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Active gas management for PEM fuel cell stacks

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Abstract

Proper gas and water management are essential to achieving and maintaining high power output in a PEM fuel cell stack. Previous experimentation with a small oxygen fuel cell stack has demonstrated that the use of an active gas management (AGM) system to control individual exhausts improved and sustained high power with oxygen operation. The active gas management system has now been employed in small and large air cathode stacks of five and six cells. The use of the AGM system increased the small five-cell stack's power output from 38.4 to 50.4 W and increased the large six-cell stack's power output from 260 to 350 W. Both large and small stack's demonstrated a 30% power increase after accounting for parasitic losses.

Keywords: PEM fuel cells; Water management; Electrode flooding; Sequential exhausting

1. Introduction

Fuel cells are a promising technology for meeting the growing energy demands of the industrialized world. Polymer electrolyte membrane (PEM) fuel cells can generate electric energy cleanly and efficiently. However, there are several barriers to widespread implementation of PEM fuel cells. One of the most significant barriers is the high cost of materials. The most immediate way to reduce material cost is to increase power density, thereby requiring less material to produce the same amount of power.

One performance limitation in a PEM fuel cell stack is the inability to handle uneven cell-to-cell distribution of liquid water, as discussed in a previous paper [1]. The liquid water evolved during fuel cell operation (or supplied for membrane humidification) can become a hindrance to performance by blocking the catalytic sites and creating mass transport limitations. Excess liquid water is normally removed by gas flow. However, in a conventional fuel cell stack, all cells are fed in parallel from a common air inlet manifold. If more liquid water is present in one particular cell than in the remaining cells, the water will create a restriction to gas flow through that cell. Since the shear force of gas flow is used to remove liquid water, the restriction of gas flow will reduce water removal rate. It follows that any cell receiving less than average gas flow will accumulate even more liquid water, creating a self-defeating and escalating hindrance to the performance of that cell. This is also a potentially dangerous condition, because an individual cell may be driven into reversal if starved of reactant gas for extended periods. It is clear that cell-to-cell gas distribution is an important performance parameter of any PEM fuel cell stack. Without proper gas and water management, a single cell will limit the performance of the entire fuel cell stack.

Without the means to handle liquid water, a PEM fuel cell stack must be operated at low power densities, requiring more materials (higher costs) to meet the required power load. Additionally, the ability of the fuel cell stack to meet the dynamic power demands of real life applications will be limited due to a small operating power range. Clearly equal gas distribution is a very important design consideration of the PEM fuel cell stack. The standard methods of insuring equal gas distribution are to design the flow fields for high pressure drop or to operate at very high stoichiometric flow rates. By making

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the pressure drop through the flow field plates the dominant pressure drop, the additional pressure drop added by liquid water and differences in the membrane and electrode assemblies (MEA) are minimized. The drawback to this approach is the necessity to pressurize the air, creating large parasitic power loss. Another method is to operate at extremely high flow rates to ensure adequate gas supply and effective water removal. Again this method will incur a large amount of parasitic power loss to generate the high flow rates.

A practical solution to the problem of unequal cell-to-cell gas and water distribution is to employ a method of sequentially purging individual or groups of cells to ensure proper water management [2]. Previous presentations of this method demonstrated a 50% increase in power output [1,3]. The previous work only provided experimental data on pure oxygen operation in small two- and three-cell stacks. This same concept of variably controlling the individual exhaust of each cell has now been applied to air operation in small (16 cm^2 active area) and large (94.3 cm^2 active area) stacks of five and six cells. The successful implementation in stacks with air cathodes and of significant size demonstrates the practical application of the active gas management (AGM) system.

2. Experimental setup

For the following experiments all stacks were designed and built in-house. The first stack tested with the AGM system was a five-cell stack with an active area of 16 cm^2 per cell. The MEAs in these stacks used Nafion® 112 membrane. The anode and cathode catalyst loadings were 0.25 and 0.55 mg Pt/cm^2, respectively. The flow field plates consisted of a serpentine flow pattern machined into a graphite plate. The anode was operated with a series flow pattern, meaning the effluent from cell 1 is the inlet to cell 2, the effluent from cell 2 is the inlet to cell 3, etc. The series flow pattern ensured that anode side gas distribution would not affect the experimental results. The cathode gas inlet was distributed in parallel with individual side exhausts. The stack provides no internal cooling or humidification. A schematic representation of the stack's arrangement can be seen in Fig. 1.

The second stack studied was a six-cell stack incorporating MEAs with an active area of 94.3 cm^2 per cell. The flow field plates consisted of a serpentine flow pattern machined into a graphite plate. The anode design consisted of a single channel while the cathode used a multi-channel design. In this stack both anode and cathode gases were distributed in parallel to each cell. The anode side shared a common exhaust manifold. Each cathode plate had individual side exhausts in the same fashion as the smaller five-cell stack. The high power stack additionally included a water-cooling system and an internal membrane humidification system. One water-cooling plate was used for every two active cells to minimize temperature variations.

2.1. AGM system

The AGM system used consisted of six solenoid valves connected to a common exhaust manifold. Each individual cell exhaust from the fuel cell was connected directly to a valve, which exhausted into the common exhaust manifold. The valves used were of normally open design. They were powered individually through a transistor array, which allowed individual control of each valve. The valves were mounted into a plastic enclosure with LED indictor lights for visual acknowledgement of valve activation. Fig. 2 shows a schematic representation of the integration of the AGM systems and the fuel cell stack.

2.2. Control scheme

In the previous study of the AGM system with pure oxygen, the standard operation was to have the valves normally closed and to occasionally open a single valve to purge excess water. This approach was logical given the pure concentration of oxygen. Since air has a reduced concentration of oxygen, a different control method must be employed because an extended operation time with closed exhaust will cause the build up of inert nitrogen. For air operation, the valves are normally open. During a purge cycle all except for a selected subset of cells are closed. The cell(s) remaining open will experience an increased flow rate that will help flush excess water from

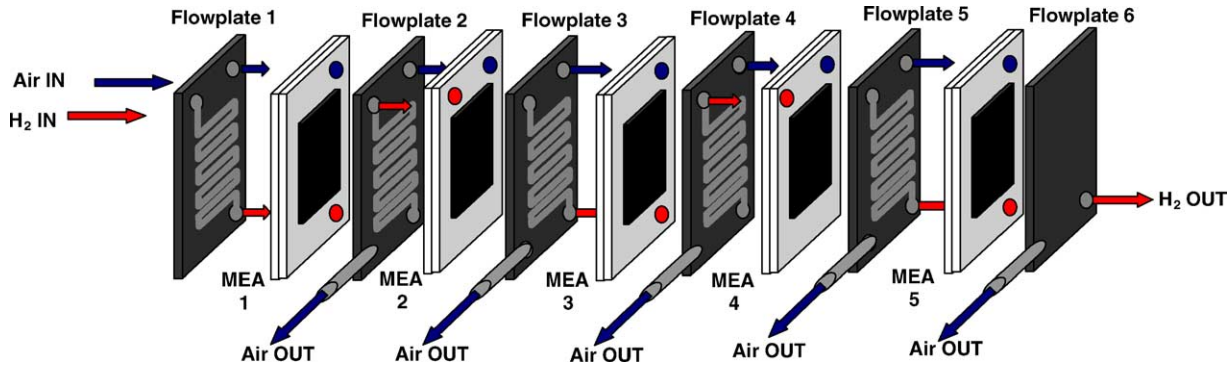

Fig. 1. Schematic representation of five-cell stack, anode with series flow pattern and cathode with common inlet manifold and individual exhausts.

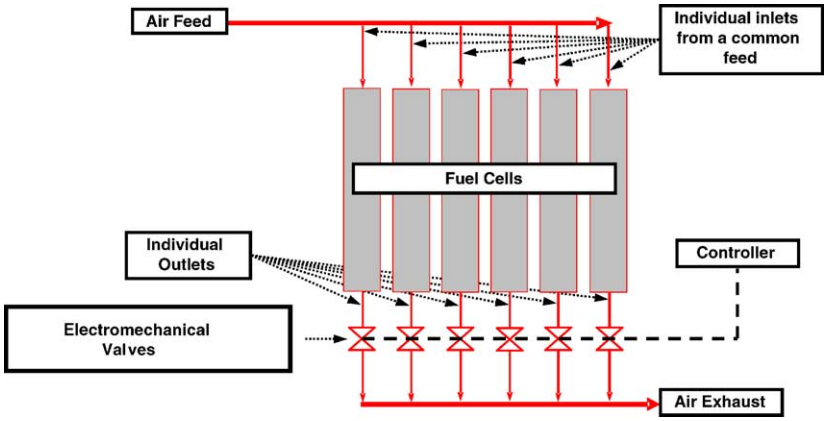

Fig. 2. Active gas management system with solenoid valves.

the system. It should also be noted that in the previous study, the AGM system was used on both anode and cathode. In the current study, the AGM was only used on the cathode.

The two main purging schemes used are referred to as single-cell purging and group purging. In single-cell purging, all valves except one are closed, forcing all of the air to flow through the single open cell. Group purging refers to leaving a group of two or more valves open, which creates an increased flow rate in the group of open cells instead of a single cell. Two timing controls were used in the experimentation. Interval time (TI) refers to the time delay in between purge cycles. Purge time (TP) refers to the time duration for which the valves are engaged for purging. The term variable group purging will also be used. Variable group purging will imply that the grouping of cells and the timing parameters were not held constant throughout the entire current range. Due to the proprietary nature, the exact optimized variable group purge pattern is not disclosed.

2.3. Test stands

Both the small and large stacks were tested using a test stand which controls air and hydrogen flow rates, stack temperature, hydrogen humidifier temperature, air humidifier temperature, air back pressure, hydrogen back pressure, and current draw. When the larger stack was tested a temperature-controlled water-cooling system was also used. The stand includes an integrated electronic load and a data acquisition board for collecting of potential, current, temperature, pressure, and flow rate data.

2.4. Experimental conditions

The primary experiment conducted was the current staircase. The current draw was varied between 0 and 1.2 A/cm^2 with a step time of 5 min. Flow rates were adjusted to maintain a stoichiometry factor of 2.5 for the air. The hydrogen flow rates were controlled to maintain a stoichiometry factor of 1.2. Flow rates on both test stands were controlled using rotameters and needle valves. For the larger six-cell stack, an additional longer time test was performed. The current draw was held at 1.0 A/cm^2 for several hours with varied AGM conditions. The stoichiometry factors of air and hydrogen were held at 3.0 and 1.2, respectively, for this experiment.

3. Results and discussion

3.1. Small stack results

The small five-cell stack was tested for a variety of purging patterns. The results, seen in Fig. 3, confirm a significant improvement from implementing the AGM system. Fig. 3 compares power output without the AGM, with single-cell purging, with group purging, and with a variable group purge. All AGM patterns showed an increase in performance over standard operation of the same stack, but the group purging and variable group purging showed further improvement over the use of a single-cell purging pattern. The reason the group purging showed an improvement over the single-cell purging was most likely due to an effective increase in purging frequency. With the same timing parameters, each individual cell will see a more frequent (although less intense) purging state. The peak power density without the AGM engaged was 0.48 W/cm^2 per cell (38.4 W total). Implementing the standard AGM pattern improved the peak power to 0.58 W/cm^2 per cell (46.4 W total). By implementing a variable group purging pattern, the power was further increased to 0.63 W/cm^2 per cell (50.4 W total), a 31% increase in power output.

Fig. 4 shows the polarization curves of each individual cell without the AGM and with a variable group purge, generated from the same data set as in Fig. 3. It can be seen that the peak power without the AGM engaged was limited by cell 3. The slope of the polarization curve shows a sharp decrease above 1 A/cm^2, indicating mass transport limitations. At the same point, the power curve flattens out (see Fig. 3), indicating that the peak power density of the entire stack of five cells was limited by cell 3. It can also be clearly seen that cell 4 performed far better than every other cell in the stack, approx-

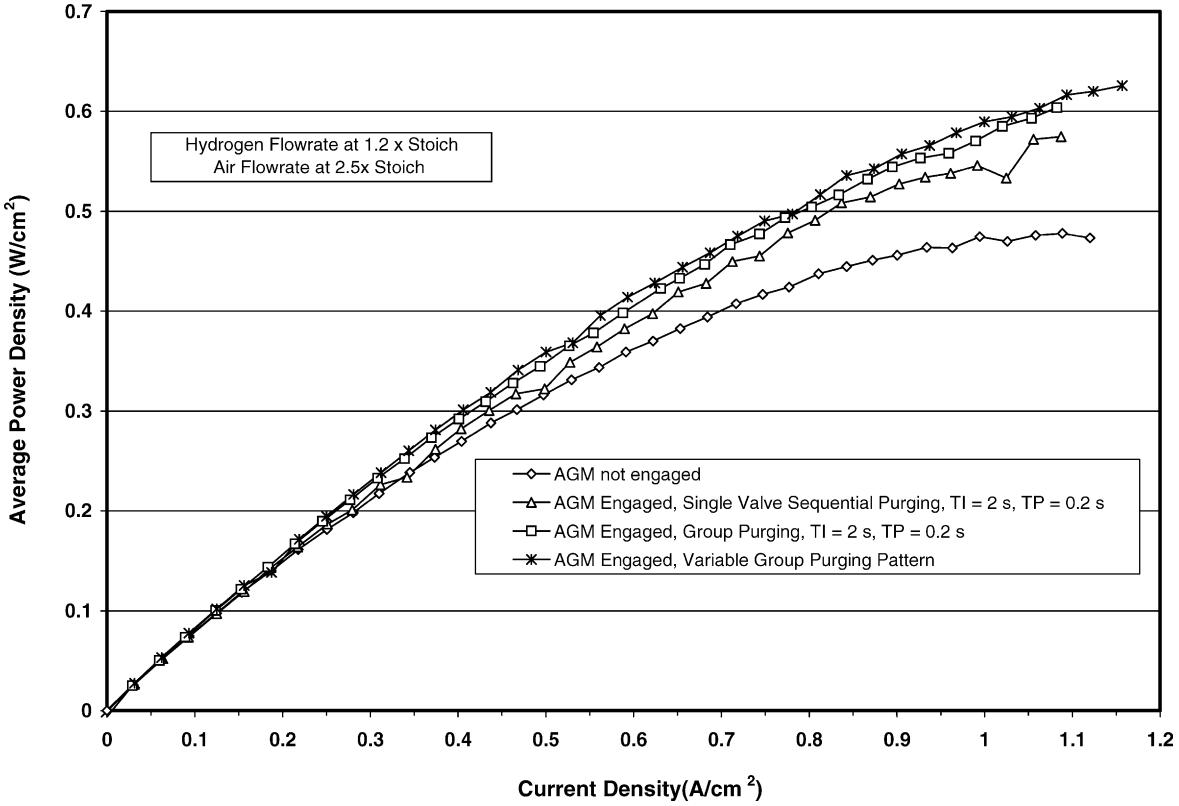

Fig. 3. Effectiveness of the AGM system in the small five-cell stack (ambient pressure, $T \sim 65$–$75\,^{\circ}C$, H_2 humidified at $80\,^{\circ}C$, dry air cathode).

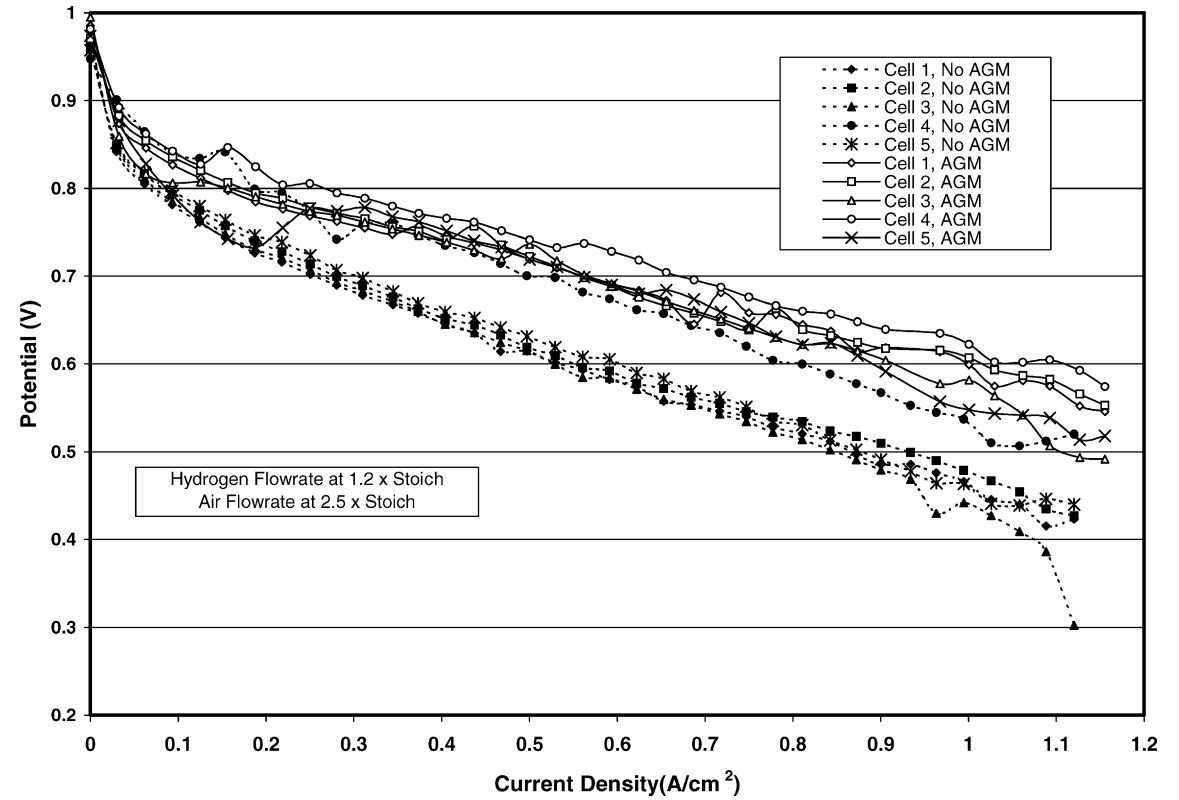

Fig. 4. Individual cell polarization curves with and without AGM engaged for the small five-cell stack (ambient pressure, $T \sim 65$–$75\,^{\circ}C$, H_2 humidified at $80\,^{\circ}C$, dry air cathode).

imately 70 mV better than the next best cell and 100 mV better than the worst cell. The difference was most likely caused by uneven gas distribution and to a lesser degree temperature variations. Due to any number of uncontrollable variations in flow field machining, flow plate hydrophobicity, gas diffusion layer (GDL) homogeneity, and even solenoid valve manufacturing, the flow path resistance that leads through cell 4 was less than the rest of the stack. Conversely, the flow path resistance that leads through cell 3 was likely higher than the other cells in the stack. It can clearly be seen that this dynamic lead to cell 4 performing better than the other cells and cell 3 performing worse and becoming mass transport limited at high current densities (above 1.0 A/cm^2).

Once the AGM system was engaged, the performance of all cells improved and the variation between cells was decreased. With the AGM engaged, cell 3 was prevented from entering mass transport limitations. It is also important to note that the performance improvement was seen throughout the operating range, not just at high current densities. The valve timings used for most staircases were a TI of 2 s and a TP of 0.2 s. The variable group purge varied the timings and groupings throughout the current range. On average, the valves were engaged for 9% of the total operating time. The engaged power use of each valve was 1.5 W. For the best case, with a grouping of three cells engaged and two open, the valve-on power usage was 4.5 W. With an average on-time of 9% of total operating time, the average parasitic power loss to the valves was 0.41 W. The total stack power output was 50.4 W, so the parasitic power loss from the AGM system was less than 1%, with a net power increase of 30%, translating to a significant reduction in capital cost in a capital intensive system.

3.2. Large stack results

The large six-cell stack utilized the same external AGM system as the small stack with the only changes being an increase in tubing size to accommodate the higher flow rates. It was seen during a staircase experiment (Fig. 5) that the AGM system again showed significant improvement in stack performance, approximately 20% peak power increase. It can be seen that performance without the AGM in this large stack was improved over performance without the AGM in the small stack. This can be primarily attributed to increased back pressure from driving higher flow rates through the solenoid valves and the addition of internal cooling to help maintain stack temperature throughout the operating range. (Note: it was found that the C_v of the valves used was approximately 1/4 the value specified by the supplier.)

Although Fig. 5 only shows a 20% increase in peak power, it was seen in the additional long term testing that this was a result of the short step time used (5 min step time) in the staircase procedure. Fig. 6 demonstrates that without the AGM system engaged, the stack cannot maintain high performance. In Fig. 6, the current was held at 1 A/cm^2 for an extended period. Initially, the AGM system was engaged enabling the

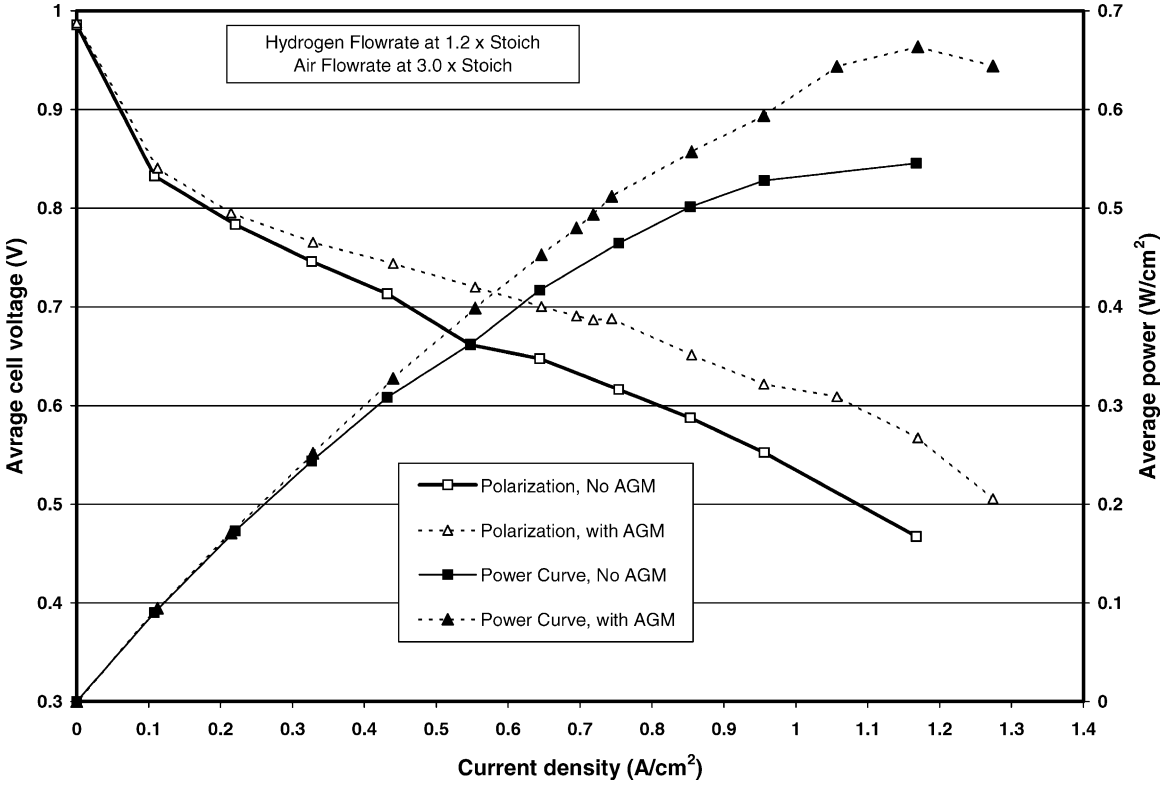

Fig. 5. Average power and polarization with and without AGM engaged for the large six-cell stack (ambient pressure, T = 60 °C, internal cooling and humidification).

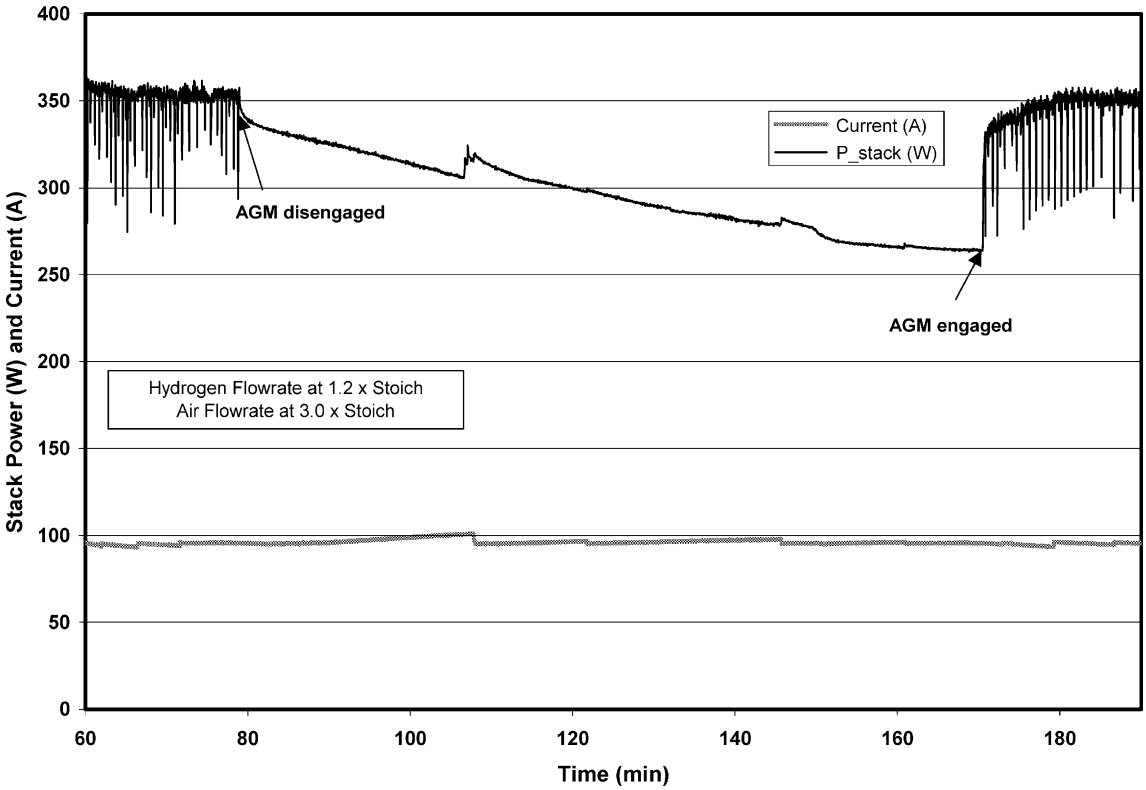

Fig. 6. Time plot of power with and without AGM engaged for the large six-cell stack (ambient pressure, $T = 60\,^{\circ}C$, internal cooling and humidification).

stack to produce 350 W of total power. Once the AGM system was disengaged, the power output began a slow decent to 260 W of power output. (Note: the current variations that disrupt the steady descent are a result of the electronic load's dependence on temperature. As the total power decreased, the load cooled necessitating an occasional adjustment.) Once the AGM was re-engaged, the power output almost immediately increased back to its previous level of 350 W, a power increase of 33%.

The parasitic power loss from the AGM system was again minimal. The valves consumed the same power of 1.5 W per active valve. For the trial at hand, the timing parameters were TI = 3.0 s, TP = 0.4 s. A group purge was used with two open valves and four closed valves, so the parasitic power loss was 6.0 W during 12% of the operating time for an average of 0.71 W. With a total power of 350 W, the percentage loss was 0.2.

Fig. 6 also demonstrates an important aspect of the sequential purging method. When operated with an air cathode, power fluctuations will occur during the purge cycle. Since the closed cells will be seeing a reduction in oxygen concentration and a build up of nitrogen, their performance will fall off during the valve-closed time. Although the magnitude of the drop varied, the maximum was seen to be about 70 W. Since this loss will occur at maximum during 12% of the operating time, the maximum average power lost to the fluctuations will be under 3%. So the net power gain of implementing the AGM system is approximately 30%.

Some final points need to be made about the successful use of group purging. The ability to improve performance with a variable group purge demonstrates that the AGM method developed here can effectively benefit large stacks in some very significant ways. As previously mentioned, the stack performance benefits from a group purge because each cell will experience a purging cycle more frequently. Additionally, the number of cells purged can help to reduce the intensity of the purging, which becomes relevant with large cells. If the purge is too intense, the cell can become dehydrated. The group purge can help reduce any dehydrating effect. Group purging will also help reduce the power fluctuations inherent in the AGM system. The relative magnitude of the power dip will depend on the ratio of the number of open cells to number of closed cells. Group purging increases this ratio and decreases the relative magnitude of the power fluctuations. The group purging also reduces parasitic power loss because fewer valves are engaged. Although the parasitic loss was shown in the current system to be minimal, reducing the parasitic power will be important to reducing power fluctuations in an integrated system. Finally, the group purge can reduce the capital cost of the AGM system. In its current configuration, the cost of the valves is approximately 90% of the AGM system. A group purge could be implemented by routing multiple cells to a single valve, reducing the number of valves and therefore the capital cost.

4. Conclusions and recommendations

It was shown that the use of the active gas management system developed here can achieve a 30% increase in power output of a PEM fuel cell stack. The performance enhancements seen in the previous work with pure oxygen operation were clearly extended to air operation. It is clear that the reason for the improvement seen from the AGM system is due to its ability to compensate for unequal flow path resistance. Given the materials used and the dynamic nature of water distribution and evolution, building a PEM fuel cell stack that initially has equal gas distribution and can maintain that equal distribution throughout the dynamic load conditions of real world operation will be nearly impossible. The advantage of this AGM system is that it does not allow these differences to accumulate over time and limit the fuel cell's performance.

Additionally, it can be observed from this study that the performance improvement is independent of flow field design, as previous studies were performed with an interdigitated flow field design [1,4] and the current study was performed with a serpentine design.

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