Study of a PEMFC performance based on a novel current distribution measurement method

Guangsheng ZHANG* , Hong SUN∗, Liejin GUO*, Dehua SHANG*, Hongtan LIU∗,b

*State Key Laboratory of Multiphase Flow in Power Engineering, Xi'an Jiaotong University, Xi'an, Shaanxi 710049, China, lj-guo@mail.xjtu.edu.cn; zhanggs@mailst.xjtu.edu.cn
bDepartment of Mechanical Engineering, University of Miami, Coral Gables, FL 33124, USA, hliu@miami.edu

ABSTRACT:

With the novel and simple current distribution measurement gasket developed by MPFL, the performance of a single PEM fuel cell with serpentine flow field was investigated without modifying any of its components. Inhomogeneous current distributions were demonstrated clearly by the measurement results. Current distribution at different cell operating parameters, including reactant gas flow rate, reactant gas humidification temperature and cell operating temperature, were measured and the effects of such parameters were analyzed. Reactant gas flow rate exert effects on current distribution by influencing the reactant concentration distribution, while the critical effects of gas humidification and cell temperature is caused by their significant influence on water balance and water distribution in PEM fuel cell. To fully understand the combined effects of such factors, simultaneous measurement of current distribution, reactant distribution, temperature distribution and humidification distribution is necessary and will be helpful.

KEYWORDS: PEMFC, current distribution, measurement, gasket

1. Introduction

Proton exchange membrane fuel cell (PEMFC or PEM fuel cell) has a very promising future in portable, automotive and stationary power generation applications due to its high efficiency and low pollution. Great research efforts have been made to better understand its internal mechanism and improve its performance. Among those efforts, current distribution measurement is an important and helpful approach to studying the transport phenomena and the details of local performance in PEM fuel cells. Therefore, many techniques have been developed to measure current distribution in PEM fuel cells in the past 10 years. Cleghorn et al. [1] measured the current distribution in a PEM fuel cell by segmenting the flow field plate/current collector with printed circuit board (PCB) technology. Stumper et al. [2] developed three methods to measure the current distribution in PEM fuel cells, including partial membrane electrode assembly (MEA) method, sub-cell method, and current distribution mapping method. The sub-cell method was modified and further developed by Rajalakshmi et al. [3] and Liu et al. [4]. Wieser et al. [5] developed a Hall effect based technique using a magnetic loop array embedded in the flow field plate to measure current distribution in a PEM fuel cell. Then Geiger et al. [6] further developed this method by using closed-loop Hall effect current sensors and it allows an easy and highly flexible implementation. Noponen et al. [7] developed segmented flow field approach and measured the current distribution in a free-breathing PEM fuel cell. This method and its derivatives [8, 9, 10] are now popular techniques in measuring current distributions.

All the techniques mentioned above have obtained interesting results, but all of them require either specially designed fuel cells or modifications of collector plates and/or electrodes. Moreover, none of the existing method can be easily used in fuel cell stacks.

Recently, an innovative and simple technique named current distribution measurement gasket was developed in MPFL (State Key Laboratory of Multiphase Flow in Power Engineering, Xi'an Jiaotong University, China) and was used successfully in a single PEM fuel cell [11]. This current distribution measurement gasket can be used in an existing fuel cell without modification of any of its components. More importantly, this technique can be easily used to measure the current density distribution in any or every cell in a fuel cell stack. The measurement gasket is also low-cost and simple.

In this work, the performance of a single PEM fuel cell with serpentine flow field was studied base on the current distribution measurement gasket technique. With current distribution data obtained, detailed information about the effects of operating parameters, like gas flow rate and humidification etc. were investigated and discussed.
2. Experimental

2.1 Current distribution measurement gasket

Schematic diagram of the current distribution measurement gasket is shown in Fig.1. The current distribution measurement gasket is basically a dielectric substrate with slots forming a pattern of the flow field in the measured fuel cell. Top surface of the areas corresponding to flow field shoulders, as marked by Goldfoil strip in Fig.1, is plated with copper and then gold for conducting local currents laterally out of the fuel cell. At the end of those strips, terminals are made for connecting the strips and potentiostat. Two alignment holes are used for ensure good alignment of the measuring strips with flow field shoulders.

Fig.2 is a photo of the current distribution measurement gasket used in this study, which is put on the anode flow field plate. Substrate of the current distribution measurement gasket is made of epoxy glass, which is cheap and common material in PCB industry. 23 measuring strips are used in this work, corresponding to the flow field of the fuel cell being studied. They are numbered sequentially from gas inlet to the outlet as shown in Fig.1. Plated copper layer and gold layer on surface of the measuring strips are 30 µm and 2 µm in thickness respectively. Overall dimension of the gasket is 108 mm in length, 76 mm in width and 0.2 mm in thickness. Slots in the gasket are 40.0 mm in length and 0.75 mm in width. Strips are 0.95 mm in width. It can be seen that the 24 slots and 23 strips in the gasket match flow channels and shoulders in the flow field very well.

2.2 How the current distribution measurement gasket works

As is shown in Fig. 3, the current distribution measurement gasket is inserted between flow field plate and GDL (gas diffusion layer) in the anode side, considering that hydrogen in the anode transfers and reacts more easily and would be influenced less by the gasket than air in the cathode. Gold plated surface of the gasket faces and contacts the GDL. Since the gasket substrate is dielectric, measuring strips are insulated from each other and from the flow field plate; thus, the fuel cell is electrically divided into 23 local areas. Local currents from the 23 measuring strips are conducted out of the fuel cell laterally instead of to the flow field shoulders. Since the current density gradient across the fuel cell is small, symmetry can be assumed. Therefore, each measuring strip measures the current from a local area covering one shoulder and two half-channels except numbers 1 and 23, measuring area of which covers one shoulder plus one and one-half of a channel. Two alignment holes and careful cell assembly ensures good alignment of the measuring strips with the flow field shoulders. In addition, uniform compression is important to minimize errors due to non-uniform contact resistance.

Fig.3 Schematic diagram of the position of the current measurement gasket in a PEM fuel cell
2.3 Current distribution measurement system

Fig. 4 is a flow chart of the experimental system for current distribution measurement of PEM fuel cell. Operating parameters are controlled and measured by a fuel cell test system from Fuel Cell Technologies, Inc., which regulates reactant gas flow rate, fuel cell operating temperature, reactant gas humidification temperature and operating backpressure. Hydrogen and air/oxygen flow rates are controlled by two mass flow controllers and their respective humidities are controlled by regulating the temperature of water inside the humidifier. The operating pressures are regulated by the backpressure regulators. A nitrogen purging system is incorporated into the experimental system to purge both the anode and cathode sides before and after experiments to ensure safety. Currents from the 23 measuring strips are measured by a 24-channel potentiostat with high resolution from Arbin Instruments.

With the measurement system, the performance of a single PEM fuel cell with an active area of 16 cm$^2$ was investigated. Nafion™ 112-based CCM (Catalyst coated membrane) with a thickness of 54 µm was used and loadings of catalyst Pt are 0.4 mg/cm$^2$ for both sides. Toray carbon fiber paper “TGP-H” with thickness of 375 µm was used as GDL in both anode and cathode sides. The flow field plates were made of graphite, and identical single serpentine flow channels with 23 shoulders were carved in both plates. Overall dimension of the flow field plate is 76 mm × 76 mm. Width of the flow channels is 0.75 mm and the depth is 1 mm. Width of the shoulders is 0.95 mm and the length is 40 mm. The end plates were made of copper. Detailed information of the fuel cell is listed in Table 1. Pure hydrogen (99.99%) and commercial air ($V_{N2}: V_{O2} = 79:21$) were used as fuel and oxidant respectively. Parallel flow (co-flow) is used for hydrogen and air in all the experiments reported in this study.

<table>
<thead>
<tr>
<th>Table 1. Geometric parameters of the experimental fuel cell</th>
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<tr>
<td>Active area (cm$^2$)</td>
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<tr>
<td>Channel length (mm)</td>
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<td>Channel width (mm)</td>
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<td>Shoulder width (mm)</td>
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<td>Channel depth (mm)</td>
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<td>Number of flow channels</td>
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<td>GDL thickness (µm)</td>
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<td>CCM thickness (µm)</td>
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3. Results and discussion

Since measuring strip numbers 1 and 23 measure the current from a larger area of one-half of a channel than strip numbers 2 to 22, only the local currents measurement data from strips 2 to 22 are used in the result presentations and analysis. Even though the current data from strip numbers 1 and 23 are not used in the final result analysis, these two strips must be put in place and connected to the same potentiostat to ensure the validity of the symmetry assumption for the two adjacent measuring strips. To make the results comparable with the widely used form of current density, measured currents data were divided by the area per strip measures and converted into current density data.

3.1 Inhomogeneous current distribution

Fig. 5 shows current distribution at different cell voltages for the case of insufficient hydrogen. Humidification temperatures and fuel cell operating temperature were all set to be 343 K with backpressure set to be 0.10 MPa, which is typical setting of operating parameters for PEM fuel cells. It is demonstrated clearly in Fig.5 how the current distribution varies with cell voltages. When the fuel cell is at high voltage of 0.8 V, the current distribution curve is quite even. But as the cell voltage decreases, the current distribution curve becomes more and more uneven, indicating inhomogeneous current distribution in the PEM fuel cell. The inhomogeneousness of current distribution in this case is mainly caused by the decreasing hydrogen concentration along the flow direction and current distribution is more inhomogeneous at lower cell voltages. At a lower cell voltage, the activation overpotential is higher and thus the current density is higher, as indicated by result of strips close to the inlet in Fig.5. Higher current densities near the inlet cause faster hydrogen consumption and thus cause a lower hydrogen concentration downstream. At a certain point where the effect of reduced hydrogen concentration is greater than that of higher overpotential, the local current density at a lower cell voltage will become lower than those at a higher cell voltage; just as shown in Fig. 5, current densities at 0.4 V are even lower than those at 0.7 V for strips number 13 to 22. Current densities for strips 19 to 22 are nearly zero at 0.4 V, indicating the depletion of hydrogen in these areas.

To demonstrate the inhomogeneous current distribution in PEM fuel cell more clearly, current distribution measurement results for the case shown in Fig. 5 were plotted in the form of local polarization curves in Fig.6. For ease of reading, only 6 representative polarization curves were plotted instead of the entire 21. It’s clearly seen that strips number 2 and number 6 have typical overall polarization curve of PEM fuel cell with complete three overpotential regions (activation overpotential region, ohmic overpotential region and mass transport limitation overpotential region)\(^{[12]}\). While it is interesting to find that polarization curves for strips numbers 14, 18 and 22 go backward due to insufficient hydrogen instead of going forward normally like those for strips number 2 and 6. Note that the current distribution curves in Fig.5 are not monotonic increasing or decreasing. Sharp fluctuation at strip number 4 is probably caused by instrumental error from fabrication or assembly of the current distribution measurement gasket. While examining the overall profile of the curves in Fig.5, it can be seen that highest current densities appear in the middle part near inlet but not the inlet areas where the hydrogen concentration is highest, indicating that inhomogeneous current distribution in PEM fuel cell is caused not only by uneven reactant concentration, but also by other factors like water distribution, temperature distribution, etc. Effects of water distribution can be deduced partially from measurement of current distribution at different reactant gas humidification temperatures and different cell temperatures. While the effects of temperature distribution is difficult to investigate since there is no effective method for
measurement of temperature distribution in PEM fuel cell up to now. Therefore, it will be helpful to develop an effective method that is able to measure current distribution and temperature distribution in PEM fuel cells at the same time. Of course, it would be much better if the water distribution in PEM fuel cell can be measured together as well. Effects of some factors on current distribution in the PEM fuel cell, including gas flow rate, gas humidification and fuel cell operating temperature, were investigated and discussed as follows. During the investigation, all the parameters except the one being studied were kept unchanged.

3.2 Effects of reactant gas flow rate on current distribution

Fig. 7 shows the current distribution at 0.6 V for different air flow rates. Since hydrogen flow rate is set to be 300 sccm, equivalent to 2.69 A/cm², it is believed to be high enough to minimize the influence of insufficient hydrogen. It can be seen that local current densities generally increase with higher air flow rate and higher air flow rate also favors evenness of the current distribution curves. When air flow rate is at 50 sccm and 100 sccm, which are cases of insufficient air, the current distribution curves decrease steeply. Current densities in the areas near outlet even are almost zero for case of 50 sccm, indicating the depletion of oxygen. As the air flow rate increased to 1200 sccm and 1500 sccm, equivalent to 4.06 A/cm² and 5.13 A/cm² respectively, the current distribution curves are quite even, with the middle part being generally flat.

3.3 Effects of reactant gas humidification on current distribution

Reactant gas humidification, for both hydrogen and oxygen/air, is widely used in PEM fuel cell operation because fully humidification of proton exchange membrane is necessary for effective conduction of proton. But excessive water from reactant gas humidification and the reaction may lead to accumulation of liquid water, which could block effective transport of reactants to the active reaction sites and therefore lower the performance of PEM fuel cell. Thus it is critical to keep water balance in PEM fuel cell operation. In this study, effects of reactant gas humidification on current distribution were investigated.

Fig. 9 shows the effects of air humidification on current distribution. When air humidification temperature is 343 K, equal to that of hydrogen and cell temperature, pattern of the current distribution curve is similar to that in Fig.7 (Note: the two current distribution curves are not exactly the same although operating parameters are identical in both cases, because the MEA used in the work mentioned above was damaged due to excessive cell temperature during the investigation of cell temperature effect on current distribution. A new MEA consisting of exactly the same materials was assembled with the same procedure. Similarity between the two curves suggests the repetitiveness of the current distribution measurement.). However, when air humidification temperature is 323 K, 20 K lower than that of hydrogen and cell temperature, it can be seen obviously that the pattern of current distribution curve is much different from that of 343 K. The local current densities start very low and then increase along the flow direction until strip
number 10 instead of number 6 in the case of 343 K. Current distribution curves for air humidification temperature at 333 K has the same pattern as that of 323 K. This phenomenon is caused by the humidification variation along the flow direction. When air humidification temperature is low, the air is far from saturated, and therefore water in the membrane and cathode catalyst layer would be absorbed into the air. That will lead to partially dryness of the membrane and lack of water in Nation content in so called “three-phase activation zone”\cite{13} in cathode catalyst layer. Therefore, current densities in the areas where the humidification is insufficient will be lower than that in the case of fully humidification. As more water is produced along the flow direction, the humidification will increase and the performance gets better along the flow direction until to the place where water is excessive.

For the case of 343 K, the humidification is sufficient even from the inlet, so the decrease of oxygen concentration will play a role and leads to generally decreasing current distribution along the flow direction. When air humidification temperature is 353 K, the humidification is excessive and flooding will appear, which lowers the performance of PEM fuel cell, just as shown in Fig.9. Since humidification is sufficient for both cases of 343 K and 353 K, the two current distribution curves present similar patterns.

Effects of hydrogen humidification is shown in Fig.10 and it can be seen that current distribution curves in the cases of insufficient humidification have the same pattern as that in Fig.9, indicating the humidification variation along the flow direction in anode side. Compared with Fig. 9, it is found that the fuel cell performance in the cases of insufficient hydrogen humidification is better than that of insufficient air humidification. As is shown in Fig.10, local performance in some middle areas in case of 333 K is better than that in case of 343 K. This is probably caused by the combined function of electro-osmosis and back diffusion of water. It’s interesting to see that the curve in case of 353 K shows generally an opposite trend compared with that in Fig.9. This can be attributed mainly to the effect of electro-osmosis of water. Water is transported from anode side to cathode side through the membrane due to electro-osmotic drag and therefore the water concentration in the anode is decreasing along the flow direction. Since there is excessive water in anode in this case, decrease of water will moderate the flooding and therefore improves the performance. Inspired by this phenomenon, it is presumed that proper excessive humidification of hydrogen and insufficient humidification of air may lead to good performance of PEM fuel cells.

3.4 Effects of cell temperature on current distribution

Fig.11 shows current distribution at 0.6 V in cases of different cell temperatures. The result in Fig.11 is generally consistent to that in Fig.9 and Fig.10 since variation of humidification temperatures and cell operating temperature both influence the water distribution and water balance in PEM fuel cell. Higher cell temperature may favor the reaction rate in PEM fuel cell, but the influence on reaction rate is not as significant as that on water balance and water distribution according to the result in Fig.11. When cell temperature is lower than or equal to gas humidification temperatures of 343 K, which means sufficient or excessive humidification. The current distribution curves present similar trend as that in Fig.9. The overall performance improves with higher
cell temperature since higher cell temperature moderates the influence of excessive humidification. When
cell temperature is 353 K or 363 K, higher than 343 K, the humidification will be insufficient. Therefore, the
current distribution curves show convex patterns, i.e. currents increase along the flow direction to certain
places and then start decreasing.

4. Conclusions

With the novel and simple current distribution measurement gasket developed by MPFL, the
performance of a single PEM fuel cell with serpentine flow field was investigated without modifying any of its
components. Current distributions at different operating parameters were measured and effects of operating
conditions on current distribution, including reactant gas flow rate, reactant gas humidification temperature
and cell temperature were investigated. Based on the measurement results and analysis, the following
conclusions can be drawn.

- Current distribution in the PEM fuel cell is inhomogeneous, which lowers the overall performance. The
  inhomogeneity of current distribution is caused by many factors, like uneven reactant
  concentration, water distribution and temperature distribution in the PEM fuel cell. To better understand
  the combined effects of these factors on current distribution, which shows the performance of PEM fuel
cell in details, simultaneous measurement of current distribution, reactant distribution and temperature
distribution as well as humidification distribution is necessary and will be helpful.
- Reactant gas flow rate exert effects on fuel cell performance and current distribution because the gas
  flow rate influences significantly the reactant concentration and distribution. Higher gas flow rate leads
to better performance and more homogeneous current distribution, while insufficient reactant gas flow
  rate may lead to very poor performance in outlet areas due to depletion of oxygen or hydrogen. Current
distribution curve for insufficient hydrogen case is much steeper than that for insufficient air case
  because hydrogen transfers and reacts much more easily than oxygen in the air.
- Reactant gas humidification has critical effects on cell performance and current distribution, mainly
  because the humidification influences the water balance and water distribution in PEM fuel cells.
  Insufficient gas humidification leads to poor performance near the inlet areas while excessive
  humidification would lower the overall performance. Current distribution in case of excessive hydrogen
  humidification presents opposite trend from that of excessive air humidification, which is attributed to
  electro-osmosis of water.
- Cell temperature also has effects on current distribution, which is consistent to the effects of reactant
  gas humidification, because both of them can influence the water balance and water distribution in PEM
  fuel cells. Higher cell temperature may favor the reaction rate in PEM fuel cell, but the influence on
  reaction rate is not as significant as that on water balance and water distribution according to the current
distributions at different cell temperatures.

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