



Perforated Metal Sheets as Gas Diffusion Layers for Proton Exchange Membrane Fuel Cells

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The use of perforated metal sheets as engineered gas diffusion layers (GDL) in proton exchange membrane (PEM) fuel cells was investigated. The effect of different thicknesses, perforation diameter, and in-plane diffusion capabilities were analyzed along with freestanding microporous layers in order to improve gas and water transport. Although these structured GDLs are in an early stage of development, they provide baseline performance at lower current densities, and may already have potential for some specific applications. In addition, the design, manufacturing, and modeling processes with predictive capability can be improved due to their simplified nature.

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The two materials used the most as gas diffusion layers (GDL) in the proton exchange membrane fuel cell (PEMFC) industry are carbon fiber papers (CFP) and carbon cloths (CC).¹ However, they have a number of drawbacks, particularly with respect to their design and model complexity. One of the main issues with the CFP/CC used as GDLs is the non-controlled variation in porosity (and other localized properties) since the porosity characteristics between CFP are not always repeatable.² Many of the water management and mass transport issues with GDLs could be improved considerably if the GDLs could be carefully tailored to specific fuel cell applications.

One approach to the design of these engineered GDLs is through the use of non-porous conductive materials that are perforated based on a detailed design. Research groups from Ballard Power Systems and Graftech Inc. have presented designs of engineered GDLs based on graphitic foils.^{3,4} A number of different designs (e.g., geometry, cross-sectional shape, and hole density) were also proposed. Unfortunately, to the best of our knowledge, there are limited published results from Graftech but none from Ballard that show complete studies of how these perforated graphitic foils perform inside a fuel cell. Other groups have also proposed other non-porous materials as engineered GDLs.^{5,6} None of these studies attempted to understand in detail how the proposed GDLs affected fuel cell performance.

Another approach to develop engineered GDLs is through the use of perforations and grooves in CFPs and the weave design in CCs. Based on the earlier work of Wilkinson et al.,^{7,8} the main idea behind the modification of porous CFPs with perforations is to improve liquid water transport at specific locations of the GDL. More recently, several researchers have shown an improvement in fuel cell performance at different operating conditions by perforating and/or making grooves to conventional CFPs.^{9–14}

In this study, *in-situ* experiments of perforated stainless steel sheets as GDLs were performed to study the effects of different engineered sheet designs on the performance and transport characteristics inside a PEMFC.

Experimental

For all the measurements, a single cell fuel cell with an active area of 49 cm² was used. The perforated sheets (PS) were made out of stainless 316L steel sheets and were perforated by VACCO Industries using a photo-etching process. Other manufacturing machining methods were considered but presented several issues regarding the quality of the finished product. Fig. 1 shows a schematic of two typical PSs used in this study. The spacing or landing between the perforations, and the width and depth of the channels connecting the perforations

in each sheet were chosen based on the restrictions posed by the photo-etching manufacturing process.¹⁵ Table I shows the detailed characteristics of the PSs used the most in this study. It is important to note that these PSs were not tested when placed directly beside the catalyst layer for more than 12 hours in order to avoid any corrosion issues. No indication of corrosion was found on the surface of the sheets for testing over this period of time.

For all the tests, a Sigracet 25 DC GDL (SGL Carbon) with a micro-porous layer (MPL) was used as the anode GDL. A Primea 5510 catalyst coated membrane (CCM) (W.L. Gore) was used. Every membrane electrode assembly (MEA) was initially conditioned with fully humidified gases at a constant current density (associated with an output voltage of 0.3V) for around 10 hours. For the various polarization tests, the single cell fuel cell was compressed to 792.9 kPa, the gases were pressurized at the inlet to 206.8 kPag, the gas, cell, and dew-point temperatures were 75°C (100% relative humidity), and the air/hydrogen stoichiometric ratio was kept constant at 2.0/1.5. Polarization tests with heliox (21% O₂ and 79% He) as the oxidant gas were also performed. Heliox was used in order to give a better understanding of the mass transport effects in the fuel cell.^{16–18}

In order to investigate the fuel cell and GDL performance potential with minimal mass transport limitations due to water accumulation, the anode water removal (AWR) method was performed with various PSs as GDLs. Details regarding the AWR method can be found elsewhere.^{19,20} The AWR method can be used to determine the peak

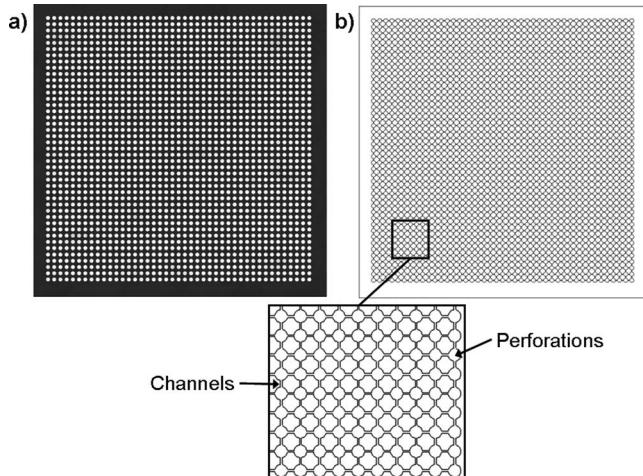


Figure 1. Schematic of stainless steel perforated sheets (70 mm x 70 mm) with 1 mm diameter holes for the case (a) without channels, and (b) with channels connecting the perforations.

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Table I. Cell voltage values at 200 mA/cm² and peak cell voltage with anode water removal tests for perforated sheets with different thicknesses (*t*), channel widths (*Cw*), and depths (*Cd*). The perforation diameter (*d*) for all the sheets was 1 mm. All the cell voltages are corrected for resistance.

Name	<i>d</i> [mm]	<i>t</i> [mm]	<i>Cw</i> [mm]	<i>Cd</i> [mm]	Cell Voltage at 200 mA/cm ² [mV] ^a	Peak Cell Voltage in Anode Water Removal Test [mV] ^b
PS-A	1.00	0.05	0.00	0.00	423 ± 12	677 ± 4
PS-B	1.00	0.05	0.15	0.04	419 ± 7	655 ± 6
PS-C	1.00	0.05	0.50	0.04	475 ± 9	656 ± 9
PS-D	1.00	0.05	1.00	0.04	429 ± 11	593 ± 10
PS-E	1.00	0.10	0.00	0.00	359 ± 15	421 ± 12
PS-F	1.00	0.10	0.50	0.05	447 ± 12	517 ± 13
PS-G	1.00	0.10	0.50	0.08	472 ± 10	595 ± 13
PS-H	1.00	0.10	1.00	0.05	442 ± 13	535 ± 10
PS-I	1.00	0.10	1.00	0.08	461 ± 12	570 ± 10
PS-J	1.00	0.20	0.00	0.00	356 ± 20	423 ± 16
PS-K	1.00	0.20	0.50	0.10	307 ± 18	437 ± 16
PS-L	1.00	0.20	0.50	0.15	577 ± 11	700 ± 9
PS-M	1.00	0.20	1.00	0.10	376 ± 19	502 ± 15
PS-N	1.00	0.20	1.00	0.15	422 ± 16	550 ± 10

^a The gases, dew point, and cell temperatures were 75°C. The pressure for both gases was 206.8 kPag (approx. 30 psig) and the air/hydrogen stoichiometry ratio was 2.0/1.5.

^b These tests were performed at a constant current density of 200 mA/cm².

cell voltage corresponding to the best performance of the cell with minimal mass transport losses. For the AWR tests, the current density was kept constant at 200 mA/cm² (no anode humidification and variable anode stoichiometry).

Results and Discussion

A number of stainless steel sheets with different perforation diameters were first tested as GDLs in order to evaluate the effect that each design had on the fuel cell performance. Since it was desired to evaluate these sheets with minimal interference from associated mass transport resistances due to water accumulation in the catalyst layer (CL), the AWR method was used. Fig. 2 shows that the PS with the

greatest open area (67.5%) and perforation diameter (10 mm) had the lowest peak voltage during the test. During the AWR tests, it is assumed that all of the water inside the cell is removed through the anode side.¹⁹ The 10 mm PS had 1 mm separation between holes compared to the 0.3 mm separation for the 1 mm PS, which may explain the lower AWR peak cell voltage performance. Larger distances under the solid material reduce oxygen diffusion and catalyst utilization. In addition, the high frequency (HF) resistance measured for the sheet with the 10 mm perforations was 26 to 32% greater than the resistance of the other sheets, which represents an approximate 55 mV of loss at a current density of 200 mA/cm². Although these losses are significant, mass transport limitations represent the largest contribution to the performance losses. Moreover, the sheets with large perforations do not provide appropriate mechanical support for the CCM.

On the other hand, the peak cell voltage difference between the other three PSs was not as great (54 mV between the 1 mm and the 0.15 mm PSs). However, the difference between the open areas is significant when considering water accumulation inside the cell. In general, the PS with the 1 mm perforations (and 34.7% OA) had the best performance and lowest resistance, resulting in the best balance between electrical contact and gas transport. This sheet also gives enough mechanical support to the CL and membrane to prevent damage.

The performance of these PSs was still poor compared to conventional CFP GDLs (see Fig. 2) since the transport of the gases (and liquid water) inside these sheets was limited to just the through-plane (i.e., in-plane transport was not present). The very thin CLs (12 to 15 μm) provided all of the in-plane diffusion, which was insufficient for uniform oxygen distribution over the active area. Another performance issue was the lower open area of the perforated sheets compared to the open porosity of CFPs.

Therefore, in order to improve the in-plane diffusion of the oxidant gases over the CL the use of channels connecting the perforations on the side of the PSs next to the CCM was investigated (see Fig. 1). Sheets with 1 mm perforations were chosen for the new designs with channels. The main parameters changed were the material thickness, and channel width and depth (see Table I).

Although control of the PS parameters was limited by the manufacturing method used, several trends can be determined from the data in Table I. In general, there is an increase in performance with an increase in channel depth and a decrease in sheet thickness. There is an optimum perforation size and channel width for performance. The overall best performance and peak voltage (with AWR tests) was shown by the thicker PS-L sheet in Table I. This may be due to the deeper channels that allow for enhanced gas diffusion and water removal. However, the sheet with wider channels but same depth (PS-N) did not show a significant improvement in gas and water transport. This is due to the higher capillary forces present with narrow channels (<1 mm) that improve water removal.^{21,22}

Ideally, the perforations should be interconnected in a way in which the gas and water transport are enhanced due to in-plane diffusion. These connections should be tailored for specific transport mechanisms (i.e., gas and/or liquid water). However, current manufacturing capabilities limit the parameters (size, length, depth) of such connections without damaging the sheets.

Although the addition of channels in the PSs did improve performance, it did not improve gas in-plane diffusion as significantly as expected. Therefore, the use of a freestanding MPL between the perforated sheets and the CCM was investigated. The MPL used was a 50 μm thick Gore Carbol (MP30z) sheet, which has similar characteristics to those MPLs used in typical PEMFCs (e.g., mean pore diameter of 30 nm, hydrophobicity, and thickness).²³ The PSs chosen for these experiments were the sheet without channels (PS-A) and the one with channels that showed the best performance (PS-L). Fig. 3a shows that without an MPL, up to a current density of about 100 mA/cm², the two PSs have comparable performance, but at higher current densities the PS-A without channels experienced greater water accumulation and corresponding mass transport losses. In addition, the PS-L with channels showed better performance and voltage stability (indicated

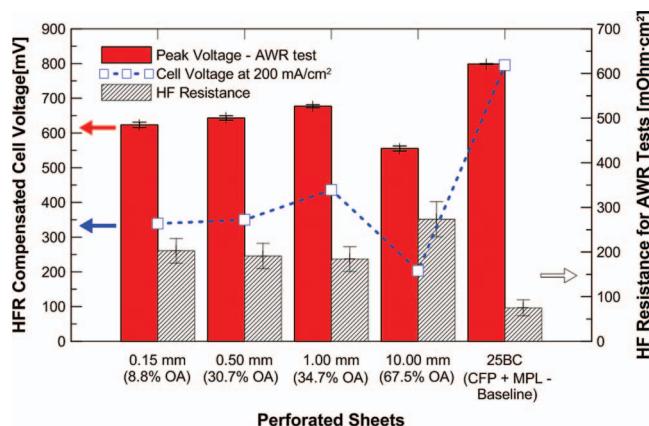


Figure 2. Comparison of peak cell voltage in anode water removal (AWR) tests for metal perforated sheets (PS) with different perforation diameters (0.15, 0.5, 1, and 10 mm) and open areas (OA) (8.8%, 30.7%, 34.7%, and 67.5%). The voltage value for fully humidified conditions at 200 mA/cm² is also shown. The results with a conventional gas diffusion layers (GDL) (Sigracet 25BC) are also shown. This GDL is made of carbon fiber paper (CFP) with a micro-porous layer (MPL).

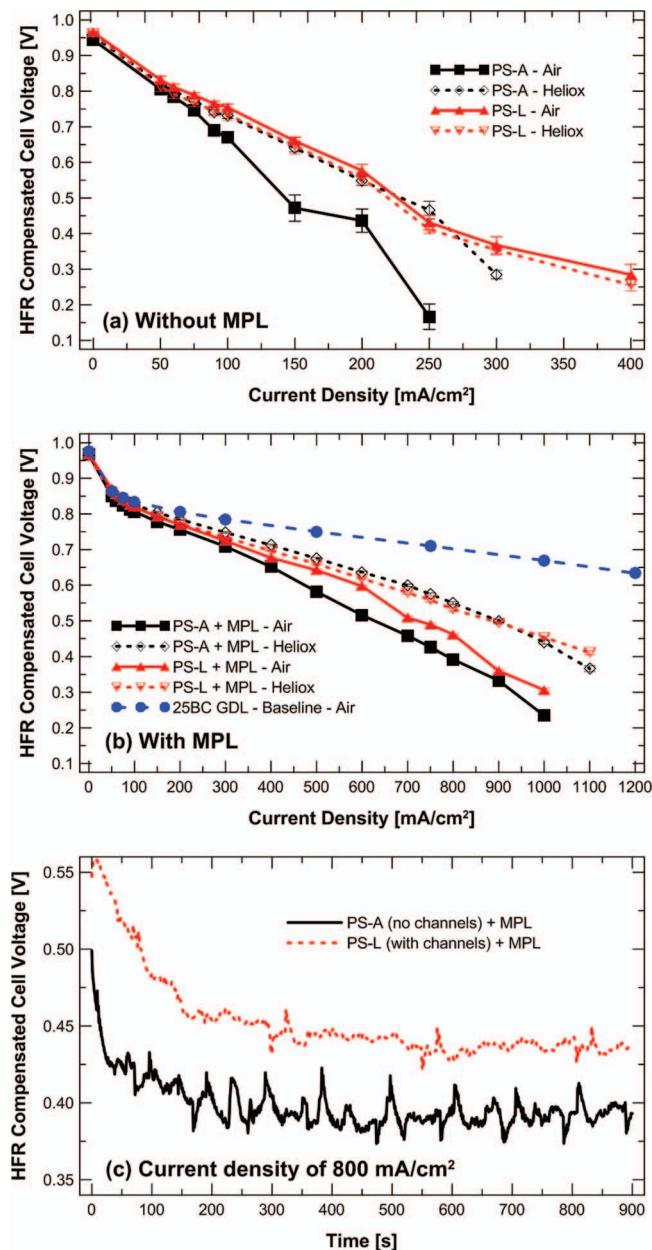


Figure 3. (a) Fuel cell performance of two different perforated sheets (PS), PS-A (no channels) and PS-L (with channels), without a micro-porous layer (MPL); (b) fuel cell performance of PS-A and PS-L sheets with an MPL; and (c) comparison of voltage stability between PS-A and PS-L sheets with an MPL. Air and heliox were used as oxidant gases for (a) and (b). The baseline case was performed with a Sigracet 25BC gas diffusion layer (GDL) in the cathode side.

by the size of the error bars). The use of heliox (improved oxygen diffusion) had a large effect on the PS-A with no channels but little effect on the PS-L with channels.

The lack of in-plane diffusion for the PS with no channels coupled with the water accumulation inside the cathode catalyst layer (as observed by the greater error bars) affects the mass transport losses significantly. Thus, the channels improve water removal and gas diffusion inside the cell.

Fig. 3b shows that the performance of both PSs with an MPL are similar in the low current density range (<400 mA/cm²). Above 400 mA/cm², the PS-L with channels exhibits better performance, indicating a decrease of mass transport losses compared to the other PS as a result of improved water removal capability, i.e., due to the

channels connecting the perforations. Both PSs with an MPL show a similar performance of around 24% (at approximately 0.4 V) with heliox as the reactant gas. For both the cases with and without an MPL there is very little difference in the heliox performance for the two PSs but a significant difference with air. The PS-L with channels clearly improves the air performance approaching the heliox performance. It is also observed, that the PS-L with MPL has similar performance to the baseline GDL at low current densities, indicating that at these conditions the PS approach, even at this level of non-optimization, could be used in certain fuel cell applications.

In general, voltage fluctuations are a function of water accumulation in the catalyst layer, GDL, and flow field channels. Thus, In terms of voltage stability the PS with channels experienced a decrease in voltage fluctuations over all current densities but especially at high current densities compared to the sheets without channels (see Fig. 3c). This is due to an improvement of the water removal capability when channels are used. Thus, the case without channels (PS-A) experiences more water build up in the catalyst layer.

It is important to note that the performance of these sheets is still well below the performance observed with conventional GDLs. However, they have the potential to be used as GDLs with more detailed modeling and optimization and improved manufacturing processes. The use of an MPL does add another variable to the development of structured GDLs. However, the use of the MPL in this study allowed for a better understanding of the diffusion-related issues related to the PSs and should be improved in future designs. Another important objective would be to indentify sheet materials that have structured in-plane porosity. In addition, materials that are conductive and corrosion-resistant should be taken into consideration, since stainless steel sheets can experience corrosion when exposed to an acidic environment and oxidative potentials for long periods of time.

Conclusions

This paper presents an investigation of structured perforated sheets (PSs) used as a replacement for conventional GDLs. It was concluded that PSs with just perforations show low performance due to a lack of in-plane diffusion. The use of channels that connect perforations on one side of the sheets showed an improvement in water transport and gas diffusion inside the fuel cell. In general, PSs with channels improve voltage stability and water removal capabilities compared to PSs without channels. These results, along with the other investigations found in the literature,^{6,24} suggest that engineered GDLs have the potential to be used for specific applications and operating conditions. In fact, at low current densities the PSs, without optimization, showed similar performance to the baseline GDL and may have advantages with respect to mechanical strength. These engineered GDLs will be improved once other manufacturing capabilities/methods evolve in order to facilitate the tailoring of new materials (softer and corrosion-resistant) that can work in fuel cell applications. In addition, modeling should also be implemented in order to facilitate the design and optimization of these GDLs.

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