Investigation of porous water transport plates used for the humidification of a membrane electrode assembly

Xiaoqian Guo, Yachao Zeng, Zhiqiang Wang, Zhigang Shao, Baolian Yi

Fuel Cell System and Engineering Laboratory, Dalian Institute of Chemical Physics, Chinese Academy of Sciences, Dalian, Liaoning 116023, China
Graduate University of Chinese Academy of Sciences, Beijing 100049, China

Highlights

- A novel porous hydrophilic acetylene black plate (HABP) is fabricated.
- The HABP possesses water permeability and gas blocking properties.
- The characteristics of HABP influencing water permeability are discussed.
- A transparent end plate allowing water circulation is designed.
- PEMFC performance under low humidity is improved by employing HABP as an anode plate.

Abstract

In this study, a novel porous hydrophilic acetylene black plate (HABP), possessing water permeability and gas-blocking properties, is employed as a water transport plate with which to improve the performance of a proton exchange membrane fuel cell under low-humidity. Porosity, tortuosity, hydrophilic pore size, hydrophilic pore fraction and wettability of the HABPs which may influence the permeated water flux, are measured by mercury intrusion, weighing and contact angle methods. By introducing nano-sized hydrophilic acetylene black (HAB) powders into the HABPs, the porosity, hydrophilic pore fraction and wettability increase, while the tortuosity and hydrophilic pore size decrease, which results in higher permeated water flux. By employing the HABP as an anode plate, the maximum power density of the cell is 194.3 mW cm$^{-2}$ higher than that with a conventional solid plate. The favorable performance of the cell indicates that the HABP is a promising plate material for water transportation.

© 2015 Published by Elsevier B.V.

1. Introduction

Proton exchange membrane fuel cells (PEMFCs) have been attracted much attention over the past decades due to their high power density, easy operation, high energy conversion efficiency and zero harmful emissions [1,2]. In order to maintain the performance of the cell, membranes are required to retain high humidity levels for adequate ionic conductivity, which is generally fulfilled by auxiliary humidifying devices. Nevertheless, the external devices bring a burden to fuel cell systems, especially for systems with constraints in size and portability. Thus, there is a growing awareness of the need to keep proper hydration of the membrane without external humidification.

Various approaches have been proposed in order to obtain appropriate water retention without the need for an external humidifying system. One of them is the modification of the membrane electrode assembly (MEA). Hydrophilic particles (e.g. SiO$_2$, TiO$_2$) with a capacity of water retention were doped into the membrane [3–10] or the catalyst layer [11–15] in order to endow the MEA with self-humidifying ability. In addition, higher cell performance under low-humidity can be achieved by employing a hydrophilic layer between the gas diffusion layer and the catalyst layer by virtue of a satisfactory water distribution in the MEA [16–19]. Another approach to optimize water management is to apply an improved flow field. Qi et al. [20] designed a cathode double-path-type flow-field utilizing adjacent outlet gas channels to moisten dry inlet gases. A more pervasive approach involves an integration of wicking components into the flow field [21–25]. The casted wicks absorbed the produced water and transported it...
to the inlet region in order to humidify the dry inlet gases, which significantly improved the cell performance under low-humidity. However, for those approaches discussed above, only internal water was regulated to achieve the water balance in the PEMFC. Due to the complex process of water transportation in the membrane coupled with diffusion and electro-osmotic drag (protons drag the water molecules), the optimum operation condition is difficult to achieve.

A promising approach to improve the cell performance under low-humidity is the usage of water transport plates (WTPs) [26–30], designed by the United Technologies Corporation (UTC). Different from conventional solid plates (SPs), the WTPs are made with porous materials, as shown in Fig. 1(a). When the gas streams are not saturated, the WTPs provide water to transport into the gas channels in an attempt to humidify them. Due to the participation of external water to regulate the water balance, the WTPs decouple the association of the cell performance and internal water transportation in the MEA, affording more control over the system.

In this study, a novel porous hydrophilic acetylene black plate (HABP), serving as a WTP, was fabricated using a hot compression molding method. Nano-sized hydrophilic acetylene black (HAB) powders with high conductivity were introduced to generate nano-sized hydrophilic pores for water transportation. Furthermore, the characteristics of the HABPs influencing the permeated water flux were discussed and the performance of the cell with varied HABPs under low-humidity was evaluated.

### 2. Experimental

#### 2.1. Preparation of HAB

In order to obtain hydrophilic acetylene black (HAB) powders, raw acetylene black (AB) nanoparticles (20 nm) were immersed in a strong acid solution for 24 h, in which the volume ratio of H$_2$SO$_4$:HNO$_3$ was 3:1. Subsequently, the HAB nanoparticles were washed with deionized water twice and dried at 100 °C for 24 h.

#### 2.2. Preparation of HABPs

The key property of the water transport plate is water permeability, which is affected by the structure of hydrophilic pores. The varied contents of HAB powders might lead to the different hydrophilic pore structures. To find the proper permeated water flux which is balanced with the electrical conductivity and flexural strength, the HAB powders with varied contents were mixed with graphite powders (KS75, 55.8 μm), carbon fibers (length 0.2 mm, diameter 11–15 μm), and phenolic resins using a roll milling method. Then the mixture was placed into a mold and HABPs were fabricated by a hot compression molding method under a pressure of 2 MPa at 150 °C for 20 min. Table 1 shows the compositions of samples.

#### 2.3. Characterization of HAB and HABPs

**2.3.1. Fourier transform infrared spectra (FT-IR) test**

In order to detect the hydrophilic groups on the surface of the HAB, infrared reflection measurements (Bruker, Tensor 27) were performed. The infrared spectra were recorded in the range of 650 cm$^{-1}$ – 4000 cm$^{-1}$ with a resolution of 4 cm$^{-1}$.

**2.3.2. Electrical properties measurement**

As the main role of collecting and conducting current, the HABPs should possess good electrical conductivity. To investigate the electrical conductivities of different HABPs, in-plane, through-plane electrical conductivities and interfacial contact resistances (ICRs) were measured. The in-plane electrical conductivity was examined with a four point probe detector (ST-2258A) that has a linear configuration with a spacing of 1 mm between the probes. The samples are cylinders with a diameter of 30 mm and a thickness of 1 mm.

A universal testing machine (WDW-1010) tested the through-plane electrical conductivity and ICR. A given current, fixed at 5 A, was applied to two gold-coated copper plates. Then the resistance was calculated according to the output voltages displayed by a multimeter (U3402A). The resistance calculated is the total resistance consisting of a bulk resistance (through-plane resistance) and two ICRs. In an attempt to isolate the bulk resistance and ICR, the HABPs with different thicknesses were tested in the experiment. Since the ICR stays the same, the through-plane resistance could be deduced from the total resistance measurements by performing a

---

Table 1

<table>
<thead>
<tr>
<th>HABPs</th>
<th>Weight fraction based on HABPs</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>HAB</td>
</tr>
<tr>
<td>A0</td>
<td>0</td>
</tr>
<tr>
<td>A5</td>
<td>5</td>
</tr>
<tr>
<td>A8</td>
<td>8</td>
</tr>
<tr>
<td>A10</td>
<td>10</td>
</tr>
<tr>
<td>A15</td>
<td>15</td>
</tr>
<tr>
<td>A20</td>
<td>20</td>
</tr>
</tbody>
</table>

A5 stands for 5% HAB nanoparticles added based on the weight of carbon plates.
series of experiments of various samples with different thicknesses [31]. Then the ICR could be acquired by subtracting the through-plane resistance from the total resistance.

2.3.3. Mechanical property measurement

As supporting materials, the HABPs should have sufficient mechanical strength. In order to characterize the mechanical properties, three-point bending tests were carried out by using a WDW-1010 according to ASTM D790-02 [33]. The size of all the samples was 28 mm × 10 mm. The support span was 20 mm with a cross-head speed of 1 mm min⁻¹.

Flexural strength can be calculated based on the following equation:
\[
\text{Flexural strength (MPa)} = \frac{3FL}{2WT^2}
\]
where \( F \) is the breaking force of the samples (N); \( L \) is the support span (mm); \( W \) is the width (mm); and \( t \) is the thickness of the samples (mm).

2.3.4. Bubble pressure measurement

The HABPs, serving as the water transport plates, should have the capacity to block gas leakage. To investigate the gas-blocking property, a bubble-point test was conducted using a home-made apparatus, as illustrated in Fig. 2(a). The HABP with a thickness of 1 mm and a diameter of 30 mm was incorporated into the apparatus and fastened by two rubber sealers. Nitrogen was fed into the bottom side of the apparatus and water was fed into the opposite side. Then the pressure of the gas chamber was gradually increased, until gas bubbles were observed in the water chamber. A magnifying glass was placed on the top of the apparatus for a better observation of the bubble formation.

2.3.5. Permeated water flux measurements

To evaluate the water permeability property of the HABPs, a permeated water flux test apparatus was designed, as shown in Fig. 2(b). A 30 mm diameter HABP sample with a thickness of 1 mm was placed between the water and gas chambers. A graduated pipette was connected with the water chamber and the decrement rate of liquid water in the pipette indicated the flow rate of water permeating through the samples. To simulate the cell operating condition, the pressure of the water chamber was set to 0.01, 0.02, 0.03 and 0.04 MPa, respectively, while the pressure of the gas chamber was fixed at 0.05 MPa with a nitrogen flow rate of 100 ml min⁻¹. The temperature of both water and gas chambers was fixed at 65 °C.

2.3.6. Contact angles measurement

To characterize the wettability property of the HABPs with different HAB amounts, contact angles were measured by a sessile drop method. Pure water droplets of 3 μL were dropped onto the surfaces of HABPs. Then contact angles were calculated by fitting a tangent to three-phase point using a drop shape analyzer (KRUSS).

2.3.7. Microstructure characterization

To investigate the effects of the HABPs’ microstructure characteristics on the water permeability property, open porosity, tortuosity, pore size distribution and hydrophilic pore fraction were measured. A weighing method was adopted to determine the hydrophilic pore fraction by immersing the HABPs in water at 80 °C for 8 h [32], and mercury porosimetry (PoreMasterGT 60) was used to measure the pore size distribution, porosity and tortuosity. A scanning electron microscope (SEM, JEOL JSM-7800F) was used to get an insight into the pore structures of the HABPs. To ensure the accuracy and reproducibility of the experimental results, three samples with the same HAB content were measured.

2.3.8. Single cell test

To characterize the effects of the water permeability property on cell performance, single cell tests under low-humidity were conducted. Pt/C catalyst inks (Johnson Matthey, 70 wt.%) were sprayed onto a Nafion® 212 membrane as anode (0.4 mgPt cm⁻²) and cathode (0.4 mgPt cm⁻²) catalyst layers with an active area of 5 cm². The HABPs possess parallel flow channels with the following dimensions: thickness of 1.3 mm, channel width of 1 mm, rib width of 1 mm and channel height of 0.3 mm.

To characterize the cell performance by employing the HABPs, a novel single cell system was designed, as shown in Fig. 1. The HABP was inserted into the anode end plate, while a normal solid plate was used on the cathode side. To make water have access to reach the HABP, the anode end plate was hollowed-out. circulating water in the water chamber passed through the hollowed-out channels of the anode end plate and reached the surface of the HABP. Due to the capillary force of the HABP, water permeated through the HABP from the water chamber in an attempt to humidify the unsaturated gas streams. To directly check the airtightness and gas barrier property of the HABP, an organic glass was mounted in the anode end plate as a window.

Hydrogen and air (anode/cathode) were supplied at flow rates of 100 ml min⁻¹/800 ml min⁻¹ at 0.05 MPa. These gases were humidified identically at 30% relative humidity (RH) [14] with the

![Diagram](attachment:image.png)
cell temperature kept at 65 °C. Circulating water at 65 °C was pumped into the water chamber and the pressure of the water chamber was adjusted to 0.03 MPa. Polarization curves were measured using a Kikusui electrical load (KFM 2030, Japan) to evaluate the cell performance. The steady state voltage values were collected by holding the cell at each current density for 10 s. Cell resistances were determined by applying electrochemical impedance spectroscopy (EIS, Solartron 1260 + 1287) at 100 mA cm$^{-2}$ and 1200 mA cm$^{-2}$.

3. Results and discussion

3.1. Infrared characterization of HAB

To evaluate the groups attached onto the acetylene black surface, infrared spectra were performed, as shown in Fig. 3. The peaks located at 2884, 2999 cm$^{-1}$ were attributable to the asymmetric and symmetric vibrations of C–H, and the peak at 1536 cm$^{-1}$ was ascribed to the vibration of C–C. For both AB and HAB, the three peaks were presented in the spectra, which proved that the carbon skeleton of the HAB was not seriously destroyed by the treatment of the strong acid. The absorption bands at 1095 cm$^{-1}$ could be assigned to the symmetric stretch vibrations of S=O [34], which verified the generation of hydrophilic sulfonic acid groups. Moreover, the broad resonant peak located at the range of 2900–3500 cm$^{-1}$ signified the presence of hydrophilic hydroxyl groups. The two hydrophilic groups (S=O and –OH) demonstrated that the HAB was obtained.

3.2. Physical properties of the HABPs

3.2.1. Electrical property of HABPs

To investigate the electrical property of HABPs, in-plane, through-plane electrical conductivities and ICRs of HABPs with varied HAB amounts were measured. As shown in Fig. 4(a), with the increase of HAB contents, the in-plane electrical conductivity decreased by a factor of 2.5, from 113.1 S cm$^{-1}$ to 44.4 S cm$^{-1}$ and the through-plane electrical conductivity also decreased from 175.4 S cm$^{-1}$ to 45.9 S cm$^{-1}$. As shown in Fig. 4(b), the higher the HAB content in the HABP was, the higher the ICR would be. One factor that contributes to the decrease of in-plane, through-plane electrical conductivities and the increase of ICRs with increasing HAB contents is the lower electrical conductivity of the HAB nanoparticles than that of graphite powders. Another factor might be the increased porosity with the increasing HAB contents, as shown below, which results in less electrically conductive paths.

3.2.2. Mechanical property of HABPs

In order to investigate the mechanical property, flexural strengths of different HABPs were measured. The flexural strengths of HABPs were 59.7, 46.2, 45.3, 40.1, 20.6, and 13.5 MPa for A0, A5, A8, A10, A15 and A20, respectively. With the increase of HAB contents, the flexural strength decreased apparently, since the existence of HAB nanoparticles increased the porosity of HABPs and made the composite fluffy, which is shown below.

3.3. Effects of characteristics of HABP on permeated water flux

The HABPs, as the water transport plates, should possess gas-blocking and water permeability properties. As for the gas-blocking property, when the HABPs were abounded in liquid water, the bubble pressure of each HABP was larger than 0.100 MPa, which was enough to prohibit gas leakage under the operating conditions of the fuel cell. As for the water permeability property, the results with various HABPs as a function of the differential
pressure between the water and gas chambers were displayed in Table 2. When the differential pressure remain the same, the permeated water flux of HABPs increased obviously with the increase of HAB contents, while for the HABPs with the same HAB content, the permeated water flux increased with the increasing differential pressure.

The water permeation through the water transport plate is a complicated process combining heat and mass transfers: the liquid water flows through the hydrophilic pores and vaporizes at the surface [27]. At a steady state, the permeated water flux is determined by the lower rate between the liquid water flow process and the evaporation process. In this work, the rate determination process is the liquid water flow process because the permeated water increased with the rising differential pressure between the supplied water and gas chambers, as shown in Table 2, otherwise, the water flux would remain constant.

The liquid water flow can be written in the same form as the Darcy's equation [35], with the capillary potential as the driving force. Therefore, the permeated water flux can be represented by the following equations:

$$Q = \frac{K A P}{\mu L} = \frac{K A (P_c + \Delta P_d)}{\mu L}$$  \hspace{1cm} (2)

$$P_c = \frac{2 \gamma \cos \theta}{r}$$  \hspace{1cm} (3)

where $Q$ is the permeated water flux, $K$ is the permeability, $A$ is the geometric area of the samples, $\mu$ is the viscosity, $L$ is the height, $\Delta P_d$ ($-0.02$ MPa) is the differential pressure between the supplied water and gas chambers, $P_c$ is the capillary force, $\gamma$ is the surface tension, $\theta$ is the contact angle, and $r$ is the pore radius. In Eq. (2), the permeability $K$, representing the ability of a porous media to transmit fluids, is determined by the geometric construction of the porous media. Therefore, the key factors affecting the permeability $K$ are porosity and tortuosity.

Thus, in terms of the equations above, the critical factors influencing the permeated water flux are porosity, tortuosity, hydrophilic pore fraction, wettabiliy and pore size, which will be discussed in detail below.

### 3.3.1. Effect of porosity and tortuosity on permeated water flux

As for the tortuosity and porosity, decreasing the tortuosity means dislodging the barriers for the water transporting from the water chamber to gas chamber, while the increase of porosity implies that there more passageways for water transportation are built. Therefore, the permeated water flux is proportional to the porosity and inversely proportional to the tortuosity. Because only hydrophilic pores allow water infiltration, the fraction of hydrophilic pores was determined by a weighing method. As shown in Table 3, with the increasing addition of the HAB, the porosity and hydrophilic pore fraction increased and the tortuosity decreased. Consequently, the permeated water flux of the HABP increased, which is in accordance with the experimental results listed in Table 2.

### 3.3.2. Effect of wettability on permeated water flux

According to the Eqs. (2) and (3), the more hydrophilicity the HABP is, the higher the permeated water flux will be. The wettability of HABPs was investigated using a sessile drop method. The contact angles were $111^\circ$, $92^\circ$, $89^\circ$, $83^\circ$, $78^\circ$ and $69^\circ$ for A0, A5, A8, A10, A15 and A20, respectively. This reveals that with the increase of HAB contents, the hydrophilicity of the HABP improved, which might be attributed to the increasing amount of the attached hydrophilic sulfonic and hydroxyl groups on the HAB. Consequently, the permeated water flux of the HABP increased due to the improved hydrophilicity, which is in line with the experimental data represented in Table 2.

### 3.3.3. Effect of pore size on permeated water flux

Based on the Eqs. (2) and (3), the hydrophilic pore size is also a critical factor to determine the permeated water flux. The pore size distribution of varied HABPs was measured using a mercury intrusion method. As shown in Fig. 5, the intrusion curves showed two pore zones, the micropores that were accumulated by the intrusion method. As shown in Table 3, with the increasing addition of the HAB, the porosity and hydrophilic pore fraction increased and the tortuosity decreased. Consequently, the permeated water flux of the HABP increased.

---

**Table 2**

<table>
<thead>
<tr>
<th>HABPs</th>
<th>$\Delta P = -0.04$ MPa (mg min$^{-1}$ cm$^{-2}$)</th>
<th>$\Delta P = -0.03$ MPa (mg min$^{-1}$ cm$^{-2}$)</th>
<th>$\Delta P = -0.02$ MPa (mg min$^{-1}$ cm$^{-2}$)</th>
<th>$\Delta P = -0.01$ MPa (mg min$^{-1}$ cm$^{-2}$)</th>
<th>RH % in fuel cell$^b$</th>
</tr>
</thead>
<tbody>
<tr>
<td>A0</td>
<td>0.17</td>
<td>0.25</td>
<td>0.39</td>
<td>0.5</td>
<td>48</td>
</tr>
<tr>
<td>A10</td>
<td>0.61</td>
<td>0.85</td>
<td>1.04</td>
<td>1.24</td>
<td>78</td>
</tr>
<tr>
<td>A15</td>
<td>0.89</td>
<td>1.06</td>
<td>1.32</td>
<td>1.69</td>
<td>92</td>
</tr>
<tr>
<td>A20</td>
<td>1.56</td>
<td>1.73</td>
<td>1.96</td>
<td>2.06</td>
<td>122</td>
</tr>
</tbody>
</table>

$^a$ The permeated water flux is measured at the differential pressure between water chamber and gas chamber.

$^b$ RH in fuel cell is calculated by Eqs. (4–6).

---

**Table 3**

<table>
<thead>
<tr>
<th>HABPs</th>
<th>Porosity (%)</th>
<th>Tortuosity</th>
<th>Fraction of hydrophilic pore (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A0</td>
<td>1.90</td>
<td>2.17</td>
<td>53.9</td>
</tr>
<tr>
<td>A5</td>
<td>7.63</td>
<td>2.15</td>
<td>83.9</td>
</tr>
<tr>
<td>A8</td>
<td>11.9</td>
<td>2.11</td>
<td>94.5</td>
</tr>
<tr>
<td>A10</td>
<td>13.1</td>
<td>2.09</td>
<td>97.3</td>
</tr>
<tr>
<td>A15</td>
<td>15.7</td>
<td>2.05</td>
<td>99.0</td>
</tr>
<tr>
<td>A20</td>
<td>19.6</td>
<td>1.89</td>
<td>99.8</td>
</tr>
</tbody>
</table>

**Fig. 5.** Pore-size distribution of the HABPs with varied HAB contents.
graphite powders, and the nanopores that were aggregated by the HAB nanoparticles. The nanopores consist of primary pores and secondary pores. The primary pores are identified with the space in and between the primary HAB nanoparticles in the agglomerate, and the secondary pores are those between the HAB agglomerates [36]. To further confirm the pore structures of the HABPs, SEM diagrams were measured. The results are shown in Fig. 6.

For the sake of clarity, according to the pore size distribution and SEM images, a granule packing model [36] representing the microstructures of the HABPs with the increasing HAB contents was established, as illustrated in Fig. 7. As for the A0 sample, the graphite powders with micron size accumulated under the suppression pressure of 2 MPa, which resulted in the formation of micropores (6.40 and 16.1 μm). When HAB nanoparticles were

![Fig. 6. SEM images of the HABPs with varied HAB contents (a) 0%, (b) 5%, (c) 8%, (d) 10%, (e) 15%, (f) 20%.

![Fig. 7. A schematic of internal pore structure of the HABPs.](image-url)
added, the nanoparticles covered the surface of graphite powders and filled the micropores accumulated by the graphite. As 5% HAB nanoparticles were added (A5), the HAB agglomerates dotted sporadically on the walls of the micropores as shown in Figs. 6(b) and 7(a), since there were too few HAB particles to promote the accumulation of the agglomerates, which led to an absence of secondary pores. With the increase of the HAB, the HAB agglomerates accumulated which made the secondary pores emerge in the samples of A8, A10, A15 and A20, as depicted in Figs. 6(c–f) and 7(b, c). For A8, it is not sufficient enough to make the micropores be full of HAB nanoparticles which resulted in the co-existence of micropores and nanopores. However, as for the A10 sample, because the micropores were filled with HAB nanoparticles, the micropores vanished. When the HAB nanoparticles were added continually, the HAB agglomerates got compacted and the secondary pore size reduced. Therefore, with the increase of the HAB, the average hydrophilic pore size of HABPs decreased. Consequently, the permeated water flux of HABPs increased, in keeping with the experimental results displayed in Table 2.

In summary, the increasing HAB contents led to the increase of the porosity, hydrophilic pore fraction, wettability and the decrease of the tortuosity, pore size, which resulted in increased permeated water flux.

3.4. Single cell test

In order to characterize the performance of the cell with a variety of HABPs, polarization curves with low humidity levels on both anode and cathode sides were evaluated.

Under low humidity conditions, theoretically, the dominant factor affecting the performance of the cell is the membrane resistance, which is related to the water content of the membrane. Moreover, the water content is influenced by the relative humidity of the inlet gas. By employing the HABP as an anode plate, the humidity of the hydrogen feed was improved due to the permeated water from the water chamber. The relative humidity levels corresponding to the additional water amount supplied by the HABPs was briefly calculated as follows:

\[
\text{RH} = \frac{P}{P_{\text{sat}}} = \frac{n}{n_{\text{sat}}} 
\]

\[
P_{\text{sat}}V = n_{\text{sat}}RT 
\]

\[
n = \frac{Q*A*t}{M_{\text{wat}}} 
\]

where \( P \) is the vapor pressure of water, \( P_{\text{sat}} \) is the saturation vapor pressure at 65 °C, \( n \) is the molar of water, \( n_{\text{sat}} \) is the molar of vapor water at 65 °C, \( Q \) is the permeated water flux of the HABPs measured experimentally, \( A \) is the area of the HABPs (7.5 cm²), \( t \) is the time in operation and \( M_{\text{wat}} \) is the molar weight of water. According to the Eqs. (4–6), the humidity levels of the hydrogen corresponding to the additional water amount supplied by the HABPs was calculated as follows.

Generally, contributed to the lower membrane resistance, the higher the humidity-level is, the higher the cell performance will be. Therefore, the performance of the cell with A20 should be the highest. Nonetheless, the cell with A10 and A15 performed better than that with A20. In order to explain the phenomenon above, EIS was measured at 100 mA cm⁻² and 1000 mA cm⁻², as shown in Fig. 8(b, c) and Table 4. At 100 mA cm⁻², the ohmic resistance of

![Fig. 8. (a) Polarization curves and electrochemical impedance spectra at (b) 100 mA cm⁻² and (c) 1000 mA cm⁻² with varied HABPs.](image-url)
Acknowledgment

This work was financially supported by the National High Technology Research and Development Program of China (Grant Nos. 2013AA110201-1) and the National Natural Science Foundations of China (Grant Nos. 61433013 and 91434131).

| Table 4 |
The fitting results of the resistances for the cells with varied HABPs.

<table>
<thead>
<tr>
<th>HABPs (ohm cm$^{-2}$)</th>
<th>100 mA cm$^{-2}$</th>
<th>1000 mA cm$^{-2}$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$R_{\Omega}$</td>
<td>$R_{\Omega} + \text{mt}$</td>
</tr>
<tr>
<td>A0</td>
<td>0.539</td>
<td>0.761</td>
</tr>
<tr>
<td>A5</td>
<td>0.535</td>
<td>0.745</td>
</tr>
<tr>
<td>A8</td>
<td>0.265</td>
<td>0.660</td>
</tr>
<tr>
<td>A10</td>
<td>0.255</td>
<td>0.655</td>
</tr>
<tr>
<td>A15</td>
<td>0.205</td>
<td>0.540</td>
</tr>
<tr>
<td>A20</td>
<td>0.255</td>
<td>0.555</td>
</tr>
</tbody>
</table>

$R_{\Omega}$: ohmic resistance, $R_{\Omega} + \text{mt}$: charge transfer resistance, $R_{\text{me}}$: mass transfer resistance.

the cell with A20, consisting of the membrane resistance, bulk resistance and ICR, was similar to that with A10 and higher than that with A15, which is ascribed to the higher bulk resistance and ICR of A20, as shown in Fig. 4. Owing to the higher humidity level, the charge transfer resistance of the cell with A20 is much lower than that with A10. Therefore, at 100 mA cm$^{-2}$, the order of the cell voltage is A15 > A20 > A10. With the increase of the current density, the membrane resistance decreased. This is ascribed to the increasing amount of the water generated from the oxygen reduction reaction, which weakened the effect of the membrane resistance on the cell performance. Thus, at high current density, due to the higher bulk resistance and ICR of A20, the ohmic resistance of the cell with A20 was higher than those with A10 and A15, which reduced the cell performance.

4. Conclusions

A porous hydrophilic acetylene black plate, employed as a water transport plate, was fabricated by the introduction of hydrophilic acetylene black nanoparticles. The increasing addition of the HAB resulted in the increase of the porosity, hydrophilic pore fraction, and wettability, and the decrease of the tortuosity and hydrophilic pore size, which increased the permeated water flux. Contributing to the permeated water from the water chamber for gas moistening, the cell performance under low-humidity was successfully improved by using the HABPs as the anode plates. The favorable performance of the cell indicates that the HABP is a promising plate material for water transportation.

References