VISUALIZATION STUDY OF CATHODE FLOODING WITH DIFFERENT OPERATING CONDITIONS IN A PEM UNIT FUEL CELL

Han-Sang Kim, Tae-Hun Ha, Sung-Jin Park, Kyoungdoug Min, and Minsoo Kim
School of Mechanical and Aerospace Engineering, Seoul National University, San 56-1, Shinlim-Dong, Kwanak-Gu, Seoul, 151-742, South Korea
E-mail: hsk007@plaza.snu.ac.kr, kdmin@snu.ac.kr

ABSTRACT

Visualization technique was used to better understand the water build-up phenomena on the cathode side of a proton exchange membrane (PEM) unit fuel cell. In this study, a transparent PEM unit fuel cell with an active area of 25 cm² was designed and fabricated to allow for the visualization of cathode channel with fuel cell performance characteristics. Two-phase flow due to the electrochemical reaction of fuel cell was experimentally investigated. The images photographed by CCD camera with various cell temperatures (30–50°C) and different inlet humidification levels were presented in this study. Results indicated that the flooding on the cathode side first occurs near the exit of cathode flow channel. As the fuel cell operating temperature increases, it was found that water droplets tend to evaporate easily because of increased saturation vapor pressure and it can have an influence on lowering the flooding level. The approaches of this study can effectively contribute to the detailed researches on water transport phenomena including modeling water transport of an operating PEM fuel cell.

INTRODUCTION

The PEM fuel cell has received much attention as a promising future power source for mobile and portable applications due to its high power density, quick start-up, low emissions, low-temperature operation, the ability to respond to rapid load change, and system robustness. However, because of low operating temperature (less than 100°C) of the PEM fuel cell, water management is a critical operation issue for achieving high performance and efficiency.

Figure 1 shows the schematic of water movements in a PEM fuel cell. Water is supplied into the fuel cell via humidified gas. When a current is drawn from the fuel cell, water tends to migrate from the anode to the cathode along with the protons through the membrane under the electro-osmotic drag. This electro-osmotic transport results in an accumulation of water at the cathode side together with the water production due to the oxygen reduction reaction at the cathodic membrane-electrode interface. The increasing gradient between anodic and cathodic water concentration can cause the flux towards the anode. This flux called back diffusion can work against the drying of the membrane on the anode side [Eckl et al. (2004), Janssen and Overvelde (2001), Karimi and Li (2005)].

Figure 1. Schematic diagram of the PEM fuel cell components and water movement in a PEM fuel cell
The conductivity of proton is strongly dependent on the water content of the membrane. To maintain a high ionic conductivity and performance of a PEM fuel cell, the membrane should be sufficiently hydrated with proper water management which can make the balance between water production and water removal from the cell possible [Larminie and Dicks (2000)].

If the inlet gases are not well humidified, dehydration of the membrane occurs, causing a lower power and voltage for a given current density. On the other hand, if the liquid water content is too high in the fuel cell, the flooding of electrode resulting from excess water can hinder the transport of reactant, it can constitute a severe mass transfer limitation for oxygen on the cathode and hydrogen on the anode side. Hence, this can have a detrimental impact on fuel cell performance [Mench et al. (2003)].

The importance of flooding on the cathode side has been emphasized repeatedly in the literature [Hakenjos et al. (2004), Noponen et al. (2004), Pasaogullari et al. (2004), Tüber et al. (2003), Yang et al. (2004), Yang et al. (2005)]. Therefore, for the PEM fuel cell to be commercialized as vehicle or portable applications, the flooding of cathode side should be minimized during the operation of PEM fuel cell.

The aim of the present work is two-fold. The first one is to provide a fundamental understanding of liquid water transport and its two-phase nature of flow in an operating PEM fuel cell. A transparent unit fuel cell has been developed to visualize the in situ water flooding. The physical processes on the dynamics (formation, growth, and transport) of water droplets are described and discussed.

The second one is to investigate the effects of main operation parameters on cathode flooding characteristics. Two main parameters (operating temperature and inlet humidification level) are chosen in this study. The images taken by visualization experiment for two parameters are compared and analyzed.

EXPERIMENTAL

In this study, a carefully fabricated transparent unit fuel cell was developed to understand the liquid water transport and distribution in H₂/air fed PEM fuel cell.

Figure 2 represents the picture of the transparent fuel cell. The cell consists of an acryl window cover plate, carbon plates (one on the cathode side with a thickness of 1 mm), membrane/electrode assembly (MEA) and gold-coated current collectors. The modified serpentine flow path with rectangular channels of 0.7 mm in width, 1.0 mm in depth, and 35 passages was adopted for the anode and cathode. The anode and cathode flow fields are in counter-flow configuration. MEAs of 25 cm² were used for the experiments. The MEA used in this study is based on Nafton® 112. The total MEA thickness (membrane, catalyst, and GDLs (gas diffusion layers)) is 0.65 mm.

Figure 3 shows a schematic diagram of experimental setup, which consists of a gas supply unit, unit fuel cell, electronic loader, different sensors, personal-computer (PC) based data-acquisition system, and CCD camera for visualization experiment.

High-purity (> 99.999%) hydrogen (at the anode) and high purity (> 99.99%) dry air (at the cathode) were used as reactant gases. The flow rates of hydrogen and air were controlled and measured by two mass flow controllers. The humidification temperatures of the reactant gases were controlled by adjusting the humidifier temperature.
The anode and cathode humidification temperatures were set equal to the cell operating temperature. To visualize the water flooding, the visualization experiment was carried out with cell polarization characteristics under the condition of constant voltage (0.4 V) discharge operating by applying an electronic load.

The details of test conditions are listed in Table 1. At the time when the emergence of water droplets was detected in the window of CCD camera, image recording was started. The photographed images were recorded with a time interval of 10s.

Table 1. Details of test conditions

<table>
<thead>
<tr>
<th>Flow rate (l/min) (Air/H₂)</th>
<th>0.75 / 0.15</th>
</tr>
</thead>
<tbody>
<tr>
<td>Temperature (°C)</td>
<td></td>
</tr>
<tr>
<td>(Cathode Humidification/Cell/Anode Humidification)</td>
<td></td>
</tr>
<tr>
<td>30/30/30 (Case I)</td>
<td></td>
</tr>
<tr>
<td>40/40/40 (Case II)</td>
<td></td>
</tr>
<tr>
<td>50/50/50 (Case III)</td>
<td></td>
</tr>
<tr>
<td>30/40/30 (Case IV)</td>
<td></td>
</tr>
<tr>
<td>50/40/50 (Case V)</td>
<td></td>
</tr>
<tr>
<td>Pressure (Cathode/Anode)</td>
<td>Near ambient</td>
</tr>
</tbody>
</table>

RESULTS AND DISCUSSION

Dynamics of Liquid Water Droplets

Figure 4 shows the close-up images of dynamic process of water droplets in the cathode flow channel for Case I. The images represent the evolution of water droplets related to two-phase flow due to the electrochemical reaction of the fuel cell.

Only very small liquid droplets are observed at the early stage when the current is drawn from the cell. The observations suggest that the size and frequency of water droplets increase with time. The sizes of droplets are about 0.1 - 0.8 mm and confined by the dimension of cathode flow channel. The formation of liquid droplets is not uniform on the GDL surface. It is due to the fact that the open pores of GDL are not distributed regularly. Hence, the liquid droplets are distributed discretely on the GDL and flow channel interface along the cathode channel.

The growth of water droplets is generally known to be governed by the saturation vapor pressure, the buoyancy force on the droplet, and surface tension. The size of water droplet increases very gradually with time and the locations of liquid water droplets do not change much until they grow to a sufficient size to be swept away by incoming air flow.

Hence, it clearly indicates that the surface tension has dominant effect on liquid droplet behavior in the transparent PEM fuel cell of this study [Lu and Wang (2004)].

It is observed that the flooding first occurs near the exit of the cathode flow channel. This is because the liquid water generated by electrochemical reaction is accumulated at the outlet of flow channel with the effect of air flow. Also, it is found that some of the flow channels are blocked with liquid water. This can impede the transport of reactants from the flow channel to the reaction sites.

Influence of Operating Temperature

Figure 5 displays the images of flow field flooding with different operating temperatures (30, 40, 50°C).

As the operating temperature of fuel cell increases, the flow field flooding level tends to be lowered. This can be explained by the fact that the liquid droplets can easily evaporate with the increase of saturation vapor pressure resulting from the increase in the temperature of unit fuel cell and supplied gases [Hakenjos et al. (2004)]. As the temperature increases, the surface tension between water droplets and substrate decreases. Therefore, water droplets can not continuously grow, are elongated in shape, and swept away along the cathode channel.

Especially, for the operating temperature of 50°C (Case III), the flooding areas were not observed except the outlet of the cathode flow channel. This can be understood by the steep increase in saturation vapor pressure at the temperature of 50 °C. Also the ohmic heat generated inside the fuel cell contributes to the increase in cell temperature and hence it can lower the flooding level of the flow channel.

Influence of Inlet Humidification Level

To see the effect of inlet humidification level on flooding level, the visualization experiment was conducted with varying the inlet humidification temperature. The cell temperature was set equal to 40°C. The anode and cathode inlet humidification temperature ranged between 30 and 50°C. Other fuel cell operating conditions remained unchanged.

Figure 6 shows the comparison of visualization images of water droplets for two different inlet humidification temperatures (Case IV (low humidification case), Case V (high humidification case)). At the early stage (< 5s), the condensing of water was not observed on the cathode flow channel and GDL surface, although the air was supplied with fully humidified for high humidification case. As time elapses, some fog by the instant condensation of inlet gas on the upper surface of acryl window can be seen. However, the fog disappears after a few seconds.

As time proceeds, water droplets can be seen on the GDL and cathode flow channel interface. It is found that the emergence of liquid water droplets from GDL is observed earlier for Case V than for Case IV. Also, for high humidification case, the frequency of liquid droplet occurrence increases more rapidly, larger part of the flow channels are filled with liquid water droplets. On the other hand, for low humidification case, the flooded area cannot increase much because the fuel cell inside becomes dry because of lower inlet humidity and ohmic heat generation.
CONCLUSIONS

Knowledge of the liquid water transport and its related cathode flooding phenomena in an operating PEM fuel cell is critical for proper water management. In this study, a carefully designed transparent unit fuel cell was developed. The physical process on liquid water droplet behavior related to the cathode flooding and the effect of main operating parameters on flooding characteristics were mainly investigated.

The major conclusions derived from this work can be summarized as follows;

1. The flooding starts near the outlet of the cathode flow channel. This can be explained by the effect of the accumulation of liquid water due to the electrochemical reaction and the air flow directing towards the exit of flow channel.

2. The size of liquid droplets is between 0.1 and 0.8 mm and it increases very gradually with time. The locations of liquid water droplets do not change much for the case of cathode flow channel configuration adopted for this work. Hence, it clearly reveals that the liquid droplet behavior is mainly affected by the surface tension.

3. As the operating temperature of fuel cell increases, the flow field flooding level tends to be lowered. This is attributed to the increase of saturation vapor pressure and subsequent decrease in surface tension.

4. With higher inlet humidification level, the area of flooding tends to increase and the emergence of liquid water droplets is shortened.

Finally, it is expected that the key data obtained through this study can provide basic insight into the prediction of cathode flooding mechanism and the setup and validation of three-dimensional fuel cell physical models considering two-phase flow and cathode flooding phenomena.

REFERENCES


Figure 4. Images of the evolution of liquid water droplets on the GDL and flow channel interface (Experimental parameters are cathode humidification temperature of 30°C; cell temperature of 30°C; anode humidification temperature of 30°C)
Figure 5. Images of flow field flooding with various operating temperatures
Figure 6. Comparison of flow field flooding with different inlet humidification temperatures
(The experimental parameters are shown in Table 1.)