Investigation of Water Droplet Interaction with the Sidewalls of the Gas Channel in a PEM Fuel Cell in the Presence of Gas Flow

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Water appears as a byproduct during normal operation of Proton Exchange Membrane Fuel Cell (PEMFC), and stagnates on the gas diffusion layer (GDL) affecting its performance under certain operating conditions. The primary goal of this study was to develop an ex-situ experimental setup to analyze the sidewall interactions and droplet dynamics under controlled gas flow rates. The channel open angle was varied from 30° and 90° and the superficial air flow velocities between 0.2-2 m/s. The growth of the droplet and its interaction with the side wall were captured using a high-speed camera with a microscopic lens. The experimentation revealed that the droplet-side wall interaction was dependent on the gas channel angles and also on the gas flow rate. The study provides an insight into the droplet removal process in a PEMFC and provides guidance in the gas channel design.

Introduction

Depletion of fossil fuels and ever-increasing environmental pollution has driven the need for developing alternative renewable energy sources, which could be used for commercial applications. Of the several choices available, hydrogen proves to be favorable due its abundance, efficiency as well as environment-friendliness. Though several forms of hydrogen powered technologies exist and have been well-researched, fuel cells is considered as a primary means of tapping this resource (1, 2). The process by which fuel cells create energy is the reverse reaction of electrolysis, which combines hydrogen and oxygen in the presence of a catalyst to generate energy and water. Specifically, Proton-Exchange-Membrane-Fuel-Cell (PEMFC) has been found to be more suitable for transportation applications (3).

Since the first implementation of fuel cells in Apollo space program, the basic fuel cell technology has come a long way. However, the commercialization of fuel cells has not been possible, other than limited distribution networks due to several limitations. These include continuous water accumulation on the surface of the Gas Diffusion Layer (GDL), inefficient water removal that leads to degradation of the GDL at low temperature environment, blockage of gases from diffusing on the GDL surface, and heat transfer. In addition to the water produced as a by-product of the chemical reaction, water is also generated from the humidified inlet gases and has to be managed efficiently in the fuel cells (4). Inefficient water removal results in flooding of the catalyst layer and affects the heat transfer on the membrane, thereby reducing the fuel cell output (5). Unfortunately,
the fuel cell performance is drastically affected not only by accumulation of liquid water as well as starvation of water on the membrane. Therefore, proper and efficient water management is essential for sustained and efficient operation of PEMFC and forms major motivation for the present work. A systematic and detailed study of the droplet’s dynamics that explains the effect of the GDL surface on the droplet’s pinning and its removal is warranted. This work addresses this issue and provides insight into the droplet interaction with the GDL surface and the sidewall. Such studies will aid in improving fuel cell designs for better reliability and efficiency (6).

Several research groups have studied the growth of water droplets on the GDL surface and its interaction with the sidewalls by conducting both experimental studies (in-situ and ex-situ) (7-11) as well as simulations (12) for this purpose.

Droplet pinning on the GDL surface is also a major factor impeding water removal, as it would result in sticking of droplets on the sidewall or on the GDL surfaces (7, 11). The effect of the contact angle of the GDL on the droplet’s pinning and its removal have been investigated by a few researchers under both static (12) and dynamic conditions (7). Different material samples with different PTFE contents for the GDL surfaces were tested for comparing the effects of pinning and water removal in fuel cells such as Toray and SGL (9, 10). It was concluded that the PTFE content on the GDL helps increase the efficiency of water removal by increasing the static contact angle of the surface.

Several researchers also studied the effect of sidewall on water transportation based on its hydrophilicity/ hydrophobicity (12, 13) as well as geometric characteristics (14, 15). In most of these cases, the results were at times contradictory or inappropriate due to oversimplification and exaggeration of this problem. There is a need to understand the GDL-channel interactions and their role in the water removal process. To confirm the effect of the sidewall on droplet movement in a gas channel, Rath and Kandlikar (16) showed that different sidewall angles along with the material characteristics influence the droplet behavior. This was verified using Concus Finn condition (17), in which it was stated that the two surfaces are unrestrained if the given condition is met.

\[ \alpha + \theta < \pi /2 \]  

where \( 2\alpha \) is the open angle and \( \theta \) is the contact angle that the liquid makes with the surface. Figure 1 schematically shows this condition. If the contact angle values fall in the shaded region, shown in Figure 1, then the condition is valid and a solution exists, whereas if the values fall in the region of D+ or D- then there exists no solution.

It was also concluded that Concus-Finn condition could be used to determine whether the droplet will pin on the surface or fill the corner between the sidewall and the base, which leads to slug formation. The instantaneous contact angle for the droplet interaction is very important to determine the droplet’s behavior in the gas channel. This work was performed in a static environment, where only the effect of sidewall was studied on the droplet without an air flow.
The work presented in this paper investigates a droplet’s interaction with the channel sidewalls in the presence of gas flow. This represents the actual condition that prevails in the PEMFC, and will help gain a better insight of the droplet dynamics.

Experimental Set Up

An ex-situ test set up, shown in Figure 3, was developed to study the effect of airflow on the droplet pinning on the GDL and the sidewall. The test section consists of a GDL material placed over the Lexan™ plates, which form the base section of the system. Baseline GDL with 6% wt. PTFE coating is used for the experimentation. Two angular machined Lexan™ plates are placed on top of the GDL surface to form the channel. Another smooth Lexan™ plate is placed on top of the angular sidewalls to form the top of the channel. Airflow is provided by an air generator from the opposite end of the channel with respect to the droplet location. A Syringe pump from the Harvard Apparatus (Model 11 Plus) was used to introduce water through the Lexan™ base and the GDL surface. This process simulates water droplet emergence on the GDL surface in a PEMFC. The entire test section is mounted on top of a test stand. Video images are captured using a Keyence VW-6000 high speed digital camera. The frame rate used for this experiment was 100 fps, and the resulting video is analyzed using Keyence Motion Analyzer software to visualize the droplet behavior and determine the contact angle that droplet makes with the base and the sidewall. The experimental setup was designed such that it would maintain the hydraulic diameter of the channel at approximately 3 mm for different angular configurations of the sidewall. In order to overcome the channel interior visibility limitations, the channel dimension was exaggerated compared to the actual PEMFC conditions (19).

A series of experiments were performed for different airflow rates in the channel. The airflow conditions simulated were chosen according to the current density of 1.5 A/cm², and the superficial air flow rates used were between 0.2–2 m/s which corresponded to stoichiometric value between 1 and 10. The water inlet was designed to be at the central region of the channel. A preferential pore of 180–200µm diameter was made on the GDL.
above the inlet pore on the Lexan\textsuperscript{TM} base for the droplet to come in the channel. A constant inlet water flow rate of 0.05 ml/min was used.

Figure 3: Test Set Up

Figure 3 shows the different contact lines that the droplet makes with the base and the sidewall. The upper contact line and the lower contact line (UCL and LCL) are made by the droplet and the sidewall, whereas the inner contact line and the outer contact line (ICL and OCL) are made by the droplet and the base. The angles at ICL and LCL are important in determining the conditions for the pinning of droplet on the wall, and filling the corner (where the sidewall and base meet). It should be noted that once the droplet fills the corner then its removal becomes difficult as it wets the walls. To avoid this condition, the sidewall angle has to be appropriately evaluated.

Figure 4: Different contact lines made by the droplet with base and sidewall

Prior to determining the desired angular configuration of the sidewall for efficient water removal from the PEMFC, it is necessary and important to measure the contact angle hysteresis (20). In order to quantify the hysteresis, the static advancing contact angle $\theta_{\text{adv}}$ as well as static receding contact angle $\theta_{\text{rec}}$ were measured for both the sidewall material and the base GDL material. The contact angle hysteresis was calculated by...
\[ \Delta \theta_{\text{hys}} = \theta_{\text{adv}} - \theta_{\text{rec}} \]. The contact angle measurement was done using the VCA Optima Surface Analysis System and the corresponding measurements for both GDL and the Lexan™ sidewall are given in Table 1.

<table>
<thead>
<tr>
<th>Material</th>
<th>Advancing Contact Angle (( \theta_{\text{adv}} ))</th>
<th>Receding Contact Angle (( \theta_{\text{rec}} ))</th>
<th>Hysteresis (( \Delta \theta_{\text{hys}} ))</th>
</tr>
</thead>
<tbody>
<tr>
<td>Baseline GDL</td>
<td>148</td>
<td>137</td>
<td>11</td>
</tr>
<tr>
<td>Untreated Lexan™</td>
<td>85</td>
<td>61</td>
<td>24</td>
</tr>
</tbody>
</table>

**Results and Discussion**

Keyence software was used to capture the video during the droplet growth and motion. The motion analyzer software was used to measure the angles the droplet made with the base and the sidewall on a frame by frame basis. Different open-angular configurations of 30°, 50°, and 90° were used for the experiment. For 30° and 90° channel open angles, the results were similar to the trend predicted theoretically by Concus-Finn condition. Similar results were seen for almost all the airflow rates. Instantaneous angles made by the droplet with the sidewall and the base were plotted against each other as shown in Figure 5. It shows that for the open angle of 30° all the angles made by the droplet with the sidewall and the base fall above the Concus-Finn limit line. In comparison, for the 90° open angle, the points fall below the limit line. According to the Concus-Finn condition, if the contact angle values fall below the limit line, shown by a dark solid line in Figure 5, then the corner of the channel would be filled by the droplet. On the other hand, if the contact angle values fall above the line then the corner of the channel would not be filled. Similar results were observed in the experiments. For all the airflow rates, the channel corner was filled for the 90° open angle, whereas for the 30° open angle channel the corner was not filled. These results were consistent with the findings shown by Rath and Kandlikar (16) whereas for the channel with open angle of 50°, the results were quite different.

![Figure 5](image-url)
For the 50° open angle channel, the droplet fills the corner under static condition (with no airflow). This could be explained by considering the Concus-Finn condition using the plot shown in Figure 4. According to this plot, the instantaneous angle made by the droplet with the base and the sidewall is such that few angles fall below the limit line, whereas few angles fall above the line. Once the angle made by the droplet crosses the critical limit the droplet fills the corner. $\Delta \theta_B$ shows the contact angle hysteresis along the base, and the $\Delta \theta_W$ shows the contact angle hysteresis along the sidewall.

![Figure 6: Instantaneous wall angle vs base angle for 50° angled channel with no airflow](image)

In contrast to the lower airflow rates for which the droplet filled the corner, for higher airflow rates i.e., the superficial air velocity of 1.2 ms$^{-1}$ and higher resulted in corners of the channel not being filled with the droplet (Figure 7). This contradicts the result predicted using Concus Finn Condition. The difference in the results shows that the airflow rate in the channel has an important role in droplet motion in PEMFC. Along with the airflow rate, the material of the sidewall also has an important contribution on the droplet’s behavior in the gas channel. To visualize the droplet dynamics under this condition, frame-by-frame sequence images of the droplet interaction with the sidewall were captured. Figure 8 shows the sequence images of the droplet without the airflow in the system. It is observed that the droplet grows to a certain size and then it is pulled towards the wall. This is due to the force from the sidewall being higher than the rest of the forces acting on the droplet. Eventually, the droplet fills the corner of the channel and the hydrophilic sidewall tends to spread the droplet along the wall as it grows. The filled corner provides resistance for removal of the droplet from the channel.

For an airflow rate of 250 sccm, it was seen that the droplet grows in a similar way as in the no airflow condition. Once the droplet reaches a critical size, it is pulled towards the sidewall, and it continues to spread along the hydrophilic wall until it nearly blocks the whole channel. The droplet would then continue to fill the corner and cover the whole cross-sectional area of the channel before it is pushed away by the airflow (Figure 9).
Figure 7: Instantaneous wall angle for 50° open angled channel using airflow rates a) 250 sccm and b) 650 sccm

Figure 8: Droplet interaction with the channel of open angle 50° in the absence of airflow in the system

As the airflow rate was increased, it was interesting to note that the droplet would grow to a certain size before it sticks to the hydrophilic sidewall. However, once it attaches to the sidewall, the droplet is observed to be pinned on one side that is closer to the corner. The other side of the droplet would spread on the sidewall as shown in Figure 10. Therefore, the corner of the channel would not be filled, and the airflow in the channel would remove the droplet before it fully blocks the channel.

Figure 9: Droplet interaction with the channel of open angle 50° in the presence of airflow of 250 sccm in the system
The time it takes for the water droplet to first emerge out of the GDL is longer for higher flow rates compared to that of the lower flow rates. Once the droplet has emerged from the GDL, the time between its growth to a critical size and its removal from the channel is comparatively low for high flow rates. Based on this observation, it could be inferred that the contact line data recorded from the front view of the droplet is not sufficient to predict the actual behavior of the droplet in the PEMFC. The front view of the droplet helped gain additional insight about the pinning behavior, and can be applied with caution to the design the fuel cell channels. However, in order to improve the accuracy of the contact line prediction, a 3D view is desirable for predicting the behavior in the PEMFC and will form the basis for future work.

It was observed during the experiments that for the 90° open angle channel, in the absence of an air flow the droplet on the GDL experienced an attractive force from the hydrophilic sidewall that pulled the droplet towards it. In the process, the droplet filled the corner of the channel. Similar behavior was observed for the droplet in the presence of an air flow at all flow rates in the system before it is pushed out from the channel. For the 30° open angle channel in the absence of an air flow, the droplet was pulled towards the channel sidewall and was pinned on it near the corner of the channel. Due to the pinning of the droplet, the corner of the channel was not filled and similar observations were made in the presence of air flow. After pinning, the droplet continued to grow further and started to spread from the other end of the droplet on the sidewall until a critical point was reached. This resulted in the blockage of the channel at all the flow rates considered that ultimately led to removal of the droplet while filling of corner was not observed at all. In the case of 50° open angle channel, droplet growth in the channel was similar to the one observed for the previous channels. However, it was interesting to note that for lower airflow rates the droplet would grow to a critical size before it is attracted to the sidewall and fills the corner. This was observed due to the oscillations observed in the droplet once it touched the side wall. Hence due to this the contact angle made by the droplet with the wall would reach the critical limit which eventually leads to filling of the corner of the channel. Whereas for higher flow rates the droplet would be pinned on the sidewall and then spread from the other contact point on the wall but does not lead to filling of the corner. This shows that the droplet removal from the channel is not only a function of the airflow rate introduced in the channel, but it is also dependent on the channel wall surface energy. It implies that this type of interaction of the droplet
with the sidewall would facilitate the removal of water from the channel. For all the three channel types, it was found that the time taken for the droplet to emerge on the GDL surface increased as the airflow rates increased. However, once it was formed on the surface, the time taken for its removal decreased as the airflow rate increased. In order to address the inconsistencies in the droplet dynamics, the three dimensional contact line of the droplet is needed. The droplet view from other sides will help to achieve that and also will aid in observing the accurate droplet behavior within the PEMFC channels. Hence, a more detailed investigation of the droplet dynamics for PEMFCs based on the three dimensional contact lines is planned as a part of the future work.

**Conclusion**

An ex-situ investigation of droplet dynamics in the channel of the PEMFC was conducted. The droplet was allowed to grow inside a channel of different open angles of 30°, 50° and 90° in the presence of different air flow rates. The droplet dynamics were captured using a high speed camera and analyzed for different droplet interactions with the GDL and the sidewall. The observed results are as follows:

- For 30° open angle channel, irrespective of the air flow rates introduced in the channel, the droplet does not fill the corner and the droplet removal from the channel is easier.
- For 90° open angle channel, irrespective of the air flow rate introduced in the channel, the droplets fill the corner. Once the corner of the channel is filled the removal of the droplet from the channel becomes difficult.
- For 50° open angle channel, at lower air flow rates the droplets filled the corner due to oscillations in the droplet after touching the side wall, whereas at higher air flow rates the droplets did not fill the corner. Hence, the droplet removal at higher flow rates is easier compared to that at lower air flow rates.

The droplet removal from the channel is thus dependent not only on the air flow rate introduced in the channel but also on the surface energy of the walls of the channel.

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**References**