Modeling gas flow in PEMFC channels: Part I – Flow pattern transitions and pressure drop in a simulated ex situ channel with uniform water injection through the GDL

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Abstract
The two-phase flow in the gas channels of a proton exchange membrane fuel cell (PEMFC) is studied with an ex situ setup using a gas diffusion layer (GDL) as the sidewall of the channels. Air is supplied at the channel inlet manifold and water is supplied continuously and uniformly through the GDL along the length of the channel. This is different from the simultaneous air and water introduction at the inlet of the channel as studied by previous two-phase flow researchers. The GDL is compressed between the gas channels and the water chambers to simulate PEMFC conditions. The superficial velocity for air and water ranged from 0.25 to 34.5 m/s and 1.54 × 10^{-3} to 1.54 × 10^{-4} m/s, respectively. The ex situ setup was run in both vertical and horizontal orientations with two GDLs, — Baseline (Mitsubishi Rayon Co. MRC 105 with 5 wt.% PTFE and coated with an in-house MPL by General Motors) and SGL 25 BC — and three channel treatments — hydrophobic, hydrophilic, and untreated Lexan, with contact angles of 116°, 11° and 86°, respectively. No appreciable effect was noted because of the orientation, GDL type or channel coatings. The flow regime is observed at different locations along the channel and is expressed as a function of the superficial air and water velocities. Flow regime criteria are developed and validated against the range of ex situ data observations. A new variable water flow rate pressure drop model is developed in order to account for the variation of water entering the channel at multiple locations along the flow length. Pressure drop models are developed for specific flow regimes and validated against experimental data. The models are able to predict the experimental pressure drop data with a mean error of less than 14%.

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1. Introduction
The single-phase pressure drop of fluids is well understood and reliable methods are available for its prediction. The pressure drop during two-phase flow is however more difficult to predict. Through an emphasis on experimental investigation, a series of two-phase pressure drop models have been proposed in literature. The majority of early research prior to the year 2000 was done using large hydraulic diameter channels and the resulting models were found to be insufficient when predicting the pressure drops in mini-channels (200 μm–3 mm) and microchannels (10 μm–200 μm).
With the decreasing diameter of the channels, the effect of surface tension increases while gravity effects become relatively insignificant.

Heat exchangers, refrigeration systems, and mini-tube condensers have adopted minichannels for two-phase flow devices and studies have been reported for flow regime and pressure drop analysis in these channels. The operating ranges of these studies have been relatively limited, normally focusing on a particular area of interest.

With respect to proton exchange membrane fuel cells (PEMFCS), the earlier studies are of limited applicability as they were performed with the entire water flow being introduced at the inlet of the channel. However, PEMFCs have a continuous water introduction along the length of the channel due to the chemical reaction, which should be taken into account. In the present work, water is introduced along the entire length of the channel through a gas diffusion layer (GDL) sidewall and carried down the channel by the air flow, replicating the flow in an actual fuel cell. The minichannels, typically rectangular or trapezoidal, are employed as gas flow channels to deliver the reactant gases and to remove liquid water.

The channel pressure drop is of great relevance as it determines the reactant pumping power, which affects the system performance. The two-phase flow in a PEMFC encounters simultaneous heat and mass transfer, with multiple channels, channel bends, channel treatments, and different GDL surfaces. An ex situ test setup is used in the present work to simplify the system and remove the effects of heat and mass transfer and focus on the effects of the GDL and channel treatments on the pressure drop.

2. Literature review

Bosco and Fronk [1] identified the pressure drop within the channels of a PEMFC as indicative of the cell performance. As such, the pressure drop of two-phase flow systems has moved to the forefront of modern research. An exhaustive review of the two-phase flow in gas channels is provided by Anderson et al. [2]. The droplet emergence from GDL surface presents a unique configuration that is not investigated in literature.

Two approaches are typically used in the evaluation of the two-phase pressure drop. The first method modifies the single-phase pressure drop by either modifying the friction factor or by using the total mass flux of the system. The second method calculates the pressure drop as if one phase is flowing alone and then multiplies it by a two-phase friction multiplier. This multiplier is found by using characteristic flow parameters and weighting them to correlate experimental data.

The use of the first method is referred to as the homogeneous flow model and involves the modification of the viscosity and density to represent the two-phase flow with a pseudo single-phase flow. The different viscosity models are well documented and are presented in an overview by Saisorn and Wongwises [3].

The second method is typically referred to as the separated flow model and was first developed by Lockhart and Martinelli [4] in 1949. The two-phase pressure drop is represented as a function of the single-phase pressure drop and frictional multipliers $\varphi_l$ and $\varphi_g$ representing the ratio of two-phase to single-phase liquid and gas pressure drops.

Chisholm [5] later provided a correlation for predicting the frictional multiplier ($\psi$) through the use of the Martinelli parameter ($X$) and the Chisholm parameter ($C$). The Chisholm parameter was found to be dependent on whether each of the phases were in laminar or turbulent flow. The value of $C$ ranges from 5 for the laminar–laminar case to 21 for the turbulent–turbulent case.

\[
\varphi_g^2 = \left( \frac{\Delta P}{\Delta X} \right)_{f} = 1 + 1 \times X^2
\]  

Several modifications have been presented to the separated flow model to match experimental data. In 2001, Mishima and Hibiki [6] studied 1–4 mm hydraulic diameter channels and developed a new correlation for the Chisholm parameter $C$. They proposed that the hydraulic diameter had a direct impact on the actual value of $C$ and as the diameter decreased so did the Chisholm parameter. A value of 21 was used for the initial value of $C$ as conditions of turbulent–turbulent flow were observed.

\[
C = 21(1 - e^{-0.319D_h})
\]  

In 2001, Lee and Lee [8] correlated the Chisholm parameter as a function of the flow conditions and fluid properties. Through the use of three non-dimensional numbers (shown by Suo and Griffith [9] to be representative of liquid flow) the following correlation was proposed.

\[
C = 6.833 \times 10^{-6} \lambda^{-1.319} \psi^{0.719} \frac{\mu_l}{\mu}^{0.557}
\]  

Another researcher has tried different approaches relating the two-phase frictional multiplier to the Weber number, mass quality, and homogeneous properties of the two-phase flow. Sun and Mishima [11] related $C$ to the liquid Reynolds number and mass quality through the following equations:

\[
C = 7.599 \times 10^{-3} \lambda^{-0.631} \psi^{0.005} \frac{Re_{l}}{Re_{l}}^{0.008}
\]  

\[
\varphi_l^2 = 1 + \frac{C}{X^{1.15}} \times \frac{1}{X^2}
\]
Friedel [12] in 1980 related the two-phase frictional multiplier to the homogeneous flow properties of the phases using the mass flux, Weber number, Froude number, and three parameters based on liquid and gas phase properties and the quality.

Later in 2001, Hibiki and Mishima [13] identified bubbly, slug, churn, annular and annular-mist flow regimes in mini-channels. Bubbly flow was defined by a continuous liquid phase interspersed with gas bubbles. Slug flow was defined by liquid slugs blocking the channel, separated by elongated gas bubbles. Churn flow formed as the gas bubbles broke down and the liquid phase began to collect on the channel walls. Annular flow was marked by the collection of liquid water along the channel sidewalls as a thin film. Annular-mist flow was designated as the removal of water from the liquid film in the form of small droplets into the gas core.

In order to identify the flow regime present in the channel, transition criteria based on the properties of both phases are needed and are typically expressed in term of the superficial velocity of each respective phase. The criteria by Hibiki and Mishima [13], Ullmann and Brauner [14], Taitel [15], Xu et al. [16], and Jayawardana and Balakotaiah [17] are commonly employed to predict the flow patterns. The criteria developed by Jayawardana and Balakotaiah compared the liquid Weber number with the Reynolds number of the two phases, while the other transition criteria are dependent upon velocity and the void fraction in the system. Fig. 1 shows the transition criteria by Hibiki and Mishima [13] with bubbleslug, churn/annular and slug annular transition lines.

Other criteria proposed in literature are similar to the model developed by Hibiki and Mishima shown in Fig. 1. Kahara et al. [18] and Serizawa et al. [19] showed the effects of the water introduction method and inlet geometry on the flow regimes observed within the channels. They both showed that the geometry of the inlet and the method of introduction for each phase are critical in modeling the pressure drop. Hence any modification to how the phases are introduced to the channel would result in pressure drop variations. It is therefore desirable to utilize the data from the same water introduction method as in the actual system where the model will be applied.

Zhang et al. [20] studied the effect of flow patterns on pressure drop by considering two-phase flow in two parallel air flow channels. They used the entrance region pressure drop method developed by Kandlikar et al. [21] for measuring the instantaneous flow rates in the channels. They observed a strong relation between the water flow rate and flow patterns on the pressure drop and developed equations for pressure drop in slug and annular flow patterns. Earlier experiments by Zhang et al. [22] showed that high gas velocities are needed to avoid channel blockage with slugs.

The instantaneous flow patterns and flow rates observed by Lu et al. [23] in ex situ tests and by Sergi and Kandlikar [24] in situ tests were similar to those found by researchers using water injection at the entrance, confirming that the uniform water injection along the flow length does not introduce any new types of flow patterns. Using the instantaneous flow rate measurement and corresponding flow patterns, Kandlikar et al. [19] and Lu et al. [23] for ex situ, and Sergi and Kandlikar [24] for in situ experiments showed that the flow rate through a channel is dependent on the downstream flow pattern. The local water emergence in fuel cell channels depends on the local water production at the catalyst layer, the storage/discharge behavior in the GDL and the droplet emergence and removal characteristics in the channels. Considering that the total pressure drop across each channel is same at any given instance, a pressure drop modeling approach based on the total air and water flow rates appears to be more desirable.

The amount of liquid present in a gas channel is an important parameter affecting the two-phase pressure drop. St-Pierre [25] presents an excellent review of the methods used to detect water in gas channels. Although these techniques are very useful, implementing them in a working fuel cell is quite challenging. Sergi and Kandlikar [24] employed high speed visualization to obtain instantaneous and simultaneous water distributions in both anode and cathode channels of an in situ fuel cell. Using image processing, they presented a water coverage ratio parameter. However, before such techniques can be integrated with pressure drop predictions, flow fields with larger visualization access and extensive in situ data are needed.

3. Experiment

3.1. Experimental setup

The ex situ test setup designed in this study allows for the observation of two-phase flow within the 8 parallel gas channels as well as for the measurement of the pressure drop. The channels of the ex situ setup are cut into a block of Lexan to allow for visualization with a 1024 × 1024 pixel resolution high speed camera. The channels are 0.4 × 0.7 × 182 mm each with a 0.5 mm land dividing them as shown in Fig. 2. A 5° cutback weave is used to prevent shear stress on the GDL when clamped over the corresponding water channels. The water channels have the same geometry with an opposite cutback weave.

Deionized water is introduced into the channels by four Harvard Apparatus syringe pumps that are each connected to four separate water chambers. The multiple water chambers
provide a more uniform water introduction into the channels from the beginning to the end section. The use of a single water chamber would result in the introduction of water mainly towards the end of the channel where the water pressure is the highest. Each water section has three holes drilled in the supporting plate underneath the GDL. Water is thus introduced through these 12 holes placed at equal distance along the flow length. This configuration is based on the in situ observations reported in literature, such as Bazylak et al. [26] and Zhang et al. [27], that water emerges from fixed locations on the GDL surface.

Air is introduced through a bank of Omega rotameters. For air flow rates (AFRs) under 2000 sccm an Omega 3804G rotameter is used with a maximum range of 2300 sccm and an uncertainty of ±5% of that range (115 sccm). For AFRs above 2000 sccm an Omega 3508ST rotameter is used with a maximum range of 7500 sccm and an uncertainty of ±5% (375 sccm). For AFRs up to 500 sccm a digital flow meter is used to control the AFR within 0.5% of the recorded value. Fig. 3 shows the cross-section of the ex situ setup. It is similar to the test section used by Lu et al. [23].

The pressure drop across the flow channels is found using a Honeywell Sensotec FDW2AT differential pressure sensor with an uncertainty of ±0.25% for a range of 0–35 kPa. Eight additional Honeywell FP2000 differential pressure sensors (accuracy ±0.25% for 0–7 kPa) are used in the entrance of the individual air channels to measure the entrance region pressure drop. These measurements are used to estimate the instantaneous air flow rates through individual channels as described by Kandlikar et al. [21]. The exit manifold of the setup is left open to the atmosphere. To prevent water from blocking the exit manifold, a small piece of rolled paper was inserted at the exit from the manifold to facilitate water drainage.

The 8 individual pressure sensors are connected to the 8 channels in the entrance region and are used in the measurement of the AFR as well as for the investigation of the flow interactions among the channels. Since the pressure tap locations always encountered single-phase air flow in the entrance region, there was no issue encountered due to the water blocking the pressure taps. Using a PTFE sheet instead of a GDL sidewall, 7 of the 8 air channels were blocked and a known AFR was supplied. The procedure developed earlier by Lu et al. [23] was used in which the individual channel flow rate (AFR) was correlated by a polynomial fit with the individual channel pressure drop.

The ex situ setup was held at a compression of 2068 kPa (300 psi) using 4 springs. Two GDLs – Baseline (Mitsubishi Rayon Co. MRC 105 with 5 wt.% PTFE and coated with an in-house MPL by General Motors) and SGL 25BC – and three channel treatments – hydrophilic, hydrophilic and untreated Lexan with contact angles of 116°, 85° and 11° respectively – were investigated over the course of testing. A range of AFRs, corresponding to stoichiometric ratios varying from 1 to 45, were used in conjunction with 4 water flow rates that correspond to 4 simulated current densities. Table 1 gives the test parameters of the GDL and gas channels. Table 2 gives the air

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**Table 1** – Summary of tested GDLs and channel treatments.

<table>
<thead>
<tr>
<th>GDL</th>
<th>Channel treatment</th>
<th>Properties</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Hydrophobic</td>
<td>Hydrophilic</td>
</tr>
<tr>
<td>Baseline</td>
<td>x</td>
<td>x</td>
</tr>
<tr>
<td>SGL25-BC</td>
<td>x</td>
<td>x</td>
</tr>
</tbody>
</table>

**Table 2** – Summary of the test parameters.

<table>
<thead>
<tr>
<th>Water flow rate (mL/min)</th>
<th>Current density (A/cm²)</th>
<th>Superficial water velocity (m/s)</th>
<th>Air flow rate (sccm)</th>
<th>Superficial air velocity (m/s)</th>
<th>Air Reynolds number</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.02</td>
<td>0.2</td>
<td>1.50E-04</td>
<td>66–3962</td>
<td>0.5–29.5</td>
<td>14.8–891</td>
</tr>
<tr>
<td>0.04</td>
<td>0.4</td>
<td>3.00E-04</td>
<td>132–3962</td>
<td>1.0–29.5</td>
<td>29.7–891</td>
</tr>
<tr>
<td>0.10</td>
<td>1.0</td>
<td>7.40E-04</td>
<td>330–3962</td>
<td>2.5–29.5</td>
<td>74.2–891</td>
</tr>
<tr>
<td>0.20</td>
<td>2.0</td>
<td>1.50E-03</td>
<td>660–3962</td>
<td>4.9–29.5</td>
<td>148.3–891</td>
</tr>
</tbody>
</table>

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3.2. Flow pattern observations

During testing, three flow regimes were observed within the channels; slug, film, and mist flow. The presence of large water formations that obstructed the channels was designated as slug flow. Fig. 4(a) shows an image of the water formation (slug) growing to the width of the channel before moving down the channel. While the slugs cannot be observed to grow to the height of the channel due to imaging restrictions, it is highly plausible that the slug does completely fill the channel cross-section before it begins to move steadily down the channel. Fig. 4(b) shows the recorded pressure drop of the system. It was observed that during slug formation, the pressure drop in the entrance region for that channel increases and then decreases after the slug has cleared the channel. Fig. 4(c) shows the recorded AFR of the channels. Also, it was observed that when a slug formed in a channel, the AFR of that channel dropped and once the slug cleared the channel, the AFR increased. It may be noted that the overall pressure drop was not significantly affected by this slug occurrence in an individual channel.

The presence of water along the channel sidewall in a thin film was designated as film flow. Water droplets grew from the GDL and contacted the channel sidewalls. Once in contact, the water immediately began to move down the channel walls as shown in Fig. 5(a). Unlike during slug flow, the liquid water never fully blocked the channel width. Fig. 5(b) shows the recorded pressure drop during film flow during which rapid fluctuations were observed. These frequencies are caused by partial channel blockages as the droplets emerged from the GDL and partially blocked the channels before being pulled to the channel walls. Fig. 5(c) shows the recorded AFR during film flow and the same fluctuations seen in the pressure drop are evident in the AFR.

The flow with complete lack of water formation on the channel walls was designated as mist flow. Mist flow occurs when liquid water is pulled from the GDL sidewall as small droplets which are carried within the core of the gas flow as a fine mist. The water balance indicated that the amount of liquid water present at the exit far exceeded the saturation humidity ratio in the exit air. Similar observations were made by English and Kandlikar [7] in their experiments. Fig. 6(a) shows the water droplets were too small to be seen with the imaging techniques used in this study. Fig. 6(b) shows the pressure drop during mist flow and the pressure drop signature shows no fluctuations as there are no water formations within the channel. Fig. 6(c) shows the AFR of mist flow and, similar to the pressure drop, there were no fluctuations due to the lack of water formations.

3.3. Single-phase validation

In order to evaluate the ex situ test setup, the experimental pressure drop with the PTFE sheet (in place of the GDL) is compared with the calculated pressure drop for single-phase gas flow. The head loss as well as frictional loss is taken into account following the method described by Kandlikar et al. [21]. Fig. 7 shows that the predicted pressure drop falls

---

**Fig. 4** – Findings from the test performed at a water flow rate of 0.1 mL/min and an air flow rate of 330 sccm. a) Image of liquid slugs forming in the channels. b) Spikes in the pressure drop signature due to channel blockage with slugs. c) Air flow rate signatures of the 8 parallel channels during slug flow showing a drop in the individual channel AFRs due to slug formation.
within the uncertainty associated with the pressure drop measurement.

Through the single-phase validation, the intrusion of the GDL is also considered. GDL intrusion was identified as a contributing factor to the increase in pressure drop by St-Pierre et al. [25]. Kandlikar et al. [21,28] proposed that under compression, the GDL sidewall intrudes into the channel constricting the cross-section of the channel unevenly at

Fig. 5 — Findings from the test performed at a water flow rate of 0.04 mL/min and an AFR of 1981 sccm. a) Image of liquid film forming along the channel walls. b) Fluctuations in the pressure drop due to the liquid water droplets moving to the channel sidewall. c) Fluctuations in the AFR in the 8 parallel channels caused by the liquid water droplets forming and moving to the sidewall.

Fig. 6 — Findings from the test performed at a water flow rate of 0.02 mL/min and an AFR of 2311 sccm. a) Image of the channels during mist flow where no liquid formations were seen. b) The pressure drop signature remained constant across the range of the test. c) The AFR remains constant in all channels across the range of the test.
different locations, and a pressure drop measurement provides a means of evaluating an average equivalent intrusion. The experimental pressure drop is compared with the single-phase pressure drop under different intrusion values. An average intrusion of 15.9 μm is found to represent the pressure drop data well and is used for all further calculations. Fig. 8 shows the pressure drop calculated with various intrusions compared to the experimental pressure drop. Error bars are excluded to prevent cluttering.

3.4. Correlation of experimental data to literature

Before developing the model for fuel cell gas channels, the pressure drop of the two-phase system was compared to the separated flow models discussed previously. It is worth noting that over the range of the air and water velocities observed during the study, the various separated flow models yield similar results that are very close to each other. The results of data comparison with the model developed by English and Kandlikar [7] are presented below. The mean error between the experimental data and the theoretical predictions using average water flow rate was found to be 66%.

![Figure 7](image-url)  
**Fig. 7** – Single-phase pressure drop validation using a PTFE sheet to prevent gas crossover into the water chambers.

Figure 9(a) shows the complete range of experimental data plotted against the pressure drop model developed by English and Kandlikar [6] using the average water flow rate. This model is mainly developed based on the film flow and mist flow data. Fig. 9(b) shows the results at low superficial air velocities (0–6 m/s) corresponding to slug flow. A mean error of 104% is observed in the predicted and experimental pressure drop values. Intermediate air velocities (6–20 m/s) corresponded to film flow, and a mean error of 30% was found in the pressure drop, as shown in Fig. 9(c). At high superficial air velocities (20–35 m/s) corresponding to mist flow, a mean error of 16% was found in the pressure drop plot shown in Fig. 9(d). The large errors noted in these figures are mainly attributed to the use of constant water flow rate at the channel average value. To account for the variation of water flow rate along the channel length, a variable water flow rate model is developed and is presented in the next section.

3.5. Effect of GDL, channel coatings and orientation

As summarized previously in Table 1, the experiments were conducted with plain Lexan channels, and channels coated with hydrophilic and hydrophobic coatings. The static contact angles with these surfaces were 86°, 11° and 116° respectively. The pressure drops with all three channel treatments are found to be similar and are incorporated in the pressure drop model. The orientation also did not show any effect on the two-phase pressure drop data. Similarly, the GDL material (Baseline and SGL 25BC) did not show any effect on pressure drop over the ranges of parameters tested. From these observations, it is noted that the orientation and channel surface characteristics do not affect the pressure drop behavior in the current microscale channels (0.4 mm × 0.7 mm).

4. Development of a pressure drop model with variable water flow

As liquid water is introduced continuously, the water flow rate and thus the mass quality increase along the channel length. This is accounted in a variable water flow rate pressure drop model presented in this section. To more accurately model the pressure drop of the test setup, the channel is divided into 14 elements as shown in Fig. 10. The average water flow rate within each element was used in the pressure drop estimation for that section. The four water chambers were divided into three elements each for a total of 12 elements each measuring 13.83 mm in length. The remaining two elements represent the entrance and exit of the test setup. Each of these two elements is 20 mm in length and the first element is found to be always in the single-phase gas flow.

The complete modeling procedure is represented by the flow chart in Fig. 11. Further details of the procedure are as follows.

1) Using the input water flow rate, each of the elements is assigned a water flow rate.
2) Flow regime transition criteria are then used to determine the gas transition velocities for the flow regimes and are...
compared to the input air velocity for the assignment of flow regimes. The transition criteria are presented in Section 5.

3) A corresponding pressure drop model is used to find the two-phase frictional multiplier of the element and is multiplied by the single-phase gas pressure drop of the element. The pressure drop models are presented in Section 6.

4) Steps 2 and 3 are repeated for all 14 elements and the pressure drop from each element is summed.

5) Additional head losses for the entrance header, exit manifold, and developing flow in the single-phase region are calculated and summed up with the elemental pressure drop to obtain the total pressure drop of the setup.

Fig. 9 – Modeling of pressure drop for a water flow rate of 0.04 mL/min. a) Comparison of the experimental pressure drop with the pressure drop model developed by English and Kandlikar [6] using average water flow rate in the channel. b) Comparison with slug flow data at lower flow rates. c) Comparison with film flow data. d) Comparison with mist flow data.

Fig. 10 – Schematic showing the elements employed in the variable water flow rate pressure drop model.
Before applying a specific pressure drop correlation to each element, first transition criteria are developed to predict the existing flow patterns as a function of superficial air and water velocities and relevant fluid properties of the two phases.

5. Flow pattern transition criteria

Ex situ data were classified into slug, film, and mist flow using images taken during testing. When compared to previous transition lines established by Hibiki and Mishima [13], it became readily apparent that the transitions proposed by them all occur at very low air velocities, below 1 m/s. The transitions observed in this study occur later than those from previous studies as shown in Fig. 12. Transition lines are drawn based on the observed flow patterns. This is believed to be due to the method of water introduction which affects the two-phase flow phenomena. The transition lines shown close to the \( y \)-axis corresponding to superficial air velocities below 1 m/s are based on the previous models available in the literature. These are not applicable due to the high superficial velocities and the

Fig. 11 – Flow chart illustrating the calculation procedure in the variable water flow rate pressure drop model.

Fig. 12 – Experimental data classified into flow regimes and compared to the previous transition criteria and the observed criteria. The transition criteria defined by Mishima and Hibiki [12] all take place before 1 m/s while experimental transitions occur after 5 m/s.
microscale channel dimensions employed in the present fuel cell channels. The other two lines shown on the right side represent the current slug–film and mist–film transitions proposed in this work. The equations for these lines are derived based on a force balance model described below.

The slug flow is dominated by the surface tension as the liquid phase blocks the channel and the Weber number is used to represent this flow regime. Film flow is dominated by the viscous forces between the gas and liquid phases and the Reynolds number is used to represent this flow regime. Mist flow is dominated by the gas phase overcoming the forces in the liquid phase and is represented by the ratio of the viscous gas force and the surface tension force.

Comparing the dominant forces of the slug and film flow regimes, the following transition criterion is obtained.

\[
\frac{Re_G}{Re_L} = \frac{We_L^{1.726}}{C_{20}} 
\]

Comparing with the experimental data, the exponents and the leading constant are modified as follows to better represent the transition criterion.

\[
\frac{Re_G}{Re_L} = 2.808 We_L^{0.216} 
\]

In terms of the superficial gas velocity, the transition criterion between slug to film flow regions may be expressed as:

\[
U_c = \frac{2.808 We_L^{0.216}}{\left( \frac{\rho_G \mu_G}{\rho_L \mu_L U_L} \right)^{0.526}} 
\]

The transition from film to mist flow is found by comparing the dominant forces resulting from inertial, viscous and surface tension forces in the two phases.

\[
\frac{Re_G}{Re_L} = \frac{\mu_G U_c}{\sigma} 
\]

The exponents and the leading constant in the above equation are determined by comparing the film to mist flow transition observed in the experimental data. The following equation is obtained as the best fit resulting from this comparison.

\[
1.283 \left(\frac{Re_G}{Re_L}\right)^{-0.64} = \left( \frac{U_c \mu_G}{\sigma} \right)^{1.116} \]

The above equation is rewritten in terms of the superficial gas velocity representing the following transition criterion between film and mist flow regions.

\[
U_c = \left[ 1.283 \left( \frac{\rho_G \mu_G}{\rho_L \mu_L U_L} \right)^{-0.64} \right]^{1.116} \frac{1}{\sigma}^{1.726} \]

6. Pressure drop modeling

The new variable water flow rate pressure drop model presented in Section 4 is used in conjunction with the two pressure models available in the literature for constant water flow rate applied in each element. The constants in these models are modified to match the experimental data for the ex situ case. The details are given in Sections 6.1 and 6.2 below.


In an attempt to understand how the pressure drop varies with respect to the C value defined by English and Kandlikar [6], the value of C is back calculated from experimental pressure drop data using Equation (3). The calculated values of C range from 3000 to 100. This indicates that for small channels, the presence of water increases the pressure drop considerably as compared to the macroscale tubes for which the constant C is between 5 and 21. Fig. 13(a) shows a plot of the calculated values of C which vary proportionately with the ratio of air to liquid quality \((1-x)/x\). It was observed that as the flow regime changes to film flow, the value of C decreases. Mist flow does not correlate with this model as it is more appropriately expressed using homogeneous flow model. The following equation form is used to correlate the value of C as a function of the quality ratio.

\[
C = A \left( \frac{1-x}{x} \right)^b 
\]

Fig. 13(b) shows the variation of the constant A in relation to the superficial water velocity \((u_L)\). Similarly, Fig. 13(c) gives the value of the exponent b in relation to the superficial water velocity \((u_L)\). The following equations give the value of the constant A and exponent b respectively.

\[
A = 0.0856 (u_L)^{-1.200} 
\]

\[
b = 0.004 (u_L)^{-0.526} 
\]

Using these constants, the pressure drop is calculated for each data point. Fig. 13(d) shows the comparison of experimental data for slug and film flow plotted against the modified English and Kandlikar [6] model. The mean error is 14% between the experimental and the predicted values.

For mist flow, use of homogeneous flow model is recommended. Transition criterion given by Equation (14) is used to predict the transition to mist flow.


Due to the success of modifications to the Chisholm parameter (C) using fluid properties, the pressure drop model developed by Lee and Lee [7] is also investigated. This model correlates the Chisholm parameter with the liquid properties. As the pressure drop equation for each of the flow regimes is different, the ratio of the mass quality is used to create dependence between the C parameter and the liquid water flow rate in each channel.

Each of the terms in the original Lee and Lee correlation is weighted in order to reduce the mean error between experimental and theoretical data. The liquid to air quality ratio, \((1-x)/x\), is added to the original Lee and Lee model. The
following equations are obtained from the data analysis for the slug flow and film flow respectively.

**Slug Flow:**

\[
C_s = \frac{1.9087 \text{Re}^{-0.405} \lambda^{0.134} \psi^{-0.421} \left(1 - \frac{X}{x}\right)^{-0.107}}{\left(\frac{1}{C_0} + \frac{1}{C_1} \lambda \psi \left(1 - \frac{X}{x}\right)^{0.034}\right)}
\]  

(18)

**Film Flow:**

\[
C_f = 0.772 \text{Re}^{0.651} \lambda^{0.065} \psi^{-1.716} \left(1 - \frac{X}{x}\right)^{0.034}
\]  

(19)

Equation (18) represents the new Chisholm parameter for slug flow and is plotted in Fig. 14(a), while Equation (19) represents the new Chisholm parameter for film flow and is plotted in Fig. 14(b). The new Chisholm parameter values are found to vary from 46 to 384 for slug flow and 4.28 to 99.7 for film flow. The mean error of the new pressure drop model is 14% for slug flow and 4% for film flow.

In using the modified Lee and Lee model, transition criterion between slug and film flow is also needed, while in modified English and Kandlikar model presented in Section 6.1, the two regions were represented by a single set of equations. Equation (11) is used to predict the transition between slug and film flow regions. For mist flow, the use of homogeneous flow model, presented in Section 6.3, is recommended. Equation (14) is recommended for predicting transition to the film flow region.

### 6.3. Mist flow modeling

Mist flow is modeled using homogenous flow model developed by Dukler [29]. The single-phase pressure drop equation is used with the total mass flow rate of the two phases along with the modified fluid properties. The average viscosity and density values used in the homogeneous flow model are given by the following equations.

\[
\mu_{\text{eff}} = \beta \mu_\text{G} + (1 - \beta) \mu_\text{L}
\]  

(20)

\[
\rho_{\text{eff}} = \left[\frac{1}{\rho_\text{G}} + \frac{1 - X}{\rho_\text{L}}\right]^{-1}
\]  

(21)

As mist flow exhibits small liquid droplets within the gas flow, the homogeneous model is appropriate as the liquid droplets will flow at the same velocity as the gas phase. The model predictions are compared with the experimental data in Fig. 14(c). The mean error between the predicted and experimental values is 6%. The complete analysis across all flow regimes is plotted in Fig. 14(d) and the mean error is 9%.
6.4. Comparison of modified constant flow rate pressure drop correlations with English and Kandlikar data

The proposed pressure drop modification to Lee and Lee’s model is also compared to the earlier data published by English and Kandlikar [6] for constant water flow rate through the channel length. Four gas velocities were tested across a range of mass qualities from 0.1 to 1. Using the above developed modification to Lee and Lee’s model presented in Section 6.2, the pressure drop was predicted and compared with English and Kandlikar data. Fig. 15 shows the correlation between the model developed in this paper and the pressure drop data of English and Kandlikar. A mean error of 4% is found between the experimental data and the pressure drop predicted using the new model. Similar results were obtained with the modified English and Kandlikar model described in Section 6.1.

The agreement between English and Kandlikar [6] data and the above developed modified models suggests that the presence of GDL itself does not significantly affect the pressure drop within the channels. The only significant effect of the GDL on the pressure drop is how the water is introduced into the channel through the GDL. The other effect introduced by GDL is due to intrusion, which needs to be taken into account in modifying the flow cross-sectional area and in predicting the single-phase pressure drop as described in Section 3.3.

7. Comparison of the two constant water flow rate model modifications given in Sections 6.1 and 6.2

The modified English and Kandlikar model combines the slug and film flow regions and presents a single equation, Equation (15), for the two-phase pressure drop. The modified Lee and Lee model presents two separate equations for slug and film flows, given by Equations (18) and (19) respectively. The transition criterion between the slug and film flow patterns is given by Equation (11). This criterion is not needed while using the modified English and Kandlikar model. The selection of the final model will depend on their performance with the additional data sets, especially from the in situ testing, and introduction of other key PEMFC parameters such as gas consumption along the flow length.
The proposed variable water flow rate pressure drop model using either of the two models for constant water flow rates results in good agreement with the ex situ experimental data as seen from Figs. 13 and 14 within 14 percent. For mist flow transition using both modified English and Kandlikar, and modified Lee and Lee models, the criterion given by Equation (14) is applied. The homogeneous model given by the single-phase pressure drop equation using total mass flow rate and average properties given by Equations (20) and (21) is recommended in the mist flow region.

8. Conclusions

The differences observed between previously developed pressure drop models and the ex situ data are mainly due to the method of liquid introduction into the channels. In the conventional two-phase flow experiments, water is introduced at the entrance, and the flow rate remains constant along the channel length. In an actual fuel cell, water is introduced continuously along the flow length and the water flow rate is variable. In addition, the flow regime also changes along the length of the channel due to variable water flow rate, as opposed to a single flow regime observed in constant water flow rate experiments. Based on the ex situ experiments and modeling of pressure drop with variable water flow rate applicable to PEMFC, the following specific conclusions are drawn.

- Two-phase flow pressure drop experiments are performed in transparent gas channels of the same dimensions, (0.4 mm x 0.7 mm x 182 mm in length), as used in the actual PEMFC being currently investigated, with one side wall made of gas diffusion layer (GDL). Water is introduced uniformly at twelve locations along the flow length to simulate the fuel cell conditions. Flow regimes are observed along the flow length using high speed imaging and corresponding pressure drop data are recorded. Experiments were conducted with two GDLs, hydrophilic and hydrophobic channel surface coatings, and vertical and horizontal orientations. The effect of coating and orientation was negligible on flow patterns and pressure drop.
- Three flow regimes were found to be predominant – slug, film, and mist flow. Using a force balance approach, new transition criteria, Equation (11) for slug to film and Equation (14) for film to mist, are developed to predict the instantaneous two-phase flow regimes at given air and water flow rates.
- The three observed flow regimes within the channels were effectively predicted using the new transition criteria for the two GDL samples in both horizontal and vertical orientations with untreated, and with hydrophobic and hydrophilic coatings. The setup orientation and channel treatment did not have a significant effect on the transition criterion.
- Two-phase flow models available in the literature with a constant water flow rate were unable to predict the pressure drop by using the average water flow rates.
- A new variable water flow rate pressure drop model is developed using the pressure drop data for individual two-phase flow regimes within the channel as the basis. This model is directly applicable to PEMFC as it incorporates the increased water flow rate along the length of the channel due to the water introduction through the GDL. The flow length is divided into fourteen small elements and the constant flow rate pressure drop model available in the literature was applied in each element.
- Two successful models available in literature with constant water flow rate in minichannels by English and Kandlikar [6] and Lee and Lee [7] were modified and incorporated in the proposed variable water flow rate model. Both modifications resulted in good agreements, within 4–14%, with the ex situ data obtained in the present work. The modified English and Kandlikar, and Lee and Lee models were also able to correlate the experimental data of English and Kandlikar [6] with constant water flow rate in the entire channel with a mean error of 4%.
Two important points that this model does not address that may become significant in an operating PEMFC are the effects due to operating temperature variation and variable gas flow rate due to gas consumption and water vapor addition/reduction. In the case of cathode channels, the oxygen is consumed and water vapor is added or removed, while in the anode channels, hydrogen is consumed and water vapor is added or removed. The applicability of these models with hydrogen gas flow also needs to be tested. These factors can be readily accounted for in the proposed model and an extended variable water and gas flow rate model can be readily developed for actual fuel cell operation. This work is currently under progress and will be presented in depth in future publications.

Acknowledgment

This work is conducted in the Thermal Analysis, Microfluidics and Fuel Cell Laboratory in the Mechanical Engineering Department at Rochester Institute of Technology and was supported by the US Department of Energy under contract No. DE-EE0000470.

Nomenclature

- \( A_c \): Channel cross-sectional area, \( m^2 \)
- \( C \): Chisholm Parameter
- \( D \): Diameter, \( m \)
- \( G \): Mass Flux, \( kg/m^2s \)
- \( \Delta P \): Pressure drop, \( Pa \)
- \( Re \): Reynolds Number, \( Re = \frac{\rho u D_h}{\mu} \)
- \( u \): Superficial velocity of a phase, volumetric flow rate of the phase divided by the channel cross-sectional area, \( m/s \)
- \( We \): Weber Number, \( We = \frac{\rho u^2 D_h}{\sigma} \)
- \( x \): Quality, ratio of liquid mass flow rate to total mass flow rate
- \( X \): Martinelli Parameter, \( X = \left( \frac{\mu_L}{\mu} \right)^{0.5} \left( \frac{\mu_L}{\mu_G} \right)^{0.1} \left( \frac{1-x}{x} \right)^{0.9} \)

Greek symbols

- \( \beta \): Volumetric Quality
- \( \lambda \): Parameter, \( \lambda = \frac{\mu^2}{\rho \sigma D_h} \)
- \( \mu \): Viscosity, \( kg/m^2s \)
- \( \rho \): Density, \( kg/m^3 \)
- \( \sigma \): Surface Tension, \( N/m \)
- \( \phi \): Two-Phase Frictional Multiplier, \( \phi^2 = \frac{\frac{dP}{dx}}{\frac{dP}{dx}}_{TP} \)
- \( \psi \): Parameter, \( \psi = \frac{\mu_L(U_G + U_L)}{\sigma} \)

Subscripts

- \( f \): Film
- \( F \): Frictional

R E F E R E N C E S

18. Kawahara A, Chung PM-Y, Kawaji M. Investigation of two-phase flow pattern, void fraction and pressure drop in...


