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Short communication

# Relationship between pressure drop and cell resistance as a diagnostic tool for PEM fuel cells

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**Abstract**

An increase in pressure drop, particularly on the cathode side of PEM fuel cell, is a reliable indicator of PEM fuel cell flooding, while an increase in cell resistance is a reliable indicator of fuel cell drying. By monitoring both pressure drop and cell resistance in an operational fuel cell stack it was possible to diagnose either flooding or drying conditions inside the stack. These parameters may be used for making decisions on corrective actions.


*Keywords:* PEM fuel cell; Pressure drop; Cell resistance; Drying; Flooding

## 1. Introduction

Operating conditions such as pressure, temperature, flow rates and humidity of reactant gases have a great effect on PEM fuel cell performance. In general, performance of a PEM fuel cell is stable in a relatively narrow operational conditions window. This is mainly related to water management issues inside the cell. Although it is possible to select operational conditions to maintain required water balance at the inlet and outlet, flooding or drying may still take place due to uneven local conditions inside the cell. Too much water results in flooding, i.e., blocking of porous passages which in turn reduces the transport rate of reactants to the catalyst site. Flooding can occur on both anode and cathode side. Too little water results in membrane drying, which in turn results in increase in ionic resistance. The immediate result of either flooding or drying is the loss of cell potential. Without a proper diagnostic tool, i.e., by monitoring only the cell potential, very often it is difficult to distinguish between flooding and drying. In order to take the proper corrective action(s) it is necessary to have a reliable monitoring and diagnostic tool.

General Motors patented a method and apparatus for detection of flooding in $H_2/O_2$ fuel cells based on monitoring the pressure drops across the $H_2$ and $O_2$ flow fields and comparing them to predetermined thresholds of acceptability [1]. If the pressure drop exceeds the threshold, the corrective measures are automatically initiated, such as turning-off humidification, increasing the gas mass flow rate, reducing gas pressure and/or reducing current drain.

General Motors also patented a method for controlling the humidity level based on monitoring of the cell resistance [2]. They correlated high frequency resistance of a fuel cell to the degree of humidification in an attempt to find the optimum humidification conditions. Too much humidification resulted in cell flooding with no changes in cell resistance.

Barbir et al. [3] and He et al. [4] investigated the pressure drop as a diagnostic tool for detection of flooding in the fuel cell. They monitored the pressure drop in a fuel cell with interdigitated flow fields in a variety of operating conditions causing either flooding or drying of the fuel cell.

Rodatz et al. [5] studied the operational aspects of a large PEMFC stack under practical conditions. They particularly addressed the pressure drop, the effect of bends in the flow field and two phase flow. They observed a decrease in pres-

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sure drop when the stack current was reduced. The large time constant observed was attributed to gradual water removal from the MEA, followed by clearing out the flow passages.

While a pressure drop increase is a reliable sign of increased water content in the fuel cell, it cannot be used to detect the cell drying out, since in that case the pressure drop would remain unchanged. However, by combining the pressure drop with the cell resistance measurements it should be possible to detect either flooding or drying. The cell resistance does not change if the cell is flooding, but an increase in cell resistance would be an unambiguous sign that the cell drying is taking place. During an operational cycle a fuel cell may go through the phases of flooding and drying and a reliable method to distinguish between the two is needed in order to take the proper corrective measures.

## 2. Pressure drop

The pressure drop is a result of friction within the passages or reactant gases through the cell. Since the product water is produced at and must be removed from the cathode side, the cathode pressure drop is more important. While a certain pressure drop is beneficial for fuel cell operation because it helps remove excess liquid water from the cell, too much of a pressure drop would increase parasitic power needed for "pumping" air through the fuel cell.

The pressure drop for a continuous, straight channel can be calculated using Darcy's law for uniform, non-compressible, pipe flow:

$$\Delta p = f\frac{L\rho\bar{V}^2}{2D_{\mathrm{H}}} \tag{1}$$

where $f$ is the friction factor, $L$ the channel length (cm), $\rho$ the fluid density (g cm$^{-3}$), $\bar{V}$ the flow velocity (cm s$^{-1}$), $D_{\mathrm{H}}$ the hydraulic diameter (for rectangular channels typically defined as $4A/P$).

For laminar flow, $Re < 2000$, and in most cases the flow in fuel cell channels is indeed laminar:

$$f = \frac{64}{Re} \tag{2}$$

where $Re$ is the Reynolds number defined as $Re = \rho\bar{V}D_H/\mu$.

Therefore, for laminar flow the pressure drop is linearly proportional to velocity, i.e., to flow rate. However, in a fuel cell channel there are some deviations from the uniform pipe flow:

- roughness of the GDL is different than that of the channel walls,
- the reactant gas participates in the chemical reaction and the flow rate varies along the channel,
- temperature may not be uniform along the channel,
- typically the channel is not straight but there are numerous sharp turns (90 or 180),
- liquid water may be present inside the channel either in the form of little droplets or as a film in both cases effectively reducing the channel cross sectional area.

Even if in the channel the $Re < 2000$, there may be some turbulence at the bends or around the water droplets when present.

The Reynolds number at the entrance of the cathode flow field is:

$$Re = i\frac{A}{(w+d)N_{\mathrm{ch}}}\frac{MS}{2\mu Fr_{\mathrm{O_2}}} \tag{3}$$

where $i$ is the current density (A cm$^{-2}$), $A$ the cell geometrical active area (cm$^2$), $w$ the channel width (cm), $d$ the channel depth (cm), $N_{\mathrm{ch}}$ the number of parallel channels, $M$ the molecular weight of gas (g mol$^{-1}$), $S$ the oxygen stoichiometric ratio, $\mu$ the viscosity (g cm$^{-1}$ s$^{-1}$), $F$ the Faraday's constant (A s mol$^{-1}$), $r_{\mathrm{O_2}}$ the oxygen content by volume (20.95% in air).

## 3. Cell resistance

The conductivity of perfluorosulphonicacid (PFSA) ionomer membranes is a strong function of water content, $\lambda$, defined as the number of water molecules per sulfonate group in the ionomer and temperature [6]. Above $\lambda = 5$, the relationship between water content and protonic conductivity is almost linear. Below $\lambda = 5$, there is very little water uptake which may suggest that there is not enough water in the clusters around the ends of the sulphonated side chains and that because of that protons are sequestered by the sulphonate groups [7]. Note that conductivity at $\lambda = 14$ (membrane equilibrated with water vapor) is about 0.06 S cm$^{-1}$. Protonic conductivity dramatically increases with temperature and at 80 °C reaches 0.18 S cm$^{-1}$ for a membrane immersed in water. Based on these measurements, Springer et al. [8] correlated the ionic conductivity to water content and temperature with the following expression:

$$\kappa = (0.005139\lambda - 0.00326)\exp\left[1268\left(\frac{1}{303} - \frac{1}{T}\right)\right] \tag{4}$$

If the rate of water removal from the cell is higher than the rate of water generation and its re-distribution through the membrane due to high flow rates of unsaturated reactant gases, then the membrane water content, $\lambda$, will decrease and consequently the conductivity will decrease as well, resulting in cell potential drop.

## 4. Experimental

Fig. 1 shows the experimental setup for operation of a fuel cell at the Connecticut Global Fuel Cell Center. The fuel cell

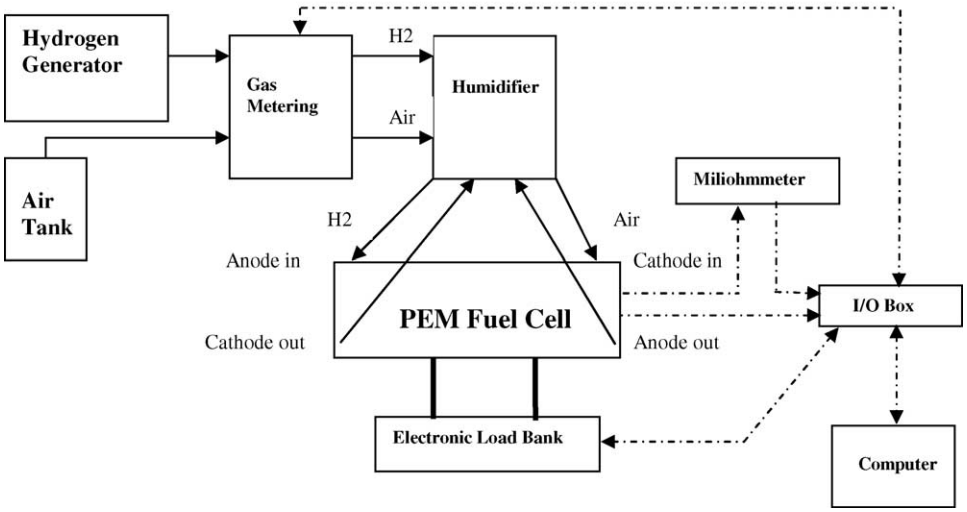


Fig. 1. Schematic diagram of experimental setup.

used for these experiments was developed and manufactured by Proton Energy Systems [9]. It consists of three cells with 65 $cm^2$ active area each. The cathode flow field consists of six parallel channels in serpentine layout, while the anode flow field has a single serpentine channel. The channels are rectangular with 0.9 mm width and depth. The stack is air-cooled.

Fig. 1 illustrates the experimental system used for fuel cell testing. Hydrogen is supplied by hydrogen generator (electrolyzer) HOGEN 40, built by Proton Energy Systems, and air is supplied from air cylinders. Hydrogen and air were fed through the mass flow meters built in Lynntech FCTS GMET/H Gas Metering System. A Lynntech Gas Humidifier, FCTS H0101, is used to achieve the desired humidification of the reactant gases before entering the fuel cell stack by controlling the humidification temperature. Cell resistance is measured by an Agilent 4338B Miliohmmeter. The pressure sensors are used to measure inlet and outlet pressures of the anode and cathode channels, and the sensors were calibrated before the experiment began. A TDI RBL 488 electronic load bank is used to generate the load current profile. Lynntech FCTS IO box is used to collect all the measured data in the test platform. Fig. 2 shows a photograph of the test bench.

The pressure drop at both cathode and anode was measured as a function of the flow rate, with and without gas humidification and with and without current, i.e., water generation.

Fig. 2. Experimental setup.

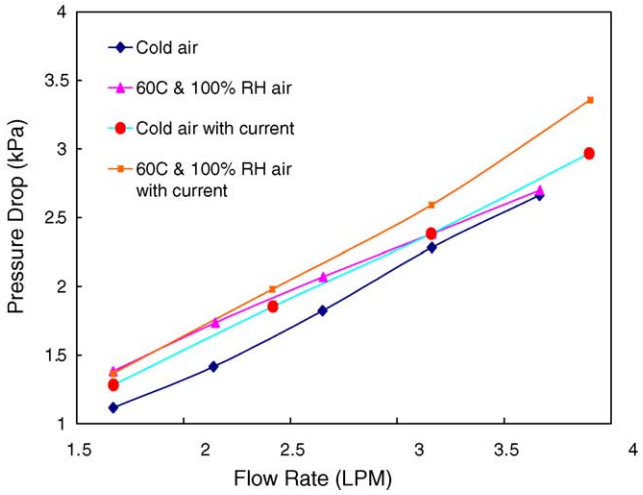


Fig. 3. Pressure drop as a function of flow rate and stack inlet conditions for both operating and non-operating stack.

The stack was then operated in a steady state and disturbances were introduced to induce either flooding or drying by adjusting the stack or the air inlet temperatures.

## 5. Results and discussion

### 5.1. Pressure drop as a function of flow rate

When dry air at room temperature is run through the stack and no current, and thus no water is being generated, the relationship between the flow rate and the pressure is linear or almost linear (Fig. 3). This should be expected since the Reynolds number at the entrance of the cathode channels is <250 at the highest flow rate. As expected, when humidified air (100% RH at 60 °C) is run through the stack the pressure drop is higher due to condensation in the cold, non-operating stack; however, as the flow rate is increased the pressure drop approaches that of the dry air. This may be explained by improved water removal from the stack at higher channel velocities.

When the stack is operational and generates water, the pressure drop is linearly proportional to the flow rate if the incoming air is dry because all the product water gets evaporated in the flow of air. Note that the molar flow rate at the exit is higher than the flow rate at the inlet since each oxygen molecule consumed is replaced by two water vapor molecules. When the incoming air is fully humidified, evaporation of the product water is no longer possible, and as the result the pressure drop starts to increase exponentially with the air flow rate (and with current, i.e., water generation rate), as shown in Fig. 3.

### 5.2. Flooding

If the humidification temperature is higher than the stack temperature, the air will cool down in passing through the stack and water will condense. This may result in inadequate water removal from the stack and flooding. This is typically characterized by erratic cell potential behavior, such as sudden cell voltage changes. The cell voltage increases suddenly when a droplet of water is expelled from a channel. Fig. 4 shows this case. As expected, the cathode pressure drop increases clearly indicating flooding conditions inside the stack. As soon as the air inlet temperature becomes higher than the stack temperature, there is no more condensation, the pressure drop starts to decline and the cell potential becomes less erratic.

### 5.3. Drying

In the case of inadequate humidification the membrane may start to dry out. This is illustrated in Fig. 5a. When the

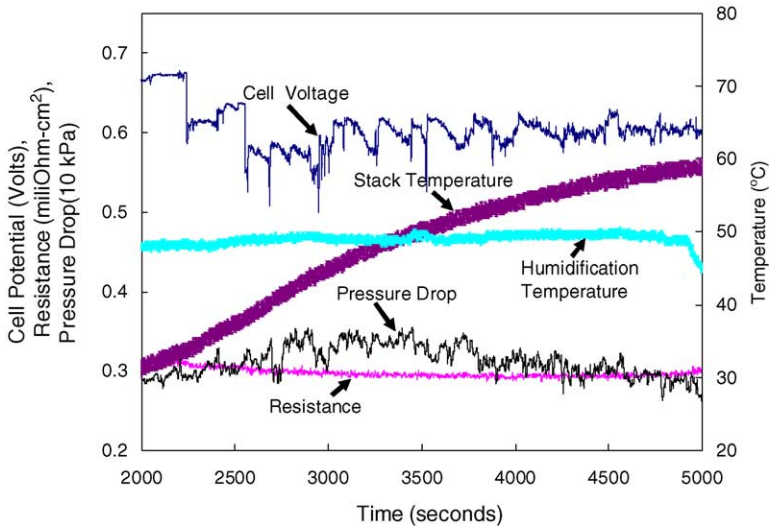


Fig. 4. Illustration of stack flooding and recovery.

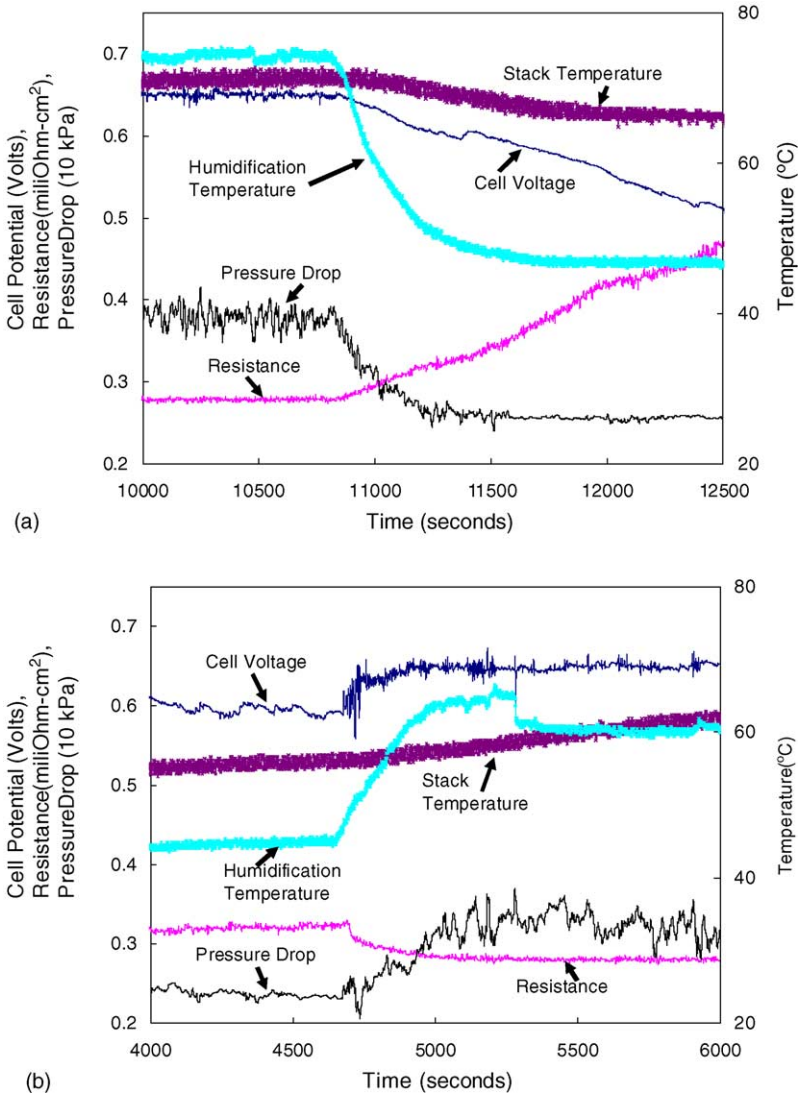


Fig. 5. Illustration of (a) stack drying (above) and (b) recovery (below).

humidification temperature decreases well below the stack operating temperature, the stack starts to dry out. This is indicated by an decrease in pressure drop which levels off at a new lower value corresponding to the pressure drop of dry air, and by a continuous increase in cell resistance. As a result the cell potential deteriorates.

When the required humidification is restored, the pressure drop increases, the cell resistance decreases and as the result the cell voltage recovers (Fig. 5b).

## 6. Conclusions

The flow in fuel cell passages is predominantly laminar, therefore a linear relationship between the pressure drop and the flow rate may be expected. Deviations from the linear relationship results from changes in flow rate due to consumption and generation of gaseous species along the channel, sharp turns, and liquid water presence.

An increase in pressure drop, particularly on the cathode side, is found to be a reliable indicator of PEM fuel cell flooding, while an increase in cell resistance is a reliable indicator of fuel cell drying. Both flooding and drying have a detrimental effect on cell potential. However, while drying typically causes a monotonous voltage decay, flooding causes a rather erratic cell voltage behavior, i.e., sudden voltage drops and increases, which are due to liquid water accumulation and expulsion inside the cell passages. By monitoring both pressure drop and cell resistance in an operational fuel cell stack it was possible to diagnose either flooding or drying conditions inside the stack. These parameters will be used to define a control strategy, i.e., for making decisions on corrective actions.

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