International Journal of ELECTROCHEMICAL SCIENCE www.electrochemsci.org

Enhanced Mass Transfer Properties of Porous Nickel Foam as Flow Field for Fuel Cells under Different Working Conditions

Yuzhen Xia, Hui Zhu, Zichen Wang, Feifan Sun, Yousheng Xu, Guilin Hu^{*}

Zhejiang University of Science & Technology, School of Mechanical and Energy Engineering, Hangzhou 310023, China *E-mail: <u>enehgl@163.com</u>

Received: 11 April 2021 / Accepted: 6 June 2021 / Published: 30 June 2021

High-porosity metal foam, with the advantages, such as low price, good electrical and thermal conductivity, performs high performance as flow field for fuel cells. The mass transfer properties of porous metal foam (PFM) flow fields were investigated under different working temperature and humidity conditions. Fuel cells with both of PFM1 and PFM2, with the area density of 765 and 1500g·m⁻², respectively, maintained high performances at various states; comparatively that with serpentine flow field (SFF) showed obvious voltage drops at dry and flood state. The area density influence was also discussed, and PMF2 released the largest power density of 96.7 mW·cm⁻², which is 157% of SFF. Its mass transfer ability was further studied in flooding situation, with 34% of the flow field volume occupied with water. The porous structure not only enabled the PMF flow field well anti-flood ability, but also the extra water stored in the pores could humidify the membrane at dry state.

Keywords: Fuel cell; Metal foam flow field; Humidity; Area density.

1. INTRODUCTION

Polymer electrolyte membrane (PEM) fuel cell is one of the most promising power sources for zero-emission vehicles, generating electricity from hydrogen to driving vehicles and storing in batteries or ultra-capacitors [1-2]. The reactant gas hydrogen/air is supplied to the two sides of bipolar plate and distributed on the surface of anode and cathode, respectively. Bipolar plate, used as current collector and flow field for reactants, contributes more than 70% of the weight and more than 40% of the cost of fuel cells [3-4]. A flow field plate is a good conductor of electron and heat, and functions as distributor of gas reactant, channel for liquid product removal, and support for membrane electrode assembly (MEA) [5-8]. The commonly used flow fields, including single-channel, serpentine, have been reported to have low performance in water management and high pressure loss in the flow field, leading to unstable cell

performance and short life [9-11]. Consequently, the flow field design optimization correlates with the efficiency of heat and mass transfer, which determines the improvement in power density and lifetime.

Porous metal foam (PMF), with high mechanical properties, low weight, high strength, high rigidity and large surface area per unit volume, is an ideal heat transfer and heat management medium [12-14]. It has also been regarded as one of the most important replacement for the conventional flow distributor for commercial fuel cells. The application of PMF in fuel cell as flow field, could enhance the transfer of gas reactant and reduce the pressure loss [15-27]. As early as 1998, Murphy et al. [19] invented a low-cost, light PEM fuel cell stack, with two flat porous metals, nickel foam and expanded titanium, embedded into the anode and cathode end plates as flow field materials, respectively. The utilization of PMF as flow field could reduce the weight and the costs of the fuel cell stack. More importantly, the porous structures brought sufficient gas path and uniform flow distribution on the surface of the GDL and prevented laminar flow, therefore concluded better performance than graphite flow field. The fluid performance in PMF was further optimized by optimizing the characteristics of metal foam, such as permeability, pore size, porosity, etc. Shin et al. [24] studied the effect of metal foam pore size and reported that 50.6% increase in maximum power of fuel cell was obtained by using 800 µm metal foam. Mixed metal foam (800µm and 580µm) was recommend as the flow path and 60.1% increase was achieved. Awin et al. [25] found that the aluminum-foam flow field having the lowest foam porosity of 68.3% at the anode produced the best performance, with the increase in performance was ordered according to decreasing porosity of the metal-foam flow field at the anode. However, in the work of Afshari et al. [26], the current density increased with the increase of metal foam porosity. The results from different laboratories often conflicts with each other. Compression is a common method to obtain PMF in different thickness, porosity or area density. Nevertheless, pore size in-plane direction decreases due to the compression, which also effects the results in parameters discussion [27]. The dependence on porosity and area density of PMF calls for further study and experimentation. Generally, the threedimensional structure with high porosity (>90%) and proper pore size is required, and also high area density is essential to ensure sufficient strength of flow field and high interface contact surface.

Ni foam, which is a widely used industrial material, with the advantages of low price and easy processing, is an ideal candidate for flow field. In this work, Ni foam flow field with high porosity above 96%, area density from 765 to 1500 g·m⁻² were used as the flow field in both anode and cathode. The Ni foam with different area density, corresponding to different contact surface area, was found to behave different ohmic and mass transport properties in fuel cell reactions. The cell performances of PMF flow field were compared with that of serpentine flow field under different temperature and humidity conditions. The mass transport ability of PMF flow field was further discussed when 1.5 g water added to the anode and the cathode, respectively.

2. EXPERIMENTAL

The catalyst coating membrane (CCM, Jiangsu Hydrogen Fuel Cell Co., Ltd., China) is made of GORE-SELECT[®] membrane and catalyst layer which has 0.25 mg·cm⁻² platinum loading for anode side and cathode side. The GDLs (Wuhan WUT New Energy Co., Ltd., China) used in this experiment has a

micro porous layer (MPL) treated with PTFE. The membrane electrode assembly (MEA) was prepared by hot pressing at 135°C, 0.15MPa, for 3 minutes.

The single cell, containing end plates, flow fields, gaskets and MEA, was assembled and tested at ambient pressure. Each end plate, made of stainless steel 316, with a groove in the center, was used as the current collector and also the holder for flow field. The size of the groove and flow field was 30 mm × 30mm × 5 mm. The graphite serpentine flow field (SFF) contained 11 channels with length 22 mm × width 1.5 mm × depth 1.5 mm, as shown in Figure 1. Two pieces of SFF were inserted into the end plates at anode and cathode, respectively, to investigate the performances of conventional flow field. The effect of area density of Ni foam flow field (Suzhou Taili Foam Metal Factory, China) was discussed between PMF1 (765 g·m⁻²) and PMF2 (1500 g·m⁻²). The detailed parameters of the three flow fields were given in Table 1, with some calculation explained in the following part.



Figure 1. Three flow fields (SFF, PMF1 and PMF2) for PEM fuel cell

	SFF	PMF1	PMF2
Size of path/mm	1.5 (width)	0.45 (diameter)	0.45 (diameter)
With of rib/mm	0.5	0.08	0.14
Area density /g·m ⁻²	-	765	1500
Contact area·cm ⁻²	4.9	4.6	5.9
Porosity /%	-	98.3	96.6
Flow field volume /cm ³	0.54	4.4	4.3

Table 1. The physical parameters of flow fields

The test system was composed of the following components: cylinders of compressed hydrogen and nitrogen, air compressor, two flowmeters, bubbler humidifier, heating elements and the single cell. The bubbler humidifier, immersed into a water bath, was used as the for humidifying air supplied to the cathode. The humidity temperature was equaled to the temperature of the water bath, at 50°C. The fuel cell temperature (T_c) was controlled by the heating elements, at 30°C, 40°C, 50°C and 60°C, respectively. At first, N₂ was used to purge the system at a flow of 200 mL·min⁻¹ at 2 bars for 10 min. Hydrogen and air were supplied to the anode and cathode, at 2 bars, with flow rate of 50 mL·min⁻¹ and 100 mL·min⁻¹, respectively. To investigate the mass transfer performance of flow field at flood state, 1.5g deionized water was added to PMF2.

The chronopotentiometry procedure has been applied on an Electronic load (FT6302A, Shenzhen Feisitaike Technology Co., Ltd, China), by adjusting the potential variations from the open circuit voltage to 0.25V. Every cell voltage step was lasted for 5s and the current density was recorded. The electrochemical impedance spectroscopy (EIS) was carried on an electrochemical analyzer (CHI604E, Shanghai Chenhua Instrument Co., Ltd, China) at 0.8 V with 5 mV amplitude in the frequency range of 10kHz to 50mHz.

3. RESULTS AND DISCUSSION

Nickle foam is a three-dimensionally porous material with large interconnected pores and high electrical conductivity. The microscopic diagrams of PMFs show that the cell shape is irregular, mainly pentagons and hexagons, in Figure 2. The shape of pore is mainly ellipse or consistent with the cell. The contact area has been calculated based on the assumption that regular hexagon cells with circular pore spread on a 9 cm² surface evenly. Their porosity parameters are given in Table1. Because of the larger area density of PMF2 than that of PFM1, the rib width of PMF2 is larger, and therefore brought larger contact area [31]. The contact area of SFF has also been estimated, which is slightly higher than that of PMF1.

The equation for calculating the porosity and the path volume of PMF flow field is as follows.

$$P = (1 - \frac{\rho_{PMF}}{\rho})$$

where ρ_{PMF} is the density of PMF with a thickness of 5mm, and ρ is the density of metal nickel, 8.9g/cm³.

The flow field volume of PMF is obtained by multiply the porosity and the subtract volume, with the dimension of length 30 mm × width 30 mm × depth 5 mm. Their value is around 7.5 times larger than that of SFF, indicating the presence of large number of flow path for the gas reactant in the porous structure. Higher contact area of SFF could promote the transfer of electron, but reduce the gas path, therefore increase the pressure drop [28]. As well as the conventional flow field in bipolar plates, PMF flow field played a role in transporting reactants and water through the channel and in providing an electrical connection through the ribs. The metal ribs in PMF brought a low intrinsic electrical conductivity and large contact area with GDL. Meanwhile, the internal 3-D porous structure perfectly resolved the problem in conventional 2-D flow field that high contact area resulted low occupation of the channels, which led to restricted mass transport of the reactant and product [29].



Figure 2. Microstructure diagrams of Ni porous foam (PMF1 and PMF2)

The relative humidity of the outlet gas has been used to estimate the work humidity of fuel cell:

$$\Phi = P_w/P_{sat}$$

where P_w is the partial pressure of water, and P_{sat} is the saturation vapor pressure of water, a function of temperature. Because the inlet air in cathode has been well humidified in the bubbler humidifier, Φ_{in} is equal to 100%. The value of $P_{w,in}$ is equal to the value of P_{sat} at 50°C, 12.35 kPa. The following equation shows the proportion of water vapor in the inlet air.

$$\varphi = P_{w,in} / (P_{in} - P_{w,in})$$

Therefore, the partial pressure of water vapor in the outlet gas is:

$$Pw, out = \frac{(0.420 + \varphi\lambda)P_{out}}{(1 + \varphi)\lambda + 0.210}$$

where λ is the stoichiometric ration of air, around 5 in this test.

The obtained relative humidity of the outlet gas at various T_c is given in Table 2. The value decreases as T_c increased from 30°C to 60°C, indicating the operating humidity conditions at flood state (30°C), moderate state (40°C and 50°C), and dry state (60°C), respectively.

	30°C	40°C	50°C	60°C
Ф/%	320	184	110	68.2

Table 2. Relative humidity of outlet gas under different working temperature

The effect of T_c on the polarization properties of fuel cells with different flow fields was first investigated. As shown in Figure 3, the cell performances increased first as T_c increased from 30 to 50°C, and then decreased. The value of maximum power density (P_{max}) at 50°C was 61.4mW·cm⁻² (SFF), 65.4 mW·cm⁻² (PMF1), 96.7 mW·cm⁻² (PMF2), respectively. Both of the two single cells with PMF flow field released larger electricity than that with SFF used. The slope of Voltage-Current density increased rapidly with current density above 0.20 A·cm⁻², indicating larger mass transfer resistance at higher current density in SFF [25]. The low flow field volume of SFF restricted large amount of reactant transportation, which was not observed in the PMF flow field.

The water management properties of flow filed might influence the performance and durability of fuel cells. Obvious reduction in cell performances was depicted in SFF fuel cell at low temperature with high humidity and high temperature with low humidity. At $T_c=30$ °C, while the fuel cell worked under water flooding conditions, excess water in the flow field bought by the highly humidified cathode gas extremely hindered the reactant accessing to the electrode. The P_{max} value of SFF- fuel cell was only 18.4 mW·cm⁻². Comparatively, PMF-fuel cells showed higher P_{max} , 64.7 mW·cm⁻² (PMF1) and 93.0 mW·cm⁻² (PMF2), which was 98.9% and 96.1% of the value at optimal conditions ($T_c=50$ °C). PMF flow field with high porosity could provide large number of channels gas reactant and water, to ensure high transfer ability under flooding conditions.





Figure 3. The polarization curves of three flow fields (SFF, PMF1 and PMF2) at various working temperature

When T_c reached to 60°C, the cell performances could be enhanced due to low electrochemical resistance at high temperature. However, the low relative humidity of the outlet gas revealed the dry state in the fuel cell. An increase in proton transport resistance was observed due to the fact that

membrane became less hydrated and its proton conductivity got low [25]. Therefore, the low humidity state led to a decline in P_{max} . Compared to SFF, higher P_{max} was obtained as PMF flow field used, at 61.9 mW·cm⁻² (PMF1) and 92.7 mW·cm⁻² (PMF2), respectively. Excess water might be stored in the porous structure to wet the membrane under dry condition.

The electrochemical performances of fuel cells with different flow fields were investigated under various T_c by EIS. The Nyquist plot tested at 0.8V, appeared to be a semicircle at low current density in Figure 4. Based on Randles equivalent circuit, the intersection value at Z' axis, was equal to the value of R_{Ω} , the ohime resistance. Otherwise, the diameter of the impedance loop, was attributed to the charge transfer resistance, R_{ct} [30]. The membrane resistance and contact resistance contributed the main part of ohmic impedance. The SFF and PMF2 fuel cells had very close R_{Ω} at $T_c=30^{\circ}$ C, around 0.029 $\Omega \cdot \text{cm}^{-2}$. PMF1 with the lowest contact area showed a R_{Ω} , 0.032 $\Omega \cdot \text{cm}^{-2}$, slightly larger than the inferior two. The membrane resistance was related to the water content in the membrane. At 0.8V, with current density around 0.02 A·cm⁻², little amount of water was produced in the cell. The state of membrane was directly affected by the cell humidification. It has been proved that porous metal foam could prevent excessive water evaporation phenomenon and resulted lower ohmic losses also well-hydrated membrane of the fuel cell [32].







Figure 4. The impedance spectra of three flow fields (SFF, PMF1 and PMF2) at various working condition

The impedance plot shrunk as T_c increased from 30°C to 50°C. At low current density, the electrochemical reaction rate was mostly controlled by the electrochemical activation rate. As T_c increased, the speed of electrochemical reaction increased, and therefore the diameter of the impedance spectrum decreased.

The lowest R_{ct} was obtained by the single cell with PMF2 at 50°C. Due to its higher contact area than that of PMF1, PMF2 had lower R_{ct} , which was consistent with the results presented in polarization curve. When T_c arrived 60°C, the diameter of the impedance loop began to enlarge because of less efficiency of membrane at dry condition.

The mass transfer performance of PMF flow field at flood state was further studied with 1.5g water added to PMF2 flow field in anode and cathode, respectively. The fuel cell test was carried out at a constant voltage of 0.5V under $T_c = 60^{\circ}$ C without humidification. In the blank experiment without water addition into the flow field, the current density decreased rapidly because of the low performance of membrane at dry state. After water added into the flow field, the current density first decreased as the mass transfer was restricted. As the fuel cell test undergoing at constant voltage, the current density increased slightly and achieved a saturated state. The water in the flow field was brought into MEA and therefore humidified the membrane. As water exhausted, the cell went to dry state. The polarization curves at initial state and saturated state were shown in Figure 5.

Compared with no obvious decline observed in fuel cell properties as 1.5g water in anode, the cell performances decreased dramatically as the same amount of water in cathode. The introduction of 1.5g water, which occupied around 34% of the flow field volume, brought larger influence in the cathode as larger amount of air was required for the electrochemical reaction. As water was brought out of the fuel cell by the outlet gas to release gas transfer channels and PEM was humidified gradually, the current density at 0.5V increased slightly. The value of P_{max} at saturated state was 115.1 mW·cm⁻² (anode) and 105.4 mW·cm⁻² (cathode), respectively. Therefore, the porous structure of PMF was proved to enhance the flow transportation in flood state, and water stored in capillary pore could humidify PEM at dry state.



Figure 5. Polarization performances of PMF2 fuel cells with 1.5g water in the anode (a) and in the cathode (b)

The metal foam flow field performances in flood state were further investigated by EIS test. The Nyquist plots tested at 0.8V and 0.7 V is shown in Figure 7, after water addition into PMF2 at the anode

or at the cathode. In the case of anode flooding, the water loss of member at 60°C at the initial state without extra humidification resulted higher membrane resistance. As the water stored in the anode humidified PEM and achieved the saturated state, both of the value of R_{Ω} and R_{ct} decreased. In the case of a high amount of water retention in the cathode, a relatively high initial resistance was also depicted. Because of water evaporation and outlet removal with the excess reactant, the mass transfer was highly enhanced at saturated state. And also lower R_{Ω} and R_{ct} was shown because of the well humidification of membrane and higher charge transfer efficiency.





Figure 6. Nyquist plots of PMF2 fuel cells with 1.5g water in the anode tested at 0.8V (a), at 0.7V (b); and in the cathode tested at 0.8V (c), at 0.7V (d)

Higher liquid saturation in the membrane was mainly due to the larger water transport resistance with the smaller hydrophobicity of PMF. The enhanced suction capability of the metal foam with a less hydrophobic indicates a self-humidified PEM fuel cell design [33].

4. CONCLUSIONS

The performance of a PEM fuel cell is sensitive to humidification because of the strong dependence of proton conductivity on water content in catalyst layer and membrane. The utilization of conventional 2-D flow field where high contact area results low occupation of the channels, contributes the difficulty of water management. SFF released a maximum power density only 30.0% at flood condition and 63.2% at dry condition of the value at optimum situation. The metal foam nickel flow field (PMF1 and PMF2, with an area density of 765 and 1500 g·cm⁻², respectively) performed good temperature and humidity adaptability. The maximum power density of PMF1 maintained from 61.9 to 65.9 mW·cm⁻², PMF2 from 92.7 to 96.7 mW·cm⁻². The internal 3-D porous structure of metal foam flow field could perfectly resolve the problem and highly improve the mass transport of the reactant and water removal at various situations. Compared with PMF1 fuel cell, PMF2 fuel cell with higher contact area and lower ohmic resistance released more power in the electrochemical reaction. Also, PMF2 flow field behaves high mass transfer properties at flood state, especially as 1.5g water addition in the anode. Meanwhile, the water stored in the pores could humidify the membrane and enhance the cell performances at dry state. Both of the ohmic and charge transfer resistance reduced at saturated state in Nyquist plots, which further proved the high performances of PMF flow field in water management.

ACKNOWLEDGMENTS

We gratefully acknowledge the support from Department of Education of Zhejiang Province (No. Y201839674) and the support from the National Nature Science Foundation of China (No. 11972324).

References

- 1. Y. Manoharan, S.E. Hosseini, B. Butler, H. Alzhahrani, B.T.F. Senior, T. Ashuri and J. Krohn, *Appl. Sci.*, 9 (2019) 2296.
- 2. S. Ahmadi, S.M.T. Bathaee and A.H. Hosseinpour, Energy. Convers. Manage., 160 (2018) 74-84.
- 3. R. Taherian, J. Power Sources, 265 (2014) 370-390.
- 4. Y.S. Song, C.Z. Zhang, C.Y. Ling, M. Han, R.Y. Yong, D. Sun and J.R. Chen, *Int. J. Hydrogen Energy*, 45.54 (2020) 29832-29847.
- 5. J. Wang, Appl. Energy, 157 (2015) 640-663.
- 6. K. Lim, N. Vaz, J. Lee and H. Ju, Int. J. Heat Mass Transfer., 163 (2020) 120497.
- 7. Y. Wei, T. Yong, X. Yang and Z. Wan, *Appl. Energy*, 94 (2012) 309-329.
- 8. Z. Bao, Z. Niu and K. Jiao, Appl. Energy, 280 (2020) 116011.
- 9. Y. Wu, J.I.S. Cho, T.P. Neville, Q. Meyer, R. Zeische, P. Boillat, M. Cochet, P. R. Shearing and D.J.L. Brett, *J. Power Sources*, 399 (2018) 254-263.
- 10. Y. Leng, P. Ming, D. Yang and C. Zhang, J. Power Sources, 451 (2020) 227783.
- 11. M. Mortazavi and K. Tajiri, Renew. Sust. Energ. Rev., 45 (2015) 296-317.
- 12. W.C. Tan, L.H. Saw, H.S. Thiam, J. Xuan, Z. Cai and M.C. Yew, *Renew. Sust. Energ. Rev.*, 96 (2018) 181-197.
- 13. S. Rashidi, M.H. Kashefi, K.C. Kim, and O. Samimi-Abianeh, *Applied Energy*, 243 (2019) 206-232.
- 14. L. Zhang, K.C. Zhou, Q.P. Wei, L. Ma, W.T. Ye, H.C. Li, B. Zhou, Z.M. Yu, C.T. Lin, J.T. Luo and X.P.Gan, *Applied Energy*, 233-234 (2019) 208-219.
- 15. F.S. Anuar, I.A. Abdi, K. Hooman and M. Odabaee, Exp. Therm. Fluid. Sci., 99 (2018) 117-128.
- 16. Z. Bao, Y. Wang, and K. Jiao, J. Power Sources, 480 (2020) 229150.
- 17. B.T. Tsai, C.J. Tseng, Z.S. Liu, C.H. Wang, C.I. Lee, C.C. Yang, and S.K. Lo, *Int. J. Hydrogen Energy*, 37 (2012) 13060-6.
- 18. T. Wilberforce, A.A. Makky, A. Baroutaji, R. Sambi and A.G. Olabi, *Power & Energy Conference*, (2017).
- 19. O.J. Murphy, A. Cisar and E. Clarke, *Electrochim.* Acta, 43(1998) 3829–3840.
- 20. Z. Bao, Z. Niu and K. Jiao, Int. J. Hydrogen Energy, 44.12 (2019) 6229-6244.
- 21. C.J. Tseng, B.T. Tsai, Z.S. Liu, T.C. Cheng, W.C. Chang and S.K. Lo, *Energy Convers. Manage.*, 62 (2012) 14-21.
- 22. S. Huo, N.J. Cooper, T.L. Smith, J.W. Park and K. Jiao, Appl. Energy, 203 (2017) 101-114.
- 23. C.J. Tseng, Y.J. Heush, C.J. Chiang, Y.H. Lee, and K.R. Lee, *Int. J. Hydrogen Energy*, 41 (2016) 16196-16204.
- 24. K.S. Dong, H.Y. Jin, G.K. Dong, and S.K. Min, Renew. Energy, 115 (2018)663-675.
- 25. Y. Awin, and N. Dukhan, Appl. Energy, 252 (2019) 113458.
- 26. E. Afshari, M. Mosharaf-Dehkordi and H. Rajabian, Energy, 118(2017)705-715.
- 27. J.E. Park, J. Lim, S. Kim, I. Choi, C.Y. Ahn, W. Hwang, M.S. Lim, Y.H. Cho and Y.E. Sung, *Electrochim. Acta.*, 265 (2018) 488-496.
- 28. H. Chen, H. Guo, F. Ye, and C.F. Ma, J. Power Sources, 472 (2020) 228456.
- 29. Z. Wan, Y. Sun, C. Yang, X. Kong, H. Yan, X. Chen, T. Huang and X. Wang, *Energy. Convers. Manage.*, 231 (2021) 113846.
- Y. Xia, T.T. Nguyen, S. Fontana, A. Desforges, and F. Lapicque, J. Electroanal. Chem., 724 (2014) 62-70.
- 31. J.E. Park, W. Hwang, M.S. Lim, S. Kim, C. Ahn, O. Kim, J. Shim, D.W. Lee, J.H. Lee, Y. Cho and Y.E. Sung, *I. J. Hydrogen Energy*, 44 (2019) 22074-22084.
- 32. D.G. Kang, C. Park, I.S. Lim, S.H. Choi, D.K. Lee, M.S. Kim, *International Journal of Hydrogen Energy*, 45 (2020) 27622-27631.
- 33. A. Jo, S. Ahn, K. Oh, W. Kim, H. Ju, International Journal of Hydrogen Energy, 43 (2018) 14034-

14046.

© 2021 The Authors. Published by ESG (<u>www.electrochemsci.org</u>). This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution license (http://creativecommons.org/licenses/by/4.0/).