 FDMP, vol.5, no.4, pp.399-409, 2009

Fuel Cell Performance Augmentation: Gas Flow Channel Design for Fuel Optimization

A. B.Mahmud Hasan[1,2], S.M.Guo[1] and M.A.Wahab[1]

Abstract: The effects of gas flow channel design were studied experimentally for increasing fuel cell performance and fuel optimization. Three types of gas flow channels (serpentine, straight and interdigitated) were designed on the basis of water flooding due to electrochemical reactions, electro-osmotic drag, etc. Experimental results indicate that the best cell performance can be obtained by arranging interdigitated gas flow channel at the anode side and serpentine gas flow channel at the cathode side. Detailed analysis on complex two phase water generation and electrochemical phenomena behind those results were analyzed in this work to find out the best design for gas flow channels.

Keywords: Gas Flow Channel Design, PEMFC, Water Flooding, Fuel Utilization Rate, Gas Diffusion Layer (GDL).

1 Introduction

Proton Exchange or Polymer Electrolyte Membrane Fuel Cells (PEMFC) is the most promising choice of next generation power production for stationary and mobile devices. Though the commercialization of this cell is slow due to water flooding and lack of an efficient way to remove the water from the cell, it is still a promising source of power generation for future decades. The removal of water droplets from the cell largely depends on efficient design of gas flow channel. In that case, gas flow channels or feeding channels are the crucial parts of PEMFC. Nowadays, most of the research efforts have focused on developing and designing the optimized gas flow channel that can enhance the performance of fuel cells.

The major functions of a PEMFC gas flow channel includes distribution of fuel and oxidant uniformly over the entire MEA (Membrane Electrode Assembly) active areas, removal of heat from the cell, conduction of current from cell to cell

[1] Mechanical Engineering Department, Louisiana State University, Baton Rouge, LA-70803, USA
[2] Contact address: Tel.: +1-225-382-2153; fax: +1-225-578-5924; E-mail: ahasan94@gmail.com

and prevention of gas leakage. Typically, the function of a PEM involves complex species transport, chemical reactions, thermal, and electrochemical processes. The transport resistances of gaseous species in the feeding channels and the porous electrodes, studied by Zhu and Kee (2003) also by Fukunaga, Ihara, Sakaki and Yamada (1996), lead to the so-called concentration overpotential. The local concentration of fuel cell and oxidant is affected by the mixing of multiple gases in the feeding channels. It is well known that the mass transfer processes could limit the cell power density. For a high performance PEMFC, choosing the best feeding configuration is one of the possible ways to mitigate the water-flooding problem. Weng, Su, Hsu, and Lee (2006) as well as Su, Weng, Hsu and Chen (2006) made prototypes of fuel cell and tried to observe the water flooding phenomena. However, their study did not properly address water generation in the original fuel cell because, a prototype cell will show different behavior than an original or actual cell. Hasan, Guo, and Wahab (2008, 2009) have analyzed the effects of temperature variation and flow rate inside the tube that can cause the drop in efficiency. Boddu, Marupakula, Summers, and Majumdar (2009) have investigated bipolar plates with different serpentine flow channel configurations using computational fluid dynamics modeling. The flow characteristics including the variation of pressure in the flow channel across the bipolar plate are presented. However, this study did not deal with straight and interdigitated flow channels. Li and Chyu (2004) have shown the enhanced mass transfer in terms of different feeding channel designs without market available designs. Thus, the manufacturing of these designs will lead to a problem. Yoon, Lee, Park, Yang and Kim (2004) have investigated the effects of widths of rib and channel of a flow field plate on the performance of a PEMFC in an effort to optimize the dimensions of rib and channel using four different plates. This work did not deal with market-availability and other flow channel designs. Zee, Shimpalee, and Khan (2004) have designed various feeding channels and tried to determine the best performance in terms of minimum flow rate, temperature distribution, heat flux distribution, output power, and cooling. However, issues concerning thermal and fluid flow in PEMFCs were not studied. Guo and Hasan (2009) have investigated whether blowing excess oxygen will improve performance of cell by converting poisonous carbon monoxide (that can exist in fuel) to carbon dioxide when CO can make a layer over the platinum (Pt) layer and hinder electrochemical reaction.

In research literature, very little work has been published to demonstrate systematically that how gas flow channel configurations could affect the PEMFC performance. Therefore, experimental studies of the effect of gas flow channel design on the performance of PEMFC are still lacking in the literature. In this paper, the influence of gas flow channel design on the performance of PEMFC was studied experimentally. The objective of this paper is to find the best performance of a cell using a combination of three basic gas flow channel designs: straight, serpentine and interdigitated. Performance is analyzed in terms of percentage of water in the gas flow channel, the flooding pattern of water, the fuel utilization rate, the different reacting gas flow rates, and the cell voltage versus current density curve.

2 Components of fuel cell and equipments

Figure 1 shows typical fuel cell, gas flow channel, heater with power outlet ports. In general, there are three designs of feeding channels available in the market as described by Lim and Wang (2004), Wilson, Springer, Davey and Gottesfeld (1995) and Um, and Wang (2000): serpentine (denoted as 'S'), straight (denoted as 'St') and interdigitated channel (denoted as 'I'), which are shown in Figure 2. In this study, straight and interdigitated gas flow channels were conveniently produced by modifying the pre-existing market-available serpentine type gas flow channels. For all tests, a commercially available five-layer (gas diffusion layer in both sides of anode and cathode, electrolyete, and catalyst layer also in both sides) Membrane-Electrode Assembly (MEA) was used. The MEA area is 5.05 cm by 4.95 cm. Hydrogen and oxygen flow through anode and cathode in a co-flow manner; i.e., both flows are parallel and in the same direction. Laboratory temperature was air-conditioned at 21˚C. The pressure of both oxygen and hydrogen in the cell was close to ambient pressure.

Figure 1: Fuel cell gas flow channel by Fuel Cell technologies, Inc.

3 Dimensions of Components of Fuel Cell

The gas flow channel block has an outer dimension of 7.65 cm by 7.65 cm, and has a thickness of 1.3 cm. The gas flow channels have a width of 1 mm and a

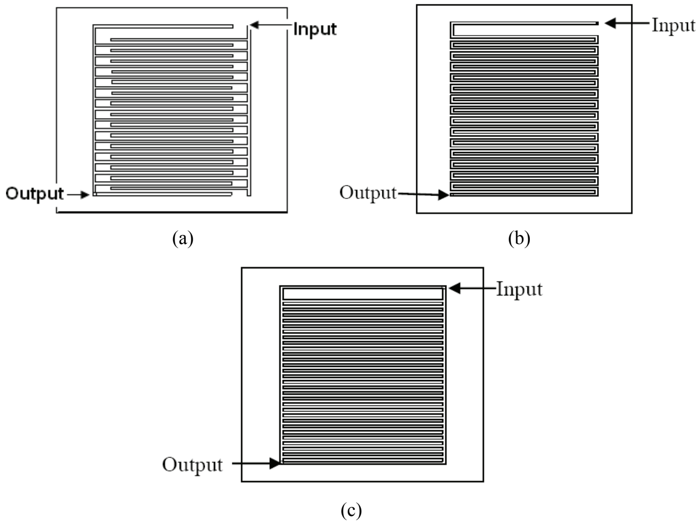

Figure 2: Gas Flow channels: (a) interdigitated (b) serpentine (c) straight design.

depth of 1 mm. The fuel cell was connected to variable load resistors to observe the variation of cell performance with loads. In total twelve (12) resistors: four 0.68 ohm, two 0.56 ohm, two 0.39 ohm, and four 0.27 ohm were used to form the load bank. By connecting some or all of these resistors in serial or parallel manner, different loadings conditions were achieved.

4 Experimental Setup

Overall schematic as well as block diagram of the experimental setup is shown in Figure 3. Unused oxygen was released at the cathode side outlet port. No suction device was used in the oxygen outlet port and oxygen was free to release outside and mix with the outside ambient atmosphere. However, the hydrogen outlet port was connected via a long tube with a laboratory hood for rapid removal of unused hydrogen gas from the lab. As hydrogen is a potentially dangerous combustible gas, so this precaution was necessary.

5 Operation of the Fuel Cell

The gas flow rate of hydrogen was varied from 20 to 100 sccm in the tests to observe cell performance dependence. However, the oxygen flow rate was maintained constant at 46 sccm (standard cubic centimeters per minute) for all the tests. The fuel cell output voltage was monitored using a multimeter. The cell current is ob-

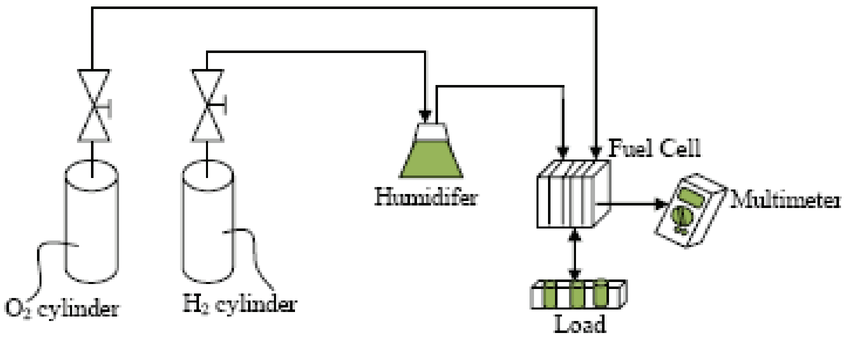

Figure 3: Experimental test stand.

tained by calculating the measured voltage divided by the relevant resistance that was involved; and the cell power is obtained by multiplying the current density and the voltage data that were obtained. The testing cell is inserted with two cartridge heaters for maintaining an elevated operating temperature. To avoid the overheating of the cell and membrane-thermocouple, readings were taken from the testing cell when these heaters were used.

6 Experimental Results and Discussions

For the straight gas flow channel, once the gases enter the channel, they will try to find the shortest way to release from fuel cell. Therefore, the gas flow distribution in the straight gas flow channel is unlikely to be uniform. For serpentine gas flow channel, gases have to follow the direction of the serpentine channel. Due to the relatively defined gas flow path and a long travel distance, high-pressure losses are expected for the serpentine design. interdigitated feeding channel forces the fluid to go inside the porous gas diffusion layer towards the membrane. Thus high fuel/oxidant partial pressure at the three-phase region is expected and the fuel might be used more efficiently.

Efficient hydrogen utilization of a cell is a prime criterion for fuel cell performance. Hydrogen utilization is defined as the ratio of the theoretical flow rate and experimental flow rate of hydrogen into the cell. The experimental flow rate of hydrogen is obtained from the flow meter reading and the theoretical flow rate of hydrogen is calculated from the measured cell power output. After analyzing experimental results, it is found that all gas flow channel configurations show a similar trend in hydrogen utilization. Moreover, data shows that under high load, the interdigitated gas flow channel in anode side and serpentine gas flow channel in cathode side show slight improvement of hydrogen utilization.

P-I (Power-Current) and V-I (Voltage-Current) relations at 21˚C operating temperature using serpentine gas flow channel at the anode and cathode sides are observed for various flow rates of hydrogen. As the local current density (I) is a function of hydrogen and oxygen partial pressures, increasing the fuel flow rate will increase the partial pressure at the later portion of fuel flow channels, thus improving the performance of the cell. Accordingly, from the data it is observed that at the fuel flow rate of 100 sccm, the maximum current density is three times that of 20-sccm.

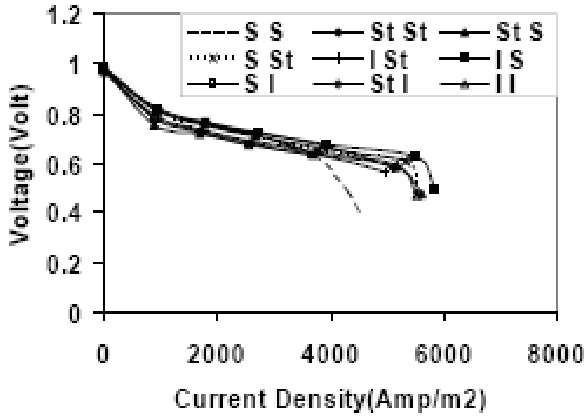

Figure 4: V-I curve at 60 sccm Hz flow rate for different gas flow channel configurations.

Figure 4 shows voltage-current density relations for 60 sccm flow rate of Hz and 21˚C operating temperature for various arrangements of gas flow channels. Experiments were conducted for 9 combinations of gas flow channel arrangements. Also for lower gas flow rates, V-I relations at 20 sccm flow rate and 21˚C operating temperature for various arrangements of gas flow channels are shown in Figure 5. Based on these results, the interdigitated gas flow channel in the anode side and the serpentine gas flow channel in the cathode side show the best performance out of all gas flow channel configurations that were studied. In the same way, V-I curves under hydrogen flow rates of 40, 80 (as shown in Figure 6) and 100 sccm and at 21˚C operating temperature for various arrangements of gas flow channels are observed. Again, the interdigitated gas flow channel in the anode side and the serpentine gas flow channel in the cathode side have the best performance.

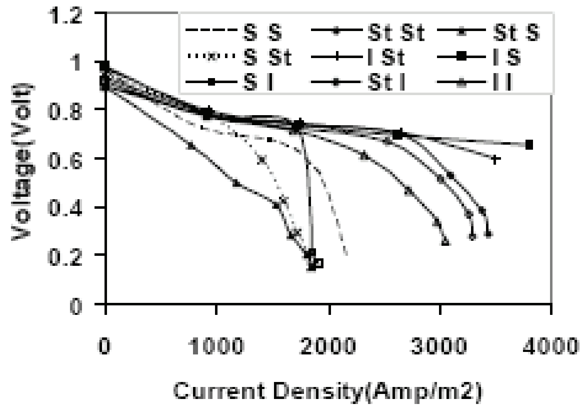

Figure 5: V-I curve at 20 sccm Hz flow rate for different gas flow channel configurations.

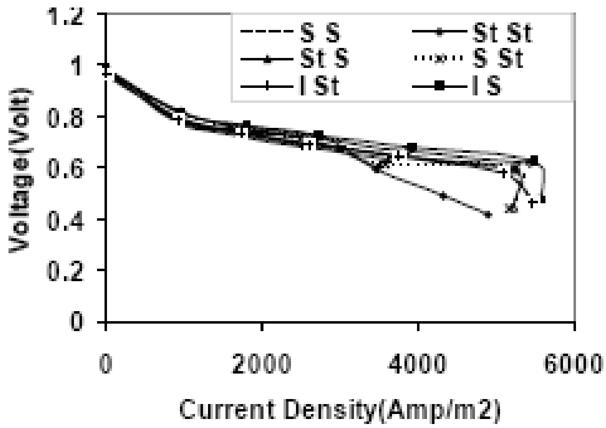

Figure 6: V-I curve at 80 sccm Hz flow rate for different gas flow channel configurations.

The amount of water at a particular location may not block the gas flow channel completely, and the water pattern along the flow channel may not represent the water flooding in the gas diffusion layer. A uniform water pattern in the middle of the gas flow channel region may provide adequate water to saturate the membrane and thus make it function properly. For the case of an interdigitated channel in the cathode side, the water flooding in the channels occurs near the inlet port, and water in those places introduces hindrance to the flow. The oxygen flow rate is not large enough to blow them through the channels, resulting in an undesirable cell performance. For the case where the anode side is the straight channel, an unacceptable water pattern is observed almost everywhere in the exit portion of flow channel. Here, hydrogen will try to take the shortest distance to find the exit port situated at the lower channels. This result in greater water generation in the upper part, so water will flow from the upper part to the lower, causing water jamming in the lower part. In another case, when the straight gas flow channel is used at the cathode side, and the interdigitated gas flow channel at the anode side, it will lead to small patches of localized flooding patterns in the gas flow channels. Images and results of the cell performance have shown that this configuration is good under high loading. These results also indicate that the serpentine at the cathode side and the interdigitated at the anode side will show the best water flooding pattern.

To operate the cell effectively, it is very important to humidify/wet the membrane. However, too much humidification of the membrane may cause water flooding, which can lead to low performance of the cell. For this reason, the performance of the cell was also tested with and without the use of the humidifier. Under high load, more water generation and stronger transportation of water from the anode to the cathodes, due to the electro-osmotic drag, makes the use of a humidifier unnecessary in the cathode side.

After operating the fuel cell at high current density until it showed steady data in multimeter, the cell was opened, and the patterns of water flooding in the cathode side gas flow channels were photographed. Table 1 lists the percentage of area covered by water in the flow channel for different combinations of gas flow channel arrangements. All combinations appear to have wet areas along the feeding channels. Water is generated due to the reaction of hydrogen and oxygen, and water particles are carried by electro-osmotic drag from the anode towards the cathode. After observing water flooding and percentage of water in the cell from Table 1, it is found that for all combinations of arrangements, the water flooding in the gas flow channel is nearly 25%. However, the real flooding problem, which seriously damages the cell performance, occurs in the porous gas diffusion layers close to the three-phase boundary. Thus, the water accumulations in the gas flow channels can only be used as an indicator for potential water flooding in the gas diffusion layers.

This paper uses cell voltage, current density, flooded area and fuel utilization to characterize the cell performance. However, another factor for the fuel cell design is the cell electric efficiency, which is not addressed here. In particular, energy is needed to blow the fuel and air through the channels, meaning more energy will be consumed. If the energy loss is considered this way, the optimal gas flow channel arrangements will have the same energy consumption and similar effects to those described above in both sides of the anode and the cathode channels.

Table 1: Percentage of water in the cathode side gas flow channels for various feeding configurations after electrochemical reaction, electro-osmotic drag etc [S: Sezpertine, St: Straight, I: Interdigitated].

Gas flow channel arrangements	% Water in the channel
S I	26%
S St	22%
S S	23%
I I	37%
I St	27%
I S	25%
St I	17%
St St	25%
St S	34%

7 Conclusion

The analyses of performance of PEMFC to predict fuels utilization by gas flow channel arrangements are presented for different designs of gas flow channels. The measurement of performance of Fuel cell is analyzed by parameters such as: polarization curve, percentage water in the gas flow channels, water flooding pattern and fuel utilization rate at different reacting fluid flow rates by using different combinations of cathode and anode gas flow channel arrangements. Overall study has indicated that an interdigitated anode gas flow channel with a serpentine cathode gas flow channel gave the best result considering those parameters. To eliminate water flooding partially, by using serpentine gas flow channel in cathode side works effectively for the reason that high flow speed of gas has capability of blowing the water droplets out of the cell. This condition prevents water flooding in the cathode side and a performance drop in the cell. It is expected that, this investigation will increase understanding of Fuel cell gas flow channel design during operation of PEMFCs in practical applications.

Acknowledgement: This work was funded by LSU Faculty Research Grant and NASA/EPSCoR grant under grant number NASA/LEQSF (2007-10)-Phase3-01. The authors greatly acknowledge for the financial support of this work. The authors are also grateful for the assistance of Dr. S. V. Ekkad.

References

Boddu, R.; Marupakula, U. K.; Summers, B.; Majumdar, P. (2009): Development of bipolar plates with different flow channel configurations for fuel cells, *Journal of Power Sources*, Vol. 189, pp. 1083–1092.

Fuel Cell Technologies, Inc. from `http://www.fuelcelltechnologies.com/fuelcell/products/single_cell_hardware.asp`

Fukunga, H.; Ihara, M.; Sakai, K.; Yamada, K. (1996): Relationship between overpotential and the three phase boundary length, *Solid State Ionics*, Vol. 86-88, No. pt 2, pp. 1179-1185.

Hasan, A.B.M.; Wahab, M.A.; Guo, S.M. (2008): Effects of Heat Affected Zones Temperature on the General Performance of High Temperature Vacuum Tube Furnace, *Structural Durability & Health Monitoring*, Vol.4, No.4, pp. 231-240.

Hasan, A.B.M.; Guo, S.M.; Wahab, M. A. (2009): Analysis of Fracture in High-Temperature Vacuum Tube Furnace, *Journal of Failure Analysis and Prevention*, Vol.9, No.3, pp. 262-269.

Guo, S. M.; Hasan, A.B.M. (2009): Proton Exchange Membrane Fuel Cell High Carbon Monoxide Tolerance Operation using Pulsed Heating and Pressure Swing, *ASME Journal of Fuel Cell Science and Technology*, Vol.6, No.1, pp. 011022-1-6.

Li, P. W.; Chu, M.K. (2004): Mass transfer Enhancement for Improving the Performance of Polymer Electrolyte Fuel Cells, *ASME Heat Transfer/ Fluid Engineering Summer Conference*, No. HT-FED04-56217, July 11-15, Charlotte, North Carolina.

Lim, C.; Wang, C. Y. (2004): Effects of hydrophobic polymer content in GDL on power performance of a PEM Fuel cell. *Electrochimica Acta*, Vol. 49, pp. 4149-4156.

Su, A.; Weng, F.B.; Hsu, C.Y.; Chen, Y.M. (2006): Studies on flooding in PEM fuel cell cathode channels, *International Journal of Hydrogen Energy*, Vol. 31, pp. 031-1039.

Um, S.; Wang, C.Y. (2000): Three Dimensional Analysis of Transport and Reaction in Proton Exchange Membrane Fuel Cells, *in Proc. of the ASME Heat Transfer Division*.

Weng, F.B.; Su, A.; Hsu, C.Y.; Lee, C.Y. (2006): Study of water-flooding behavior in cathode channel of a transparent proton-exchange membrane fuel cell, *Journal of power sources*.

Wilson, M.S.; Springer, T.E.; Davey, J.; Gottesfeld, S. (1995): Alternative Flow-Field and Backing Concepts for Polymer Electrolyte Membrane Fuel Cells, *Electrochemical Soc. Proc. Ed.*

Yoon, Y.; Lee, W.Y.; Park, G.G.; Yang, T.H., Kim, C.S. (2004): Effects of channel configurations of flow field plates on the performance of a PEMFC, *Electrochimica Acta*, Vol.50, pp.709–712.

Zee, J.W.; Shimpalee, V.; Khan, J.A. (2004): Effect of Bipolar Plate Cooling on Fuel cell heat generation, *Proceedings of HT-FED04, ASME Heat Transfer/ Fluid Engineering Summer Conference*, No. HT-FED04-56707, July 11-15, Charlotte, North Carolina.

Zhu, H.; Kee, R.J. (2003): A general mathematical model for analyzing the performance of fuel-cell membrane-electrode assemblies, *Journal of Power Sources*, Vol. 117, No. 1-2, pp. 61-74.