Two-phase pressure drop response during load transients in a PEMFC

Rupak Banerjee

Mechanical Engineering and Microsystems Engineering, Rochester Institute of Technology

Rochester, New York, USA – 14623

Satish G. Kandlikar (Corresponding Author)

Mechanical Engineering and Microsystems Engineering, Rochester Institute of Technology

Rochester, New York, USA – 14623

Telephone No.: +1 585 475 6728

Email: sgkeme@rit.edu

Fax No.: +1 585 475 7710

Abstract:

Transient behavior of PEM fuel cells can be categorized into electrochemical, thermal and two-phase flows. Overshoot/undershoot behavior has been observed in electrochemical cell voltage during transients, and are attributed to the transition time required for saturation conditions to reestablish. Similar behavior has been reported in two-phase flow pressure drop overshoot/undershoot in a previous work by the authors. In this work, three different temperatures, five ramp rates and four amplitudes of load change were used to investigate the transient two-phase pressure drop behavior. The overshoot/undershoot behavior is observed predominantly at the lower temperature of 40C, and is found to decrease at higher cell temperatures. There is a linear increase in the overshoot/undershoot behavior with increase in amplitude of load change. The overshoot/undershoot behavior was found to be independent of the ramp rates used to change the load current. The magnitude of overshoot in pressure drop was always larger than the magnitude of undershoot. The pressure drop required a longer time to return to steady state after an undershoot compared to the time required to return from an overshoot incident.

Keywords: PEM fuel cell; two-phase pressure drop; pressure overshoot; transient; load change

1. Introduction

Water is generated at the cathode catalyst layer and is transported through the gas diffusion layer (GDL) to emerge in the reactant delivery channels. The water appears in liquid form depending on the local temperature and saturation condition and results in two-phase flow in the channels. These channels, with hydraulic diameters on the order of 0.5 mm, encounter a unique two-phase flow condition. The water is introduced along the flow length through a porous wall, while the reactant gases are being consumed. This means that the mass fraction of water is increasing along the length of the channel, while the mass of reactant is decreasing [1,2]. Therefore, the two-phase flow in PEMFC reactant channels have different flow patterns along the length of the channels, further complicating the investigations and our understanding of the phenomenon.

The key diagnostic techniques employed for studying the two-phase flow in the reactant channels are flow pattern visualization and pressure drop measurement [3,4]. Although different types of visualization studies have been reported [5,6], optical visualization remains the most commonly employed technique for investigating the presence of liquid water in the reactant channels [7–11]. The other key diagnostic tool used widely in studying the two-phase flow characteristics is the channel pressure drop measurement [12–14]. Both ex situ and in situ studies have incorporated pressure drop measurements in fuel cell research reported in literature [15–23].

Significant attention has been given to the steady state two-phase flow characteristics in PEMFC reactant channels. Anderson et al. [3] presented a comprehensive review of two-phase flow in reactant channels. They considered numerical investigations, ex situ experiments as well as in situ studies. Kandlikar et al. [4] presented a review of the different challenges in understanding

two-phase flow in the different component layers of PEMFCs and the associated interfaces. They explored the steady state two-phase flow phenomenon through the GDL as well as the reactant channels. However, the transient behavior of two-phase flow in PEMFCs has not been explored in enough detail. A few works that have explored the transient behavior of two-phase flow in both numerical and experimental domains, have focused on the porous media [24–28]. Rabbani and Rokni [29] showed that although at steady state only 10% of the power is used in parasitic power, it could be as high as 15% of the generated power under transient conditions. Therefore, a clear understanding of transient changes is needed to minimize the power lost under these conditions.

In an earlier work, Banerjee and Kandlikar [28] highlighted the need to direct attention to the transient behavior of two-phase flow in PEMFCs. It was shown that with a change in temperature, the two-phase flow behavior changes and can be identified through changes in pressure drop signatures. Also, when the operating current density was changed, there was a distinct change in the two-phase flow behavior. An overshoot in pressure drop was observed for the first time when the current density was increased. On decreasing the current density, a pressure drop undershoot was observed. They also observed that the overshoot/undershoot behavior was only present at 40°C. When the temperature was increased to 60 and 80°C, the pressure drop reached the steady state value without showing any overshoot tendency.

Overshoot in the current response under constant voltage operation was numerically predicted by Meng [25]. Both single-phase and two-phase investigations were conducted and it was observed that the overshoot tendencies were more prominent during the two-phase conditions. This behavior was attributed to the time required for the system to reach steady state due to the changes in saturations levels in response to the new flow condition.

Although Meng [25] showed that two-phase effects resulted in longer transients, Song et al. [30] and Yan et al. [31] used analytical models to predict that increased presence of liquid water in the channels resulted in shorter transients. Song et al. [30] focused on the cathode GDL and its associated interfaces. Their analysis showed that a higher level of water helped the system reach saturation conditions quickly and therefore resulted in shorter transients. Yan et al. [31] investigated the water transport in the PEMFC with a focus on the porous media and the membrane. Their conclusion of increased liquid water resulting in shorter transients is mainly related to the hydration of the membrane. With less liquid water at low reactant humidification levels, the membrane starts to dehydrate and results in a more pronounced transient behavior. However, these conclusions cannot be related directly to the effect of liquid water in the reactant channels.

Yan et al. [32] experimentally showed the effect of the different parameters which affect the transient overshoot observed in the cell voltage under constant current operation. Higher stoic ratios, high operating pressure and higher reactant humidification on the cathode resulted in a rapid response time after the transient change. Therefore these factors can be used to improve the transient behavior of PEMFCs. Hussaini and Wang [26] also investigated the effect of inlet reactant humidification on transients and concluded that higher humidification results in shorter transients in the cell voltage when the operating current density is changed. The voltage undershoot was explained as resulting from loss in hydration of the membrane on the anode side.

It may be noted from the literature that overshoot in the cell voltage and the operating current has been observed by many research groups. Similar overshoot behavior in the two-phase flow pressure drop was reported for the first time by Banerjee and Kandlikar [28]. However, they did not investigate the magnitude of the overshoot/undershoot in the pressure drop for different

transient conditions studied. Further, the effects of different ramp rates and amplitude of load changer were also not investigated. The current work provides a broader parametric investigation covering the effects of three temperatures, five ramp rates and four amplitude of load changes on the transient response in the pressure drop behavior focusing on overshoot/undershoot phenomena.

2. Experimental Setup

a. Experimental Test Setup

In order to investigate the overshoot/undershoot behavior in the two phase pressure drop, it was essential to conduct experiments on an operating PEMFC while imposing the transient changes. The fuel cell used was a non-visualization cell with custom hardware, built to automotive specifications as per the targets set by the US-Department of Energy (US-DOE). The PEM used in this study is 18 μm thick. MRC 105 GDL is used on both the anode and the cathode sides with 5% PTFE loading and a proprietary MPL coated by General Motors. The GDL (with MPL) has an uncompressed thickness of 230 μm .

Straight flow fields have been used with an 11° switchback to prevent shearing of the GDL and MPL under compression. There are 22 channels on the cathode side with a length of 233 mm. The flow field is 27.3 mm wide and has an active length of 183 mm, resulting in an active area of 50 cm^2 . The reactant channels have a depth of 400 μm and width of 700 μm . The land regions between the channels on the cathode side are 500 μm , while on the anode side the land regions are 1500 μm . The dimensions of the channels are representative of automotive fuel cell configurations. The development of the flow field is described in detail by Owejan et al. [33].

The flow fields are machined into the current collector plate in this single cell configuration. Thus, the flow field is in copper which has been gold-plated to minimize the contact resistance.

The cell also incorporated a segmented coolant loop utilizing water as the cooling fluid. The coolant loop was segmented to minimize temperature gradients. The coolant system ensured that any changes in current load do not impose a change in the cell temperature, which was controlled at the bipolar plates. Any thermal gradient in the through-plane direction was not taken into consideration. The absence of thermal gradients in the flow direction ensured that the results reported in this work can be considered to be under isothermal conditions along the flow length.

Operating current density, cell voltage, gas temperatures and dew point temperatures were measured at the test stand. A Greenlight technology G40 test stand was used for controlling the operation of the fuel cell. Data were recorded at 1 Hz at the test stand. Pressure drop and cell temperature were measured using a National Instruments' PXIE 1072 chassis. Pressure drop was recorded using Honeywell's wet/wet differential pressure drop sensors with a range of 0 – 35 kPa and an accuracy of 0.25% over the complete range. This resulted in uncertainty of ± 80 Pa (± 0.08 kPa) in the pressure drop reading. The pressure drop was recorded at a rate of 100 Hz in order to capture any fluctuations occurring at the small time scales of ~ 0.01 seconds. Temperatures were measured using K-type thermocouples placed along the length of the channels in the bipolar plates and were used to ensure that the cell temperature remained constant and temperature gradients did not exist along the channel length. Cell temperature was also recorded at 1 Hz.

b. Experimental Protocol

The PEMFC was assembled and then conditioned as described in Banerjee and Kandlikar [28]. At the start of each set of tests, the cell underwent a short conditioning cycle at the set operating temperature by maintaining a constant voltage operation at 0.6 V for 30 minutes. This was followed by setting up the initial condition of the test. The cell was maintained at steady state operation for 60 minutes and then the desired ramp rate was implemented which took the cell to the new operating condition. The cell voltage and the pressure drop were recorded for 60 minutes after the change. This ensured that the cell had reached its next steady state. These steps were then repeated for each of the test conditions.

The cell temperatures were maintained at the set values using the coolant loop described earlier. The gas flow rates, gas temperatures and the dew point temperatures (for controlling the inlet relative humidity) were controlled at the fuel cell test stand. For this investigation, the current density was varied between 0.2 - 0.6 A/cm². A constant stoichiometry of 2 was maintained on the cathode side and 1.5 on the anode side. The dew point temperature is maintained at 30°C. Table 1 shows the values of flow rate of the dry gases (before humidification) for the anode and cathode at the tested current densities.

Table 1: Flow rates and flow velocities for the different tested current densities

Current Density <i>A/cm²</i>	Cathode Flow Rate (Dry Air) <i>Kg/s</i>	Anode Flow Rate (Dry H₂) <i>Kg/s</i>
0.2	1.43×10^{-6}	7.46×10^{-8}
0.3	2.14×10^{-6}	1.12×10^{-7}

0.4	2.86×10^{-6}	1.49×10^{-7}
0.5	3.57×10^{-6}	1.87×10^{-7}
0.6	4.29×10^{-6}	2.24×10^{-7}

c. Parameters investigated

The first parameter in this study was focused on the effect of cell temperature on the overshoot/undershoot tendencies. Cell temperatures of 40, 60 and 80°C were used to obtain an initial understanding of the effect. Changing the temperature directly changed the saturation conditions and therefore affected the amount of liquid water present in the reactant channels. The dew point was held constant at the inlet by keeping the dew point temperature at 30°C for all the tests.

The second parametric study centered on the effect of ramp rate (by changing electrical load) on the two-phase pressure drop. Along with the load changes, the gas flow rates correspondingly changed while maintaining the same stoic. Five different ramp rates from 0.1 A/s to 0.9 A/s were applied. Finally, the amplitude of load change was also investigated. For increasing current density tests, the starting current density is fixed at 0.2 A/cm² (10 A for the 50 cm² cell) with increasing amplitudes being implemented. For decreasing current density tests, the ending current density is maintained at 0.2 A/cm² while the starting current density is changed to impose larger amplitudes of change. Four different amplitude values are tested, resulting in changes in amplitude from 0.1 A/cm² (5 A) to 0.4 A/cm² (20 A) in the tested 50 cm² cell.

3. Results and Discussion

In order to investigate the parameters that affect the overshoot/undershoot behavior; the tests outlined in section 2c were conducted. The interpretation of results from the pressure drop signal is presented here. The effects of temperature, ramp rate and the amplitude of load change are investigated and the results are discussed in individual sub-sections.

a. Results interpretation and processing

It was observed that the two-phase pressure drop does not reach the steady state value directly and goes through an overshoot when the current density is increased. Figure 1 shows the cathode manifold-to-manifold pressure drop recorded as a function of time for a sample case. For this case, the load was changed by 0.2 A/cm^2 (10 A over the 50 cm^2 active area) at a rate of 0.1 A/s . The cell current density changed from 0.2 A/cm^2 to 0.4 A/cm^2 over a time period of 100 seconds. The cell and gas temperatures were maintained at 40°C , while the dew point temperature was kept at 30°C . The pressure drop increases with increase in current density as the air flow increases to maintain a constant stoichiometric ratio of 2. When the load reaches the maximum value, the cathode pressure drop reaches the peak and proceeds to decrease, reaching a steady state value after about 1200 seconds. The peak pressure drop (ΔP_{peak}) observed is higher than the steady state pressure drop (ΔP_{ss}) indicating an overshoot. The magnitude of overshoot (ΔP_{MAG}) is defined as the difference between the peak pressure drop and the steady stated pressure drop, as shown in Figure 1.

Similarly, when the load is decreased by the same magnitude of 0.2 A/cm^2 (10 A for the 50 cm^2 cell), the pressure drop begins to decrease as the air flow rate is decreased, reaching a minimum

point when the current density reaches the target value. Beyond this point, the pressure drop begins to increase, even though the air flow rate remains constant, finally reaching a steady state value after about 500 seconds. This trough in the pressure drop reading is termed as undershoot. This phenomenon can be observed in Figure 2. The magnitude of overshoot/undershoot behavior is characterized in the current work. The time required for the two-phase pressure drop to return to the new steady state value is termed as the time to steady state (t_{ss}) and is defined as the time between the peak pressure drop and the time at which the pressure drop reaches the new steady state value as shown graphically in Figure 1 and 2. The peak pressure drop is the maximum value observed in the pressure drop signal.

In order to characterize the behavior shown in Figure 1, an exponential decay function is used as described equation 1. The MATLAB[®] curve fitting toolbox is used with this equation to obtain the ΔP_{ss} . The peak pressure (ΔP_{peak}) is obtained using maxima detection in MATLAB[®]. The steady state value from this equation is then compared with the experimental pressure drop to obtain the time at which the pressure drop reaches the new steady state value. The time at which steady state ($t_{@ss}$) is obtained is the time at which the signal is within 0.1 kPa of the steady state value (equation 3). The time to steady state (t_{ss}) is the difference between this time and the time at which the peak was observed.

$$f(t) = \Delta P_{ss} + (\Delta P_{peak} - \Delta P_{ss}) * e^{-t/c} \quad (1)$$

$$t_{ss} = t_{@ss} - t_{peak} \quad (2)$$

$$t_{@ss} = t \mid (\Delta P - \Delta P_{ss}) \leq 0.1 \quad (3)$$

When the operating load is decreased and undershoot is observed, the pressure drop signal reaches a minima and then increases to reach the new steady state value. In order to characterize this new behavior, the expression in equation 1 is modified as shown in equation 4. This represents an asymptotic function approaching the new steady state pressure drop value.

$$f(t) = P_{peak} + (P_{ss} - P_{peak}) * (1 - e^{-\frac{t}{c}}) \quad (4)$$

$$\Delta P_{MAG} = |\Delta P_{peak} - \Delta P_{ss}| \quad (5)$$

Another parameter which can be used to compare the overshoot/undershoot behavior is the percentage overshoot (K_{over}). It can be defined as the ratios of magnitude of overshoot/undershoot to the magnitude of the steady state pressure drop as given by the following equation.

$$K_{over} = \left(\frac{\Delta P_{MAG}}{\Delta P_{ss}} \right) * 100 \quad (6)$$

Several sample test conditions were tested for repeatability. It was observed that the pressure peaks (P_{peak}) showed good repeatability within the error of the pressure sensors (0.1 kPa). However, the time period of decay showed variability. The results presented in the following sections focus only on the peak pressure and the pressure drop overshoot / undershoot value.

b. Effect of temperature on overshoot behavior

Two-phase transient behavior at higher temperatures has been studied in the GDL by Wang and Wang [24]. The effect of changing temperature on the two-phase behavior was investigated in an earlier work by the authors [28]. However, the two-phase flow behavior in the reactant channels

has not been investigated in the transient domain. The effect of temperature on the two-phase behavior has been explored in this study and the results are presented in this section.

Table 2 shows the magnitude of overshoot/undershoot behavior observed at three temperatures of 40, 60 and 80°C when the load is changed by ± 0.4 A/cm², at a ramp rate of 0.3 A/s. As the temperature is increased from 40°C to 60°C and 80°C, no overshoot/undershoot is observed and the pressure reaches a steady state within the first 10 seconds.

Table 2: Magnitude of overshoot/undershoot observed at the different temperatures, Load change of 20 A (± 0.4 A/cm²) at a ramp rate of 0.3 A/s.

Change in Load (A/cm²)	Temperature (°C)	Magnitude of Deviation (kPa)	Time to Steady State (sec)
+0.4	40	1.03	390
+0.4	60	0.00	10
+0.4	80	0.00	10
-0.4	40	0.44	1468
-0.4	60	0.20	2
-0.4	80	0.00	0

With increasing temperature, the magnitude of overshoot/undershoot decreases. Additionally, there is a decrease in the time required to reach the new steady state, therefore the duration of the transient response is reduced. With an increase in the cell temperature, the saturation pressure of water in the air increases exponentially. Therefore, there is significantly less liquid water present

in the channels at higher temperatures [11]. Additionally, due to the increasing temperature and change in saturation pressure, more of the liquid water can be removed in the vapor form. This can be seen in Table 3, which shows the comparison of the water vapor uptake at the different operating temperatures.

Table 3: Percentage of water removed by water uptake into the reactant stream over a range of temperatures and inlet RHs.

Temperature (°C)	Inlet RH (%)	Percentage Water Removed in Reactant Stream
40	0	7.84
	50	4.07
	95	0.42
60	0	24.24
	50	13.43
	95	1.49
80	0	88.89
	50	58.12
	95	8.04

It may be concluded that increased amount of liquid water in the channels leads to longer transient durations as well as larger deviation from the steady state behavior. This is in contradiction to the findings about liquid water in the porous media, where more liquid water results in shorter transient times [30,31]. Wang and Wang [24] focused their investigation into two-phase transients at the higher temperatures. However, the effect is seen to be more significant at the lower temperatures according to the results presented here.

c. Effect of ramp rates on overshoot behavior

The second key parameter investigated is the effect of ramp rate on the magnitude of overshoot/undershoot in the pressure drop signature. Figure 3 shows the effect of ramp rate on the magnitude of overshoot when the load current is increased. For two of the lower amplitudes tested, it may be noted that ramp rate has an insignificant effect on the overshoot behavior. For the higher amplitudes tested, higher ramp rates show an increase in magnitude of overshoot. However, the effect of ramp rates may need further evaluation. The overshoot behavior currently does not show a distinct trend.

Figure 4 shows the effect of ramp rate on the magnitude of undershoot when the load current is decreased. The trend observed is similar to that seen in Figure 3. Ramp rate does not seem to have a strong effect on the magnitude of undershoot. For all cases of amplitude, it is observed that the variation as a function of ramp rate is very small. Therefore, from these two figures it may be concluded that the ramp rates do not play key roles in the magnitude of overshoot/undershoot behavior.

It is also noted from this study that it takes longer for the pressure drop to reach the new steady state value in an undershoot case (load being decreased) compared to an overshoot case (load being increased). Additionally, the magnitude is smaller in the cases of undershoot compared to the overshoot cases.

This is encouraging as it indicates that changing load does not need to be limited by the ramp rate. Thus frequent changes in the load can be made without any adverse effects. However, the changes would also have an impact on the temperature of the cell and the associated systems, which have not been considered in this discussion. In essence, this means that the rate at which

water is introduced into the reactant channels does not have much of an impact on the two-phase pressure drop overshoot/undershoot.

d. Effect of amplitude of load change on overshoot behavior

The third and final parameter investigated is the effect of amplitude of load current change on the magnitude of the two-phase pressure drop overshoot/undershoot. Table 4 give the operating conditions for investigating the effect of amplitude of change in load current. Figure 5 shows the effect of change in amplitude on the magnitude of overshoot behavior. A clear trend can be observed. The increase in amplitude results in an increase in the magnitude of overshoot. The trend is seen at all three ramp rates tested. The slope of increase in the magnitude of overshoot seems to be changing at the different ramp rates used. However, it is apparent that the change in the amplitude increases the magnitude of overshoot.

Table 4: Testing conditions for investigating the effect of amplitude of change of load current on the overshoot / undershoot behavior.

Ramp Rate (A/s)	Amplitude of Change (A/cm ²)	Current Change (A)	Starting Current (A)	Ending Current (A)
0.1, 0.3, 0.5	+ 0.1	+5	10	15
	+ 0.2	+10	10	20
	+ 0.3	+15	10	25
	+ 0.4	+20	10	30
	- 0.1	-5	15	10

	- 0.2	-10	20	10
	- 0.3	-15	25	10
	- 0.4	-20	30	10

Figure 6 shows the effect of amplitude on the undershoot behavior. The magnitude of undershoot increases linearly with the increase in the load amplitude. From the figure it can be observed that there exists a linear increase in the magnitude of undershoot when the amplitude of load change is increased. This is in agreement with the observation from Figure 5.

Both the plots for the effect of amplitude on the overshoot and undershoot shown in Figures 5 and 6 indicate that there is a direct linear trend. The larger the changes in load current, the larger is the magnitude of overshoot/undershoot that was observed. This indicates how a large change in gas flow rate and water generation directly plays into the overshoot/undershoot behavior. It is therefore suggested that large changes in load current should be avoided to avoid the large overshoot/undershoot in pressure drop. In the earlier section, it was observed that the ramp rate does not have a direct impact on the two-phase pressure drop overshoot/undershoot behavior. From these two trends, it can be suggested that short but rapid changes in the load current would be better. Rapid changes (large ramp rates) do not show any deviation from slow changes and would help to reduce the need for large changes in load current, which result in a larger overshoot/undershoot.

4. Discussion

In this work, it was observed that the two-phase pressure drop shows a peak when the operating current density is increased, before settling back down to the steady state pressure drop. As the

operating current density is increased, the air flow velocity increases as the volume of reactant gases being supplied increases. However, water is present in the reactant channels and therefore blocks the flow of the reactant gases. With the blockages present, the pressure drop continues to increase, until the pressure forces the water features to be removed from the channels. As more of the water leaves the channels, the pressure drop begins to decrease. With time, the new steady state is reached, where there is a new balance between the air flow rate and the water present in the reactant channels. It was observed in a previous work [11] that with increasing gas flow rates, there are different quantities of liquid water present, which needs to be removed for the pressure drop to reach steady state.

When the current density is decreased, the two-phase pressure drop decreases. It reaches a minimum point and then begins to increase, finally reaching the steady state pressure drop value. This dip can be explained due to changes in the saturation of the GDL. At a higher air flow rate, the GDL would have a lower saturation. As the gas flow rate decreases, the GDL would have a higher saturation, resulting in the ability of the GDL to store more water. Therefore, in the initial few seconds, the GDL continues to store the water produced by the reaction and therefore the pressure drop continues to reduce (with the reduction in air flow rates). However, once the saturation reaches a steady value, the water begins to enter the reactant channels and the pressure increases to reach the final steady state pressure drop value.

From the pressure drop overshoot / undershoot, it becomes apparent that presence of liquid water increases the overshoot behavior in the reactant channels. This is further reinforced by our investigation of the effect of temperature on the overshoot behavior. It was observed that overshoot behavior decreased when the temperature of the cell was increased to 60°C. As the temperature is increased, it had been observed from the findings our earlier work [11] that liquid

water presence is drastically reduced in the reactant channels. With this decrease in the presence of liquid water, the two-phase pressure drop overshoot is also decreased. Therefore, it seems conclusive that more liquid water in the reactant channels results in larger overshoots and larger transients. This is in contrast to the findings from literature that point to more water in the porous layers reduces the time of transience in the PEMFC operational behavior.

This also indicates that the relative humidity of the inlet gas streams would have a direct effect on the two-phase pressure drop overshoot / undershoot behavior. The RH influences the saturation pressure and thus affects the quantity of liquid water in the system. From the effect of temperature, it is apparent that the quantity of liquid water impacts the overshoot/undershoot phenomenon. Therefore the effect of inlet RH also needs to be investigated, in addition to the other factors investigated here.

The ramp rate of 'change of load' shows no particular change in the magnitude of overshoot / undershoot deviation. This indicates that the rate of change in the load does not directly affect the two-phase pressure drop. This is an important finding. It indicates that changing load does not need to be limited by the ramp rate. Thus, frequent changes in load can be made. In essence, this means that the rate at which water is introduced into the reactant channels does not have much of an impact on the two-phase pressure drop overshoot.

The effect of the amplitude of change is much more pronounced compared to the effect of ramp rate. Both plots for the effect of amplitude of change on overshoot and undershoot (Figures 5 and 6) show that there is a direct linear trend in the amplitude of change and the magnitude of deviation. The larger the change in load current, the larger the magnitude of overshoot that was observed. This indicates how the large change in gas flow rate and water generation directly

plays into the overshoot behavior and therefore, it is suggested that large changes in load current should be avoided to avoid the larger pressure drop. From these two trends, it can be suggested that short but rapid changes in the load current would be better, as rapid changes do not show any deviation from slow changes and would help to reduce the need for large changes in load current, which result in larger overshoot and more transient pumping power for the reactant supply systems. This would directly address the findings of Rabbani and Rokni [29] where they highlight the excess power consumed by the PEMFC auxiliary systems during transient operation. However, this suggestion would be incomplete without the cautionary note that similar trends may exist in the thermal transients and those need to be scrutinized to a greater degree.

A future aspect of this work could be the phenomenological modeling of the overshoot behavior in the two-phase pressure drop overshoot observed in the reactant channels. There is a time constant involved with the time water takes to emerge through the GDL from the catalyst layer. Additionally, there is a time constant involved in the change in saturation of the GDL. These two factors combined with the two-phase pressure drop modeling in PEMFC channels would be able to predict the magnitude of overshoot.

5. Conclusions

Overshoot/undershoot behavior in the cell voltage has been studied in literature when the load is changed. In a prior work, the authors reported the existence of overshoot/undershoot behavior in the two-phase flow pressure drop measured along the length of the reactant channels. A parametric study has been presented here to characterize the overshoot/undershoot in the

pressure drop and transient time (time taken to reach new steady state) following a transient incidence induced by change in load. The following conclusions are drawn from this investigation:

1. Two-phase pressure drop overshoot/undershoot behavior in PEMFC reactant channels is relevant only at lower temperatures. At temperatures of 60°C and higher, the pressure drop reaches a steady state within a few seconds of the load change. Contrarily, at the lower temperature of 40°C, it takes on the order of 100 – 1000 seconds for the pressure drop to reach a new steady state operation.
2. Ramp rates of the load change do not have an appreciable impact on the overshoot/undershoot behavior.
3. The amplitude of load change has a significant effect on the magnitude of pressure drop overshoot/undershoot. The pressure drop overshoot/undershoot increases with an increase in the amplitude of load change.
4. The magnitude of overshoot is larger than the magnitude of undershoot in all the tested cases in this study.
5. No particular relationship could be established for the time required to reach the new steady state values.
6. A longer time duration is required for the pressure drop to return to steady state after a transient undershoot compared to a transient overshoot.

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Figure Captions

Figure 1: Two-phase pressure drop when load is increased by 0.2 A/cm^2 at a rate of 0.1 A/s and a temperature of 40°C .

Figure 2: Two-phase pressure drop when the load current is decreased by 0.2 A/cm^2 at a rate of 0.1 A/s at a temperature of 40°C .

Figure 3: Effect of ramp rate on the overshoot behavior. Load is increased and the magnitude of overshoot is compared in this figure.

Figure 4: Effect of ramp rate on the undershoot behavior. Load is decreased and the magnitude of undershoot is compared.

Figure 5: Effect of amplitude on the overshoot behavior for three ramp rates of 0.1 , 0.3 and 0.5 A/s under increasing load conditions.

Figure 6: Effect of amplitude of change on the undershoot behavior for three ramp rates of 0.1 , 0.3 and 0.5 A/s under decreasing load conditions.