Experimental validation of two-phase pressure drop multiplier as a diagnostic tool for characterizing PEM fuel cell performance

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i. Abstract

Water management is a key area of interest in improving the performance of Proton Exchange Membrane fuel cells. Cell flooding and membrane dehydration are two extreme conditions arising from poor water management. Pressure drop has been recognized as a good diagnostic tool to determine the presence of liquid water in the reactant channels. Presence of liquid water in the channels increases the mass transport resistances and therefore reduces the cell performance, which is quantified by the cell voltage at a set current density. Since the two-phase pressure drop multiplier is uniquely related to the water content in the channel, it serves as a good diagnostic tool for directly predicting the cell performance. Experiments are carried out to establish the relationship between the pressure drop multiplier and cell voltage at different operating conditions. Cell temperature was varied from 30°C to 80°C and the inlet relative humidity has been varied from 0 to 95%. At the lower temperatures, a two-phase multiplier below 1.5 reduces the flooding in the flow field. However, at the higher temperatures, a two-phase flow multiplier above 1.2 is preferred as it indicates the membrane remains hydrated for improved performance from the cell. The two-phase pressure drop multiplier has been successfully demonstrated as a diagnostic tool to predict cell flooding and membrane dehydration.

ii. Keywords

PEM fuel cell; temperature; cathode inlet RH; cell voltage; two-phase pressure drop; diagnostic tool

1. Introduction

Proton exchange membrane fuel cells (PEMFCs) are being explored for the next generation of powertrains for automotive applications. PEMFC are the focus of much of the on-going research on fuel cells, including stationary, portable, and transportation applications. PEMFCs have relatively rapid start-up times, low operating temperatures and can deliver high power densities, making them most suitable for use in automobiles [1–3].

Water management in PEMFCs is considered to be one of the major roadblocks in their application to automotive platforms. Both excess water and a lack of adequate water in the system lead to loss in performance and durability [4,5]. Water management is important at the different component layers of the PEMFC system, i.e. at the membrane, catalyst layer, MPL, GDL and the reactant channels [6]. Water is generated at the cathode catalyst layer and then transported through the GDL and MPL to the cathode reactant channels, from which it is removed from the cell. Water in the membrane is transported from the anode to the cathode side by electro-osmotic drag, while back diffusion causes water from the cathode side to move towards the anode side due to concentration gradients [7,8]. Water is generated at the cathode catalyst layer and, if not removed efficiently and rapidly, it begins to accumulate in the gas channels. Buildup of liquid water at the catalyst layer blocks oxygen transport to the reaction sites resulting in an increase in mass transport resistance and a loss in cell performance [9]. This accumulation of excess liquid water at the catalyst layers is known as cell flooding and is to be avoided for efficient operation of PEMFCs. Cell flooding leads to localized starvation of reactants, loss in performance and non-uniform temperature and current distributions leading to increased degradation.

Liquid water in the GDL reduces the pores available for reactant transport. With increasing saturation of liquid water in the GDL, it becomes increasingly difficult for the gases to reach the reaction sites [10]. Liquid water in the reactant channels blocks reactant transport in two directions. First, the liquid water reduces the surface area on the GDL available for diffusion of reactant into the GDL (as shown in Figure 1), which can be quantified as Area Coverage Ratio, characterized by Sergi and Kandlikar [11] and Banerjee and Kandlikar [12]. Area coverage ratio is defined as the ratio of GDL interfacial area blocked by the presence of liquid water to the total GDL interfacial area available for reactant transport. The second resistance is due to the liquid water increasing the pressure drop along the length of the channel. This can be characterized using two-phase pressure drop multipliers, which is the ratio of the two-phase pressure drop to the single-phase pressure drop for a set gas flow rate [13].

Figure 1: Area blocked by liquid water for diffusion of reactants into the GDL. Areas 1 and 2 represent area blocked for reactant transport.

The optimal temperature of operation for PEMFCs lies between 60 and 80°C [14–16]. Low temperature (below 60°C) operation of PEMFCs suffers from cell flooding issues due to low saturation pressures of water in air, resulting in poor water removal rates in the vapor form. At

the higher temperatures, with high saturation pressure of water in air, all the water being produced can be removed in vapor form in the cathode gas stream [12]. This tends to decrease the hydration of the membrane, thereby reducing the membrane conductivity and performance of the cell [6].

For maintaining an adequate level of hydration in the membrane, the inlet gas streams on both the anode and cathode sides are partially humidified [17]. The dew point temperatures for the inlet gas streams should always be maintained below the cell temperatures to ensure that water does not begin to condense in the reactant channels increasing the two-phase pressure drop. Therefore, the cell needs to be operated with adequate levels of humidification up to temperatures of 80°C.

The present work examines the relationship between the liquid water in the reactant channels and the performance of the fuel cell. The liquid water is characterized using the two-phase pressure drop multiplier, while the cell voltage is indicative of the cell performance. The quantity of liquid water present in the reactant channels is varied by changing the operating temperature and the inlet relative humidity of the reactant gases. Changing these two parameters results in a change in the saturation pressure of water within the channels and therefore affects the quantity of liquid water in the channels. The impact of liquid water in the channels on the cell performance is highlighted. The cell voltage is also predicted for optimal water management situations for comparison. The two-phase pressure drop multiplier is shown to be an excellent diagnostic tool for predicting cell flooding and membrane dehydration at a wide range of PEMFC operating conditions.

2. Literature Review

Water management of PEMFCs has been a focus area of significant research in the past several years. Review papers [6,9,18,19] have provided an overview of the work done and have highlighted the need for further investigations into water management.

Li et al. [18] shows the impact of cell flooding on the cell performance using polarization curves with different levels of flooding. However the study does not describe the cell flooding in terms of the liquid water present. Different aspects of the cell structure and composition play important roles in the water management capability of the cell, which includes the Gas Diffusion Layer (GDL), its PTFE content, its porosity, the microporous layer (MPL), the catalyst layer as well as the design of the flow fields.

Cell operating conditions can also be a key in the water management strategy being employed for the fuel cell. Experimental results of Amirinejad et al. [17] showed that operating at higher temperatures with humidified gas streams improved the cell performance. Zhang et al. [20] used dry gases to isolate the effect of cell temperature, without inlet humidity influencing the results. The cell performance improved when temperature increased from 23 to 60°C, but decreased when the temperature was increased beyond 60°C. This was attributed to the loss in membrane hydration, highlighting the need for humidified inlet gas streams at the higher temperatures. Coppo et al. [21], used numerical modeling to show that the cell performance improves with increase in temperature. The ionic conductivity of the membrane improves with increase in temperature, along with higher diffusivity of the reactants, leading to improved performance of the PEMFC. The model was validated using a single cell PEMFC with serpentine flow fields and an active area of 5 cm². However, Zhang et al. [22] measured the open circuit voltage (OCV) as a function of temperature and showed that the OCV decreases with increase in temperature.

Operating at OCV meant no water was being generated, thus eliminating the water management issue. The operating temperature of the PEMFC plays an important role in the water management. The saturation pressure of water in air increases exponentially with increase in temperature. This changes the quantity of liquid water present in the reactant channels. Banerjee and Kandlikar [12] investigated the change in the presence of liquid water in the reactant channels as a function of temperature and relative humidity. With increase in temperature, the liquid water content in the reactant channels decreased rapidly, with negligible water being present at 60°C. However, no direct study is available which investigates the loss in voltage due to the presence of liquid water in the flow fields.

Temperature does not affect the cell voltage in isolation, the inlet relative humidity on the anode and cathode side play a significant role in the performance of the cell [23]. Dry inlet gases reduces the membrane hydration and reduces proton conductivity [24]. High inlet relative humidity on the cathode side can lead to change in water saturation pressure and result in flooding. The presence of excess water in the cell can result in non-uniform current densities [25]. For low operating voltages, a low cathode RH reduces flooding and improves performance. However, at the higher operating voltages, a high cathode RH improves membrane hydration and therefore performance [26]. Amirinejad et al. [17] showed that anode humidification was necessary to improve cell performance, but cathode humidification decreases the performance due to increased cell flooding. The above investigations show that the cathode relative humidity plays a significant role in the water management of fuel cells. The change in relative humidity and change in saturation conditions dictate the quantity of liquid water present in the flow fields. However the voltage loss has not been related to the increase in liquid water in the channels resulting from the increased inlet relative humidity.

With increase in stoichiometry, air flow velocities are higher within the reactant channels. High flow velocities are more effective at removing water from the reactant channels as shown by low ACR at the high current densities in [11,12] and also by the transition to mist flow at the higher air flow velocities [13,27].

Several visualization techniques have been used in studying the presence of liquid water in the different components of the PEMFCs and relating it to the performance. In 2005, Kramer et al. [28] reported the effect of liquid water in the fuel cell on the cell performance. As the liquid volume increased, the cell performance suffered. Owejan et al. [29] also focused on the impact of presence of liquid water on the cell performance. They used different GDL samples in an operating cell and visualized it using neutron radiography. Toray showed the highest mass of water in the system and resulted in the poorest performance of the different GDL samples tested. Other studies have also used neutron radiography [30–35] to study the presence of liquid water in the PEMFC, but without any direct comparison with the cell performance. Similarly, X-ray radiography has also been used in the visualization of water in PEMFCs [36–41]. However, as the x-ray studies focus on the water emergence at the pore scale, the overall impact on performance has not been reported. The same is also true for optical imaging, which evaluates the water content in the reactant channels without correlating it to the performance of the cell [11,42–45]. Visualization techniques are good for obtaining trends in water transport. However, these do not serve as a good diagnostic tool for operating fuel cells and stacks.

In the present work, the liquid water present in the reactant channels is quantified using two-phase pressure drop multipliers and the cell voltage is used to quantify the cell performance. Relationships between the two-phase pressure drop multipliers and the cell voltage are developed. The liquid water content in the reactant channels is changed by implementing

changes in cell operating parameters, which are within the range of automotive PEMFC conditions [46] obtained from (www.pemfcdata.org) . The temperature is varied between 30 and 80°C, while the dew point temperature is set to obtain inlet relative humidity values of 0, 50 and 95%. The associated changes in cell performance are reported in relation to the two-phase multiplier. The two-phase pressure drop multiplier is being proposed and experimentally established as a low cost non-intrusive diagnostic tool for single cell and stack level testing.

3. Experimental Setup

3.1. Test cell and equipment

An in situ experimental setup has been used for this investigation. The PEM is sourced from Gore Associates and is 18 μm thick, with an active area of 50 cm^2 . The membrane is then coated with the catalyst, with loadings of 0.1 and 0.3 mg/cm^2 on the anode and cathode sides, respectively. MRC 105 with 5% PTFE loading was used as both the anode and cathode GDL, with a proprietary MPL coated by General Motors (GM). The GDL has a thickness of 230 μm while the MPL is 30 μm ; resulting in a combined thickness of 270 μm .

The current collector was gold plated copper for reduced contact resistance and high corrosion resistance. Parallel channel configuration was used for the reactant channels, which were housed in the current collector plate. The flow field design has been discussed in detail by Owejan et al. [5]. The parallel channel 50 cm^2 single cell design represents a segment of the flow field geometry of fuel cell hardware being utilized in the automotive drivetrain and meeting the performance targets of the US-Department of Energy. The reactant channels were 400 μm deep, 700 μm wide and 183 mm long with 11° of switchback as described by Owejan et al. [5]. On the cathode side, the land widths are 500 μm wide while on the anode the width is increased to 1500

μm . In order to maintain an active area of 50 cm^2 , the width of the active area is just 27.3 mm. This results in a rectangular flow field design, housing 22 parallel channels on the cathode side. The channel and land dimensions have been optimized based on experimental and numerical results available in literature. The depth of the channel had been decided with considerations for the repeating distance of bipolar plates in the stack, in keeping with the US-DOE target for volumetric power density of 2 kW/L.

Flow field design has been shown to play a key role in influencing the water flooding in the channels. Both serpentine and interdigitated flow fields have shown reduced channel flooding compared to straight channel configurations [42]. To target low current density operation, serpentine and interdigitated flow fields are preferred due to better water removal characteristics. However, at the higher gas flow rates, straight parallel channels may be preferred due to the low pressure drop and reduced reactant starvation [18,47]. Serpentine flow fields have reduced flooding and a higher pressure drop associated with them resulting from longer channel lengths, compared to equivalent parallel channels. Therefore, for automotive PEMFCs, it is preferable to use the parallel channels in order to design for high current densities and reduced fuel cell stack volume.

Pressure taps were included into the inlet and exit manifold design to measure the channel pressure drop along the length of the channel [13,48]. The compression plates were fabricated in aluminum to minimize thermal gradients. The compression plates also housed the coolant channels, which were serpentine and were divided into four segments for a uniform temperature control. Water was used as the coolant in the compression plates.

The fuel cell test facility was centered around a G40 fuel cell test stand by Greenlight Innovation. The test stand was supplied with bottled hydrogen and air from a 'dry air generator'. The test stand was responsible for supplying the PEMFC with reactants, maintaining the reactant inlet temperatures and the respective dew point temperatures. Additional heated gas lines connect the test stand fuel lines to the PEMFC inlet ports to avoid condensation within the supply lines. Temperature of the coolant being circulated through the compression plates of the PEMFC was controlled by a temperature controlled water bath with a heating and cooling capacity of 0.5 kW. Additionally, eight 0.8 kW heaters were placed in-line with the PEMFC coolant line inlets to provide rapid heating of the cell. The coolant channels were divided into four segments on each of the cathode and anode side, with a total of eight segments, to avoid any temperature gradients. The in-line heaters mentioned above line up with each segment to provide direct temperature control for each segment.

The voltage, current, dew point temperatures and gas temperatures were measured at the test stand (Greenlight G40), using the Hyware II custom software by Greenlight Innnovation. The test stand recorded the data at 1 Hz. The cell voltage was measured to an accuracy of 0.5% while the current was measured to 0.25%. Cell temperature and pressure drop data was recorded using a PXIE chassis from National Instruments with a custom in-house developed LabVIEW VI. The temperature data was recorded at 1 Hz to an accuracy of $\pm 1^{\circ}\text{C}$, and the pressure drop was recorded at 100 Hz with an accuracy of 0.25% over the full scale. This results in an uncertainty of ± 0.08 kPa in pressure drop readings.

3.2. Test procedure

After assembly, the PEMFC was conditioned by operating through a six hour cycle. This involved increasing the operating current density to reduce the cell voltage to 0.6 V where it was maintained for 60 minutes. This was followed by a current cycling resulting in alternating low and high operating voltage. At the start of each set of tests, a shorter conditioning cycle was run, which involved 30 minutes of operation at constant voltage of 0.6 V followed by current cycling as described.

For each of the tests, the conditions were set and the cell was allowed to stabilize for 60 minutes. Data was recorded at steady state for 15 minutes which was then averaged to obtain the data points shown as part of these tests. A total of 50 tests have been conducted to study the water management and the corresponding performance of the cell as a function of changing temperature and inlet RH conditions. Additional single-phase tests have been conducted, at no load condition for comparison cases.

3.3. Test conditions

The cell was operated at temperatures of 30 to 60°C to compare the effect of temperature on the cell performance. Table 1 shows the operating conditions used for investigating the effect of temperature. The performance and two-phase multipliers are compared for cases with current density of 0.4, 0.6 and 0.8 A/cm². To investigate the effect of cathode inlet relative humidity, the cell was operated at 40 to 80°C with different inlet relative humidity. The operating conditions used for investigating the effect of inlet relative humidity on cell performance are also seen in table 1. The same dew point temperature is set for both anode and cathode sides and the gas temperatures are maintained at the same level. **Therefore, the inlet RH on both the anode and cathode sides was kept equal, for all conditions.** The table below shows the target values for the

inlet RH, while the results are reported with the relative humidity value recorded at the test stand. The reported inlet RH is for the cathode side. The cell is operated with a constant stoichiometric ratio of 1.5 and 2.0 on the anode and cathode sides respectively.

Table 1: Operating conditions for investigating the effect of temperature and inlet relative humidity on the cell performance and liquid water content in the channels.

Temperature (°C)	Cathode Inlet RH (%)	Current Density (A/cm²)	Investigated Parameter
30, 40, 50, 60	0	0.4, 0.6, 0.8	Temperature
40, 50, 55	0, 50, 95	0.8	Inlet RH
60, 70, 80	0, 50, 95	0.8	Inlet RH

3.4. Cell validation

Before commencing with the above mentioned tests for the current investigation, a polarization curve was obtained by operating the cell at 60°C with both gas streams humidified to 95% RH at the inlet of the flow fields. Figure 2 shows the polarization curve. As described above, the investigation focuses on the cell operating between 0.4 and 0.8 A/cm². It can be observed from the figure, that the cell remains within the region dominated by ohmic losses for the tested conditions. No changes were made to the cell between obtaining the cell polarization curve and operating it for the investigated conditions, discussed in Table 1.

Figure 2: Polarization curve for validating performance of PEM fuel cell. Operated at 60°C with 95% inlet RH. Stable operation up to 1.2 A/cm^2 without mass transport limitation.

4. Results and Discussion

The experiments are first conducted for single-phase flow in the channels in the absence of any reaction to obtain the single-phase flow characteristics of the cathode gas channels. These are followed by actual fuel cell testing under different operating conditions. The results are plotted as a function of the two-phase flow multiplier.

4.1. Single-phase pressure drop trends

Single-phase pressure drop tests are conducted with dry air flow in the gas channels without any reaction. In laminar flow, the single-phase pressure drop increases linearly with increase in flow rate. Single-phase pressure drop also increases with increase in temperature. This behavior is expected since the flow in the channels is laminar, and the entrance effects are not significant in

relation to the total channel pressure drop. This behavior is confirmed with the experiments as seen in Figure 3. The pressure drop is plotted as a function of cathode air flow rate with air temperature as a parameter. With increase in temperature, the density of the gases reduces, therefore the velocity increases resulting in a higher pressure drop along the same length of channel.

Figure 3: Single-phase pressure drop as a function of air flow rate (current density with cathode stoichiometric ratio of 2) and temperature.

The change in results from 23 to 80°C at the highest air flow rate come is 33%.

$$\frac{\Delta P_{80}}{\Delta P_{23}} = \frac{3.76}{2.82} = 1.33 \approx 33\%$$

The air flow reported in liters per minute (lpm) is the direction conversion of the mass consumption at room temperature and pressure. The gases are heated after they are metered, in

order to maintain constant mass flow rates. The pressure drop is a function of both viscosity and density of air, both of which are functions of temperature. The change in temperature from 23 to 80°C results in an increase in the viscosity by 15% and a decrease in density by 16%, which combine to form an increase in pressure drop of 31%. Experimental uncertainty in the air flow rates, rounding errors and the error in the pressure sensors account for this remaining difference between the experimental results and the theoretical change expected.

4.2. Two-phase pressure drop trends

Two-phase pressure drop is measured during the operation of the PEMFC. It involves the flow of air through the cathode flow field and interaction with the water being generated in the cell. Figure 4 shows the two-phase pressure drop as a function of the air flow rate at the four different temperatures for dry inlet air and fully humidified (95% RH) inlet air. The two-phase pressure drop also increases with increase in air flow rate. However, the increase in two-phase pressure drop is not linear with increase in flow rate. This was shown for the lower current densities by See [49] and can also be observed here. With dry inlet gases (Figure 4a), there is a larger variation in the pressure drop as a function of temperature. However, with fully humidified gases, the deviation in two-phase pressure drop with temperature is much less. Due to this non-linear change of two-phase pressure drop with increasing gas flow rates and increasing temperature, pressure drop for changing fuel cell conditions is best described using two-phase multipliers. Two-phase multiplier is defined as the ratio of two-phase pressure drop to the single-phase pressure drop at the same gas flow rate, and is given in equation 1.

$$\phi_g^2 = \frac{\Delta P_{2\phi}}{\Delta P_g} \quad (1)$$

Figure 4: Two-phase pressure drop as a function of air flow rate (current density with cathode stoichiometric ratio of 2) and temperature. Operated with (a) dry inlet gases and (b) with inlet RH of 95%.

4.3. Effect of increasing current density

Figure 5 shows the two-phase pressure drop multiplier and cell voltage as a function of increasing current densities from 0.4 A/cm^2 to 0.8 A/cm^2 with temperature varied between 30 and 60°C and dry inlet gases (i.e. inlet RH of 0%). We note that the two-phase multiplier decreases with increasing current density. This has been shown in prior works [12,13] and indicates lower impact of liquid water on the pressure drop. The increasing air flow velocities associated with increased current density removes the liquid water being generated more effectively, and reduces the two-phase multiplier. The increase in gas flow velocity results in a change in the flow regime from slug flow regime to film flow and subsequently to mist flow regime. The decrease in two-phase multipliers is much more prominent at the lower temperatures as there is more liquid water present in the reactant channels and flow regimes play an important

role on the two-phase multipliers. With increasing temperature, it can be observed that the two-phase multipliers remain low, near a value of 1. There is little liquid water to create an impact on the two-phase pressure drop [12]. Thus, we may conclude that with increase in temperature most of the water is being removed in the vapor phase or in the form of mist, resulting in the quantity of liquid water in the channels being insignificant. This can be observed for both temperatures of 50 and 60°C.

Figure 5: Cathode channel two-phase multipliers (fig. a) and voltage (fig. b) as a function of increasing current densities for the temperatures of 30 to 60°C, with dry inlet gases.

Figure 5(b) shows the cell voltage decreases with increase in current density. This can be expected from the standard polarization curve and is attributed to the increasing resistance from different contributions with increasing current density. As the current densities being reported are in the central segment of cell operation (Figure 2), it can be assumed that the operation is in

the segment dominated by the ohmic resistance, which is linear with regard to increasing current density. The trends in the figure also reflect a linear relationship between the current density and cell voltage. However, with increasing temperature, it can be observed that the slope of the linear relationship becomes less steep. A lower gradient indicates a lower resistance of the cell. This lower resistance can be attributed to the decrease in liquid water in the reactant channels (and in the other components / layers) of the cell. However, with dry inlet gases, as the cell temperature reaches 60°C, the voltage decreases and the cell resistance increases. This is observed from the slope of the voltage plot in figure 3. The increased cell resistance can be attributed to the decrease in membrane hydration due to the increase in temperature. The dry gases reduce the water content in the cell leading to reduced membrane hydration.

4.4. Effect of temperature

Figure 6 shows the cell voltage and the two-phase pressure drop multiplier as a function of temperature. Temperature is varied from 30 to 60°C with an inlet relative humidity of 0% on both the anode and cathode sides. The results are shown for a single operating condition of 0.6 A/cm² at the different temperatures. It can be observed that the cell voltage increases up to a peak at 50°C and then decreases. Additionally, the two-phase multiplier decreases to reach a value of 1.05 at 50°C and then stabilizes with further increase in temperature to 60°C. The tests were also performed at 70 and 80°C (under dry conditions). However, stable operation could not be obtained as the membrane began to dry out. Large fluctuations in the cell voltage and a significant drop in performance were observed, and a steady state could not be maintained for the 60 minutes and therefore no results are reported for those temperatures. The drying out of the membrane resulted in the test matrix with those points being left unfilled.

At the lower temperatures, the high two-phase multiplier indicates a large presence of liquid water in the reactant channels. This corresponds to a low cell voltage, which increases as the two-phase pressure drop decreases. At the influx point of 50°C, the two-phase multiplier is close to 1, indicating negligible presence of liquid water with the peak cell voltage obtained. As the temperature is further increased to 60°C, the two-phase multiplier remains constant suggesting no change in liquid water content in the reactant channels. At the same temperature, the cell voltage shows a decrease from the influx point. This decrease can be attributed to the decrease in membrane hydration, thus increasing the cell resistance and decreasing the cell voltage. This can be verified in the plot for 60°C in Figure 6. Figure 7 shows the same trend for a current density of 0.8 A/cm² at the same operating conditions. The drop in cell voltage at 60°C is more pronounced at the higher operating current density.

Figure 6: Cell voltage and two-phase pressure drop multiplier as a function of increasing temperature (30 - 60°C) for a current density of 0.6 A/cm² operated with 0% inlet RH.

Figure 7: Cell voltage and two-phase pressure drop multiplier as a function of increasing temperature (30 - 60°C) for a current density of 0.8 A/cm² operated with 0% inlet RH.

As discussed earlier in section 4.3, the resistance of the cell changes with change in temperature. The resistance is dominated by the resistance of the membrane and the liquid water in the reactant channels, as there is no change in the electrical resistance of the porous layers. Figure 8 shows the cell resistance as a function of temperature. The cell resistance is calculated from the

cell voltage obtained at different current densities, as seen in equation 2, using values plotted in Figure 5b. We observe that the cell resistance decreases with increasing temperature. This can be attributed to the decrease in liquid water content with increasing temperature. However, as the temperature reaches 60°C, the cell resistance increases. This can be attributed to an increase in the membrane resistance, as there is insignificant water in the reactant channels. The dry-out causes the ionic resistance of the membrane to increase significantly resulting in this increased resistance of the cell.

$$R = \frac{\Delta V}{\Delta I} \quad (2)$$

Figure 8: Cell resistance as a function of increasing temperature (30 - 60°C) when operated with dry inlet gases.

4.5. Effect of humidity

Figure 9 shows the effect of cathode inlet relative humidity on the cell performance at temperatures of 40 and 50°C. The cell is maintained at a constant temperature and the dew point temperature is changed in order to obtain different inlet relative humidities. With increasing inlet RH, the performance decreases. Simultaneously, the two-phase multiplier increases with increase in the inlet RH. The increase in two-phase multiplier indicates increased presence of liquid water in the channels. As the inlet RH increases, the ability of the gas stream to remove water in the vapor phase decreases, thereby increasing the two-phase multiplier.

Figure 9: Effect of RH on cell performance and two-phase multiplier. (a) 40°C (b) 50°C. All other conditions are maintained at constant values.

Figure 10 shows the effect of cathode inlet relative humidity on the cell performance at temperatures of 60 and 70°C. At these temperatures, with increasing inlet RH, the performance increases. The two-phase multiplier also increases with increase in the inlet RH. The increase in two-phase multiplier indicates increased presence of liquid water in the channels. As the inlet RH increases, the ability of the gas stream to remove water in the vapor phase decreases, thereby increasing the two-phase multiplier. However, at these higher temperatures, the higher inlet RH keeps the membrane hydrated thereby increasing the performance. At the lower inlet RH, water is removed very effectively and thus leads to the loss in hydration of the membrane.

Figure 10: Effect of RH on cell performance and two-phase multiplier. (a) 60°C (b) 70°C. All other conditions are maintained at constant values.

4.6. Two-phase multiplier as a diagnostic tool for cell flooding and membrane dry-out

Figure 11 shows the cell voltage as a function of the two-phase multiplier for different temperature conditions, while operating at a constant current density of 0.8 A/cm^2 . The two-phase multiplier cannot be controlled as an independent variable, but depends on the saturation conditions within the flow fields. Therefore, changing the temperature and the inlet relative humidity can result in different two-phase multipliers. Two different trends were observed for the cell voltage with increasing two-phase multipliers. At the lower temperatures, below 60°C , a two-phase pressure drop multiplier above 1.5 indicated the start of flooding conditions and resulted in a loss in the performance. However, at the higher temperatures (60°C and above), increasing the two-phase multiplier improved the performance. Using dry gases resulted in very low two-phase multipliers but also led to the dry-out of the membrane resulting in very low performance. From this we may conclude that a lower two-phase multiplier is preferred at the lower temperatures and a higher two-phase multiplier is preferred at the higher temperatures. Additionally, this information can be used to diagnose the flooding and dry-out scenarios in operating single cell and stacks of PEMFCs.

There is a clear overlap between the two-phase multipliers as reported as part of this work. At the lower temperatures, flooding is observed when the multiplier is higher than 1.5. At the higher temperature, the onset of membrane dehydration happens when the two-phase multiplier is below 1.2. The overlap region is $1.2 < \phi < 1.5$. When a fuel cell is being operated, a single pressure sensor monitoring the manifold-manifold pressure drop can be mated to a real-time data processing system (e.g. LabVIEW[®]) to obtain the two-phase multiplier. When the flow conditions change (due to change in temperature, flow or inlet humidification) and the multiplier drops below 1.2, the flow rates can be decreased to get higher multipliers. Conversely, if the

multiplier increases to values greater than 1.5, the cell starts to flood; the flow rates can be increased to counter the flooding behavior. Therefore, the real time two-phase multiplier can be used as a low cost, non-destructive diagnostic tool, to identify and monitor the optimal operation of the fuel cell.

Figure 11: Cell voltage (for constant current density of 0.8 A/cm²) as a function of two-phase multiplier indicating flooding and dry-out conditions. (a) At low temperatures, a high two-phase multiplier results in flooding and decrease in performance. (b) At higher temperatures, a low two-phase multiplier indicates membrane dry-out, again decreasing the performance.

5. Conclusions

The current study investigates the relationship between the liquid water present in the reactant channels and the cell performance. Temperature of the cell and the inlet relative humidity of the reactant gases play a key role in impacting the quantity of liquid water in the reactant channels. These two operating parameters are changed parametrically to impose different liquid water

content in the reactant channels and the effect on performance is investigated. The two-phase pressure drop multiplier is used to quantify the effect of liquid water present in the reactant channels. The following conclusions can be drawn from the current investigation:

- i) Two-phase multipliers decreased with increase in current density as the air flow velocity increased and improved water removal characteristics.
- ii) Cell resistance decreases with increase in temperature. This is due to reduced mass transport resistances with reduced water content. However, at 60°C with dry gases, the cell resistance begins to increase due to loss in hydration of the membrane.
- iii) Two-phase multipliers decrease with increase in temperature due to increased removal of water in the vapor phase. However, the cell voltage reaches a peak at 50°C with dry gases.
- iv) Loss in cell voltage due to cell flooding is more pronounced compared to voltage loss due to membrane dehydration. Therefore operating the cell in partly dry conditions is better than operating under flooding conditions.
- v) At the lower temperatures of 40 and 50°C, the cell performance decreases with an increase in inlet RH as the cell begins to flood and therefore the mass transport resistance increases. At the higher temperatures of 60 and 70°C, the cell performance increases with an increase in the inlet RH. For higher temperatures, with dry gases, the water removal rate is very high and therefore leads to loss in hydration of the membrane. With increasing RH, the membrane hydration is improved and therefore the cell performance increases dramatically.
- vi) At lower temperatures (below 60°C), lower two-phase pressure drop multiplier results in better performance. At higher temperatures (at or above 60°C), two-phase pressure

- drop multiplier should be higher than 1.2 to avoid dry-out tendencies of the membrane. This information can be used to diagnose cell flooding and membrane dry-out in operational PEMFCs.
- vii) Two-phase pressure drop multiplier has been proposed as a diagnostic tool for the accurate prediction of cell flooding and membrane dehydration.

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