PERFORMANCE OF POLYMER ELECTROLYTE MEMBRANE FUEL CELL STACK

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ABSTRACT

The performance of an air-breathing polymer electrolyte membrane fuel cell (PEMFC) stack is evaluated under different conditions. These different conditions include humidity, temperature and $\text{H}_2$ flow rate. When the humidity is less than 10 percent relative humidity (RH) at 35°C, the stack does not work properly. Self-humidifying by the product of water in the stack is observed at below 30 percent RH. It is suggested that the appropriate humidity for operating the stack is at least 30 percent RH or higher. The best operational temperature for the stack ranges from 20 to 40°C. The rate of $\text{H}_2$ flow does not have any apparent effect on the stack power output. Rather only determines the maximum operating current.

INTRODUCTION

Steadily increasing portable electric power requirements have created the need to develop more efficient and energetic power sources. The polymer electrolyte membrane fuel cell (PEMFC) is one of the best candidates for a portable power supply device for commercial applications primarily because of its lightweight and high-power density. PEMFCs have received much attention since the 1980s. Their development was helped by the invention of Nafion by DuPont in the 1960s [1]. Nafion is a perfluorinated cation exchange polymer membrane that has shown good conductivity and stability up to 100°C in fuel cell environmental operating conditions. Early research concentrated mainly on membrane electrolytes and their properties. Later research has focused on the PEMFC’s components. More recently, there have been numerous reports in the literature describing the performance of single-cell PEMFCs [2-10]. It appears that PEMFCs will be going through a commercialization and demonstration stage soon. PEMFC stacks having a variety of types and functions have been emerging from many developers [11-13], but there have been no detailed on systematic investigations evaluating their performance, which varies from one design to another.
Understanding the performance characteristics of PEMFC stacks is important for arriving at optimum cost/weight/performance ratios. The objective of this study is to bridge the gap between the development and application of PEMFC stacks for military and civilian applications. The air-breathing PEMFC stack is a two-dimensional fuel cell stack with individual cells in the same plane [11]. This allows all of the cells to access the same reservoir of hydrogen, and the opposite face to be openly exposed to air. This design has a lightweight, simple feature for portable electric power sources. In this research we investigate a class of air-breathing PEMFC stacks in which air is provided by spontaneous convection from the environment.

EXPERIMENT

The air-breathing PEMFC stack was composed of 6 bi-cells connected in series. The area of each electrode is approximately 32 cm\(^2\). The open circuit voltage was approximately 6V. The oxygen supply to the cathode was obtained by convection from the air. High-purity hydrogen (99.99\%) was used. The experiments used dry hydrogen and wet hydrogen (saturated with water). A Matheson TF601 rotameter was used for measuring the hydrogen flow rate. The temperature and humidity were controlled with a Tenney environment chamber (model BTRC) and heatless Dryer (model No. HF 200A). A Hewlett-Packard electronic load (model No. 6050B) and a Hewlett-Packard multimeter were used for measuring the stack's current and voltage, respectively. The Tenney environment chamber was controlled through a computer using Linktenn II software.

RESULTS AND DISCUSSION

It is well known that the performance of a PEMFC is a function of temperature and pressure. However, operating temperature increases will cause thermal management and membrane dry-out problems. Operating pressure increases will result in system complications. Therefore, our emphasis here is on the evaluation of ambient pressure, normal environmental temperatures, and humidity for a PEMFC stack that can be carried by one person. The air-breathing PEMFC stack was designed to use oxygen from the surrounding air. This makes it lighter, simpler and cheaper than other types of stacks because no auxiliaries for providing oxygen or air are required. The reaction product of water at the cathode electrode was automatically exhausted to the environment. The disadvantage of air-breathing PEMFC stack is that many factors present in the surrounding environment may affect stack performance. The first factor considered is humidity.
I. Humidity:

Figure 1A shows the effect of relative humidity (%RH) on stack performance at 35°C and constant H₂ flow rate. The polarization curve with 85 percent RH has the highest value of voltage at the same current. This means that the highest power output is at 85 percent RH. The performance of the stack degrades with decreasing percent RH. Between an RH of 85 and 30 percent, the voltage decreases steadily with increasing current. However, at 20 percent RH, the decrease stops. Surprisingly, when the operating current increases past 1.0 A, the voltage increases instead of decreasing. This is because of the stack's self-humidifying effect due to water production at the cathode. When the RH value is less than 10 percent the stack’s voltage decreases considerably with increasing current. Figure 1B shows the calculated stack power from the data shown in Fig. 1A. The stack’s power increases with increasing current until reaching the highest current value. If it goes above the highest current, the voltage drops to zero because the amount of hydrogen supplied is completely consumed. The stack’s performance completely deteriorates for percent RH level equal to or less than 10 percent at 35°C. The voltage and power versus current plots for different percent RHs at 10°C are shown in Fig. 2. A comparison of Figs. 1 and 2 shows that the effect of humidity on stack performance at 10°C is less than that at 35°C.

Figure 3 shows the polarization curves for the same flow rate of the hydrogen, both saturated with water and not saturated with water, that is fed into the anode at 40°C and 20 percent RH. As expected the stack performance for the hydrogen saturated with water, which is fed into the anode compartment, is better than that for the hydrogen not saturated with water.

The effect of humidity on Nafion’s ionic conductivity at different temperatures was reported by Sone et al [14]. The temperature range was from 20 to 50°C. They reported that Nafion’s ionic conductivity is significantly affected by humidity. Their results are in agreement with the experimental results shown in Fig. 1.

II Temperature:

Figure 4 shows a series of polarization curves for the PEMFC stack at constant humidity (50 percent RH) as a function of temperature. With increasing current, the voltage decreases and the power increases. The stack performance improves with increasing temperatures. In order to understand the performance of the stack in more detail, the data from Fig. 4 were used to construct a plot of voltage versus temperature at different currents shown in Fig. 5. Within the range of temperatures tested, stack performance seems to be linearly proportional to temperature at constant current applied. At lower currents, the curves show a small deviation from linearity and a smaller slope.
This indicates that the electrochemical process is controlled mainly by a charge transfer reaction or activation of the electrodes. At the higher currents, the curves show a large deviation from linearity and a larger slope, which implies that the electrochemical process is controlled mainly by ohmic polarization. Nafion’s impedance becomes more appreciable at higher currents, causing a larger IR drop when the $\text{H}^+$ ions pass through the membrane.

III. $\text{H}_2$ Flow Rate:

The air-breathing PEMFC stack was designed to work at low $\text{H}_2$ pressure. Therefore, the $\text{H}_2$ flow rate is one of the critical parameters that determine the performance of the stack. The $\text{H}_2$ flow rates were varied at constant temperature and humidity. Figure 6 shows a series of polarization curves for the stack at different $\text{H}_2$ flow rates. Surprisingly, the $\text{H}_2$ flow rate has no appreciable effect on the performance of the stack until the current increases to a maximum value. This is because the air-breathing PEMFC stack is still maintaining approximately the same $\text{H}_2$ pressure even at different $\text{H}_2$ flow rates. The voltage does drop to zero when the current is greater than a maximum value because the hydrogen at the anode compartment is completely consumed. The stack cannot be operated at a value equal to or greater than the maximum value. If it did, this value would probably damage the stack. Figure 7 shows the plot of the maximum current versus $\text{H}_2$ flow rate. As expected, it is a straight line and passes through the origin. If a high $\text{H}_2$ flow rate is applied, this may cause a waste of fuel or may also damage the stack. According to Fig. 7, a properly operating stack needs to use an appropriate $\text{H}_2$ flow rate. Because oxygen is provided from the air, the maximum performance of the air-breathing PEMFC stack is limited by the natural convection of the surrounding air. Even if an excess amount of $\text{H}_2$ is supplied, the stack's performance is still determined by the amount of oxygen supplied from the air.

IV. System Optimization and Stability:

After optimization of temperature, humidity, and hydrogen flow rate, the best performance of the air-breathing stack was obtained. Figure 8 shows the highest possible power output. It is approximately 22.5 W at operating conditions of 7.5 A, 3 V, 35°C and 85 percent RH humidity. The long-term performance of the air-breathing PEMFC stack was also evaluated at 35°C, and 50 percent RH for 4.05 A and 5.04 A. The result is shown in Fig. 9 which depicts the stack operation voltage versus time. After a 30-hour test, it was still stable at constant of 4 A and 5 A, respectively.

CONCLUSION
The humidity in the surrounding air significantly affects the performance of the air-breathing PEMFC stack. When humidity is less than 10 percent RH, the stack does not operate properly. A phenomenon of self-humidifying by the product of water in the stack is observed at an operating current higher than 1.0 A for a humidity level of a 20 percent RH. It is suggested that the appropriate humidity level for operating the stack is 30 percent RH or higher. The proper operational temperatures for the air-breathing PEMFC stack range from 20 to 40°C. Operating at temperatures lower than 5°C results in poor performance. The rate of H₂ flow does not have any apparent effect on the power output. It determines only the maximum current point at which the voltage drops to zero.

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Figure 2. Effect of H2 flow on stack power and voltage at low temperature (70°C). H2 flow rates are 2%, 20%, 40%, 60%, and 80%, respectively.

Figure 3. Effect of H2 flow on stack power and voltage at low temperature (40°C). H2 flow rates are 2%, 20%, 40%, 60%, and 80%, respectively.

Figure 4A. Effect of N2 flow on stack voltage. T = 35°C, H2 flow = 60 ml/min.

Figure 4B. Effect of N2 flow on stack power. T = 35°C, H2 flow = 60 ml/min.
Figure 4. Effect of temperature on stack voltage and power. RH = 50%, H₂ flow = 68 ml/min. Lines from bottom to top temperature (°C) are 5, 20, 30, 35, and 40, respectively.

Figure 5. Stack voltage vs. temperature with variety of current values.

Figure 6. Effect of H₂ flow rate on stack power and voltage. T = 35 °C, RH as 50%.

Figure 7. H₂ flow rate vs. current values at which voltage dropping rapidly. T = 35 °C and RH = 50%.

Electrochemical Society Proceedings Volume 98-27 477
Figure 6: Optimized performance of the air-breath PEMFC stack. RH = 85%, H₂ flow = 276 min⁻¹ and T = 55 °C.

Figure 7: Stack performance at constant current operation. Time T = 55 °C.

Stack Voltage (V)

Stack Power (W)

Stack Voltage (V)

Time (Hour)

Electrochemical Society Proceedings Volume 98-27 478