Two-phase flow in the minichannels of proton exchange membrane fuel cells (PEMFC) flow field plates

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Abstract – This work focuses on the gas-liquid flows in the cathode plate, with the objective to observe their patterns, to understand their behavior, to estimate the pressure drops and eventually, to reduce clogging and its possible consequences in term of oxygen starvation downstream. A special emphasis is put on the effect of the channel section (typically between 0.5 and 1 mm²) and on the surface properties of the flow field plate materials. The experiments are performed ex-situ. The pressure drop is measured locally along the channel as well as globally between the inlet and outlet, which put forward the existence of clogging/unclogging sequences. The characteristic frequency of these sequences increases with the air flow rate. Two main flow patterns have been observed depending on the distance from the inlet. Finally, the results show that the ratio of pressure drops in two-phase flow to pressure drops in dry flow decreases with the air flow rate while it does not seem to depend on the channel size (within the tested range).

Nomenclature

\begin{align*}
F & \quad \text{Faraday constant, C/mol} \\
HR & \quad \text{relative humidity} \\
J & \quad \text{current density, A/cm}^2 \\
l & \quad \text{width of the channel, m} \\
L & \quad \text{length of the channel, m} \\
N & \quad \text{flow rate, mol/s} \\
P & \quad \text{pressure, Pa} \\
P_v & \quad \text{vapor pressure, Pa} \\
P_{v\text{,sat}} & \quad \text{vapor saturation pressure, Pa} \\
PD & \quad \text{pressure drop, Pa} \\
PD^* & \quad \text{normalized pressure drop} \\
S_{air} & \quad \text{stoichiometry of air} \\
T & \quad \text{temperature, K} \\
\alpha & \quad \text{water partition coefficient} \\
\delta & \quad \text{bubbler} \\
d & \quad \text{dry air} \\
i & \quad \text{inlet} \\
o & \quad \text{outlet} \\
liq & \quad \text{liquid} \\
air & \quad \text{air}
\end{align*}

1. Introduction

Water management is one of the most critical issues affecting PEMFC performances, reliability and durability. Depending on the operating conditions and on the system/stack design, a compromise has to be found between the hydration of the membrane (and of the ionomer in the electrodes) and the risk of liquid water accumulation in the backing layers as well as in the flow field plates, which would increase the pressure drops and hinder gas flow [1][2].

The effect of the channel section and of the surface properties of the flow field plate materials are studied ex situ with experiments simulating the two-phase flows occurring in PEMFC.
2. Channels and plates

The three studied channels have the same width (1 mm) and the same length (225 mm) but they have different depth: 0.4, 0.7 and 1 mm. For these three channels, global pressure drops (between the inlet and the outlet) as well as local PD (ΔP_i) have been measured thanks to 2 pressure drop sensors (0-30 and 0-160 mbar) at the extremity of the plate and 6 others (0-12 mbar) along the channel respectively (Figure 1 and Figure 2).

Measurements have been done with dry air flow and two-phase flow (humid air-water) simulating the flow in the cathode channels. The studied plates are in Dural and they have a 20 micrometers thick nickel coating in order to avoid oxidation.

![Figure 1](image1.png) Channel with the positions of the pressure drop sensors

![Figure 2](image2.png) CAD representation of the plate and channel

The plate, with its engraved channel, is inserted between 4 heat exchangers which control the channel inlet and outlet temperature. Indeed, the temperature is very important for this experience because its variation along the channel is responsible for the liquid water appearance due to vapor condensation. Thus its evolution has to be controlled and imposed precisely. Then the upper face of the channel is closed with a polycarbonate plate which allows to observe the flow. Finally a clamping plate holds these pieces together (Figure 3).

![Figure 3](image3.png) CAD representation of the pieces assemblage
3. Simulating the two-phase flow occurring in a working fuel cell

3.1. In a fuel cell
Humid air is introduced at the cathode of a fuel cell. During its flow along the channel, it enriches in
the water vapor produced by the oxydoreduction reaction. Thus, the vapor pressure increases and
when it reaches the saturation pressure, liquid water appears. Assuming the temperature, the pressure,
the water partition coefficient and the current density uniform, the liquid water flow increases linearly.
The water flow rate exiting the fuel cell at the cathode channel outlet is a function of the dry air inlet
flow rate in mol/s:

\[
N_{\text{H}_2\text{O}}^0 = N_{\text{air}}^i \frac{1 - \alpha}{2.5 S_{\text{air}}} \]

With \(S_{\text{air}}\) the air stoichiometry and \(\alpha\) the water partition coefficient which represents the ratio between
the water flow rate at the outlet of the cell at the anode and the total amount of produced water.

3.2. In the simulation experiment
Saturated air at the temperature \(T_b\) of the bubbler is introduced at the inlet of the channel. The inlet
temperature, \(T_1\), is set to a value slightly higher than \(T_b\) and the outlet temperature, \(T_3\), to a value much
smaller than that of the bubbler. Thus, vapor condensates along the channel (Figure 4). The
temperature field of the inner surface of the channel \(T(x)\) sets the amount of condensed water.

\[\text{Figure 4 : Experimental setup}\]

The liquid water flow rate at the outlet of the channel is equal to the difference between the water
vapor flow rates at the inlet and at the outlet, that is to say, in mol/s:

\[
N_{\text{liq H}_2\text{O}}^0 = \left[ \frac{P_{\text{sat}}(T_b)}{P - P_{\text{sat}}(T_b)} - \frac{P_{\text{sat}}(T_3)}{P - P_{\text{sat}}(T_3)} \right] N_{\text{air}}^i \]

3.3. Link between the experiment and the fuel cell
By equaling the liquid water flow rate from equations (1) and (2), the following relation is obtained:

\[
\frac{P_{\text{sat}}(T_b)}{P - P_{\text{sat}}(T_b)} = \frac{P_{\text{sat}}(T_3)}{P - P_{\text{sat}}(T_3)} = \frac{1 - \alpha}{2.5 S_{\text{air}}} \]

\[\text{(3)}\]
Thus, when working at atmospheric pressure and setting the water partition coefficient, the air stoichiometry and the inlet temperature, the bubbler temperature (dew-point temperature) can be calculated in order for the amount of water produced in the ex situ experiment to be equal to the amount of water flowing in the fuel cell. For all the presented experiments, $\alpha = 0.5$, $S_{\text{air}} = 2.5$ and $T_3 = 8^\circ\text{C}$. Thus, we obtain $T_b = 43^\circ\text{C}$.

4. Pressure drops as function of the channel depth and current density

The tables below present the values of dry and humid air flow rates studied. The data are the times, all the more long in diphasic when the flow rate is low. As discussed in section 5, the pressure fluctuates due to the appearance of droplets and slugs. In a fuel cell, the air flow rate is a function of the electrical current according to equation (4). Therefore, the corresponding current densities are also presented.

$$I = \frac{4F}{5 \times S_{\text{air}} \times 60 \times V_m \times 2 \times l \times L N_{\text{air}}} \tag{4}$$

| Flow rate (NL/min) | Current density (A/cm²) | Time (s) |
|--------------------|-------------------------|----------|
| 0.0166             | 0.0743                  | 840      |
| 0.05               | 0.224                   | 840      |
| 0.0833             | 0.373                   | 840      |
| 0.1333             | 0.597                   | 840      |
| 0.25               | 1.12                    | 840      |
| 0.3333             | 1.49                    | 840      |
| 0.4166             | 1.86                    | 840      |
| 0.5                | 2.23                    | 840      |

**Table 1**: Dry air

| Flow rate (NL/min) | Current density (A/cm²) | Time (s) |
|--------------------|-------------------------|----------|
| 0.0166             | 0.0743                  | 99500    |
| 0.05               | 0.224                   | 29700    |
| 0.0833             | 0.373                   | 19600    |
| 0.1333             | 0.597                   | 15600    |
| 0.25               | 1.12                    | 12200    |
| 0.3333             | 1.49                    | 9500     |
| 0.4166             | 1.86                    | 4500     |
| 0.5                | 2.23                    | 2500     |

**Table 2**: Humid air

4.1. Pressure drops with dry and humid air

The pressure drops ($PD$) variations for the three channels supplied with dry and humid air as functions of current density are shown in figures 5 and 6 below.
According to the theory, we can see that the narrower the channel, the more important $PD$ are with dry air. As expected, they are proportional to the current, thus to the flow rate. Concerning the humid air $PD$, they are higher than the dry ones at the same current density and their variations are not linear.

4.2. Normalized pressure drops

We introduce $PD^*$, the normalized pressure drop, that is equal to the ratio of $PD$ in dry air to the $PD$ in humid air for the same total flow rate; its variation as a function of the current density for the three channels depths is given in Figure 7. It can be seen that $PD^*$ decreases as the current density increases, sharply at low flow rates and slower at high flow rates; however, $PD^*$ does not depend on the depth of the channel excepted at very low flow rates.

![Figure 7: Normalized PD in the 3 channels](image)

5. Temporal fluctuations of the pressure drops

5.1. Observation of the flow patterns

The values of $PD$ presented above are average values. In two-phase flow, the pressure drop fluctuates with time due to the clogging/unclogging of the channels with liquid. Figure 8 shows an example of global and local pressure drops fluctuations measured in the channel of 0.4 mm in depth and a flow rate of 0.0166 NL/min.
With a camera it was possible to observe the two-phase flows in this channel. Different regions with different flow patterns and behaviors can be identified (Figure 9). The local pressure drop $\Delta P_1$ is measured in the first part (near the channel inlet), $\Delta P_2$ and $\Delta P_3$ are measured in part 2 and $\Delta P_4$ and $\Delta P_5$ are measured in part 3.

- Firstly, in part 1, the local pressure drop $\Delta P_1$ is higher than the dry one (0.7 mbar) and is roughly constant over time. This may be explained by the fact that in this area, the water droplets start to appear on the channel walls.

- In the second part, the evolution of the local pressure drops $\Delta P_2$ and $\Delta P_3$ is different. Indeed, in humid air these PD are higher than in dry air, but they are also not at all constant. Clogging and unclogging sequences can be observed with a progressive increase of PD and then a sharp decrease (Figure 8). This may be explained by the fact that the droplets that appear in this region swell, coalesce and then are eventually evacuated due to the kinetic energy of the air flow.

- Finally, in the last part of the channel (area 3), the local PD 4 and 5 are very close to those measured with dry air because there are very small droplets in these regions. Indeed the droplets are carried away by the upstream falling drops, so they have not time to grow and to obstruct the channel.

**Figure 8**: PD at a 0.0166 NL/min flow rate and the channel of 0.4 mm depth
5.2. Variation in pressure drop
On the following graph, the standard deviations of pressure drop in dry and humid air are shown (Figure 10).

![Graph showing standard deviations in dry and humid air for the 0.7 mm depth channel](image)

**Figure 10**: Standard deviations in dry and humid air for the 0.7 mm depth channel

In dry air, the standard deviation for each measurement is very low. Conversely, standard deviations are important in humid air. This is due to unceasing cloggings and uncloggings which make the pressure drop vary around its mean value.

5.3. Eigenfrequency of the cloggings/uncloggings
The autocorrelation method was used to determine the eigenfrequency of the cloggings and uncloggings. Although the phenomenon is not perfectly periodic, one frequency stands out of the crowd. The frequency obtained for each flow rate is presented in Figure 11.

Figure 11 shows that, on average, the characteristic period decreases with the flow rate and therefore with the current density and that this trend is even more important at low flow rates. This observation is important because it indicates that for sufficiently high flow rates, the unclogging of fuel cells channels will take place frequently enough to avoid plugging of the channel.
6. Conclusion

Measurements of the local and global pressure drops allow to highlight cloggings and uncloggings sequences. At low flow rates, the pressure drop in the channel gradually increases and then decreases sharply. The frequency of these sequences increases with the air flow rate. Furthermore it was shown that the ratio of the two-phase PD by the PD in dry air decreases with the air flow rate, independently of the size of the channel. Finally, direct observations of the flow patterns associated with the measurements allowed to locate an area in which the droplets coalesce to a sufficient size to be tore off and taken away by the flow. To find solutions to this identified problem of cloggings and uncloggings, similar experiments with plates treated with hydrophilic and hydrophobic coatings are in progress.

References

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