 s. Figs. 10 and 11 shows the results of 50 and 100 SCCM.

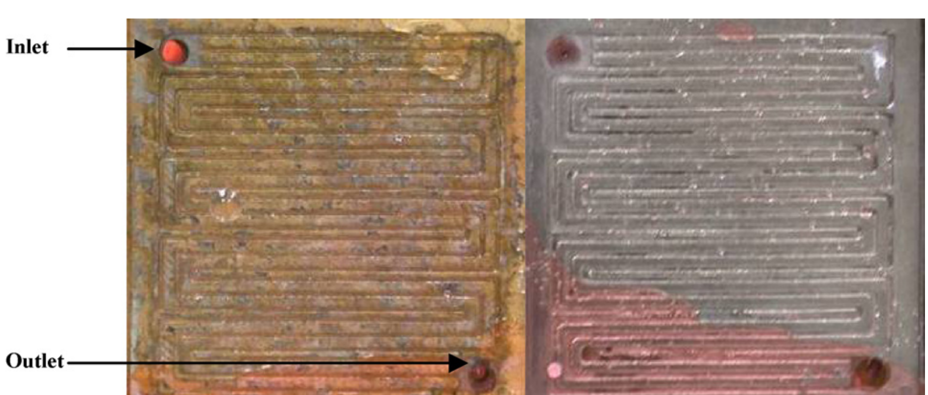
At 50 SCCM, Fig. 10(b) shows the bipolar plate without micro-features still has water-flooding situation. The flooding area is around a quarter of the flow field. On the other hand, the flooding area of the micro-feature flow field is just at the bottom of the flow field. The area is less than half of the flow field without micro-features. Therefore, the water-draining capability of the bipolar plate with micro-features seems much better than that without micro-features.

At 100 SCCM, the oxygen flow rate is increased. The water-flooding situation is less damaging than 50 SCCM. Fig. 11(b) shows the flooding situation of the flow filed without micro-features. It is still serious than that with micro-featured flow field.

From these results, the water-draining capability of the micro-feature bipolar plate is better than that without micro-features.

3.3. Cell performance tests

Cell performance tests are conducted with 50, 100, 150, 200, 250 and 300 SCCM, respectively. Pure dry oxygen and hydrogen and the cell temperature is controlled at 49 °C. *I–V* curves of these cell performance tests are plotted in Fig. 12. At the initial test of 50 SCCM, the internal flooding is not obvious. The



(a) (b)

Fig. 10. Water-draining test at flow rate of 50 SCCM: (a) with micro-features, (b) without micro-features.

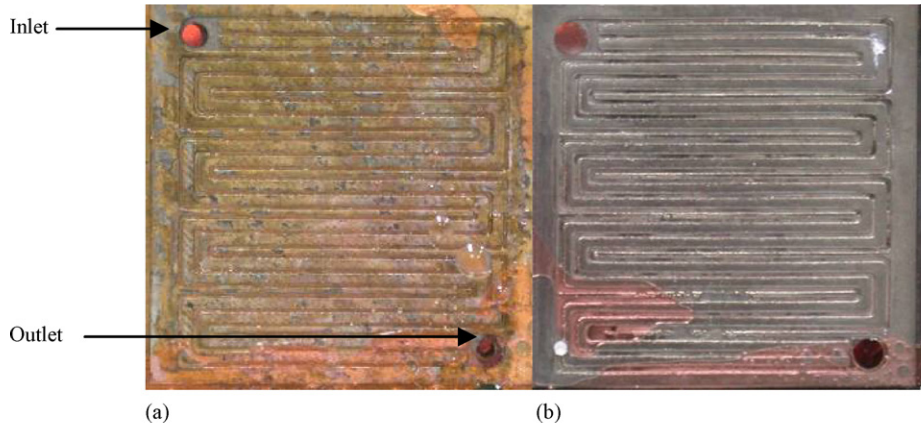


Fig. 11. Water-draining test at flow rate of 100 SCCM.

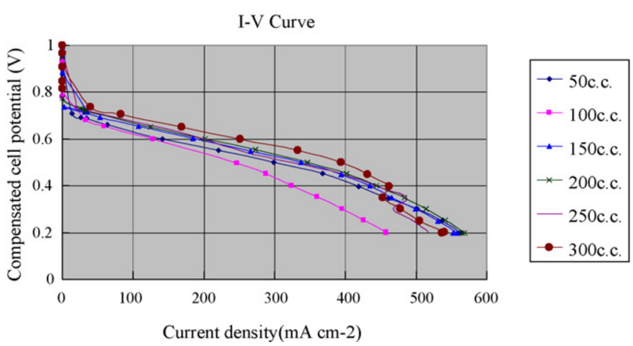


Fig. 12. *I–V* curves of the cell performance tests.

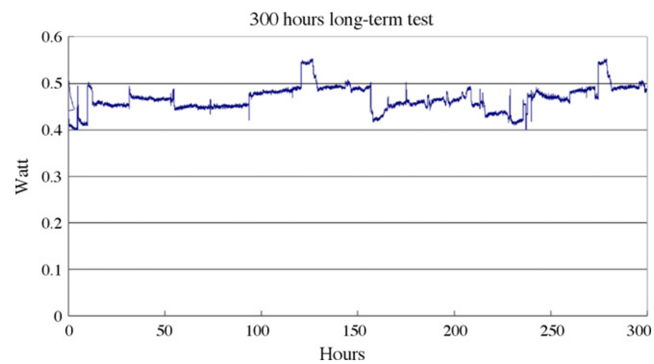


Fig. 14. 300 h long-term test with micro-features of single cell.

cell performance decreases toward the flow rate of 100 SCCM. The cell performance stabilized when the flow rate exceeds 150 SCCM. For flow rates of 150 SCCM and 300 SCCM, the current densities at 0.6 V are 190 mA cm^{-2} and 250 mA cm^{-2}, respectively.

The leveling of cell performance could be caused by blockage of micro-features by the GDL. Thickness of the GDL, 0.42 mm, is much larger than that of the micro-features, 0.05 mm. The optimal current density is 250 mA cm^{-2} at 0.6 V for flow rate of 300 SCCM. The total current output is 1 A and power output is 0.78 W. The average power density is 195 mW cm^{-2}.

Fig. 13 shows the results of performance tests for both with and without micro-features. At the initial test, regardless of functional micro-features, the cell performance seems to be the same. At 400 mA cm^{-2}, nearly the end of *I–V* curves, the cell voltage with functional micro-features could maintain upper 0.4 V. However, without the functional micro-features, the cell voltage decreases toward 0.35 V. Also, from the maximum power density point of view, the cell with functional micro-features is 173 mW cm^{-2} much higher than without. These results indicated that, all the tests, without functional micro-features, the internal flooding may be very serious. However, the cell with functional micro-features could improve the draining ability. The cell performance could thus be higher.

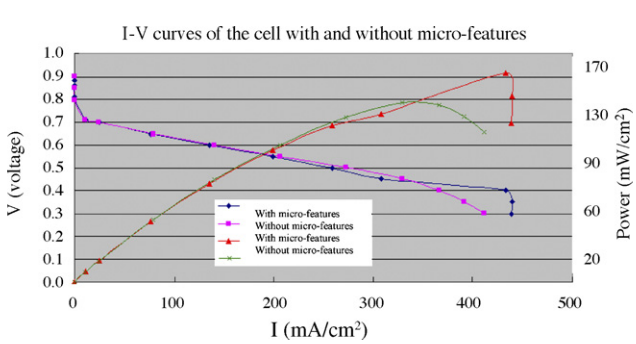


Fig. 13. Cell performance tests.

In order to study the stability in performance, the single cell with functional micro-features goes through continuous operation of 300 h. The cell is operated with a constant load of 0.4 V. Other settings are the same with those of cell performance tests. Fig. 14 shows long-term test results. During the duration, the cell power is maintained between 0.4 W and 0.55 W (75 mW cm^{-2} and 110 mW cm^{-2}) and temperature is between 49 °C and 52 °C. The cell power fluctuated are just slightly.

These results indicated that the functional micro-features have greatly improved the cell-draining capability. The effect of cell internal flooding is not obvious. Therefore, the cell performance is very stable.

4. Conclusions

1. Through the UV–LIGA and electroforming process, the high mechanical strength and good electrically conductivity metallic bipolar plate and miniature fuel cell had been

developed. The reaction area of the prototype of single cell was 4 cm^2. The overall size was 16 cm^2 with thickness of 2.6 mm.
2. Through numerical simulation, it was concluded that the micro-features could provide a more uniform gas concentration environment in the bipolar plate flow field. Thus, the cell performance could be improved.
3. From results of water-draining tests, regardless of gas flow rate, the bipolar plate with micro-features could greatly improve cell-draining capability.
4. The results of cell performance tests show that the cell average power density has reached 195 mW cm^{-2}. The long-term tests also verify their stable performance.
5. The proposed manufacturing procedures proved to be a promising technology in producing metallic bipolar plates with micro-features.

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