Performance studies on serpentine flow channel of a proton exchange membrane fuel cell

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Abstract. The results of the experimental investigations on the performance of a Proton Exchange Membrane Fuel Cell (PEMFC) with serpentine flow field is reported in the present work. The serpentine flow channel considered in the present work has an active area of 50 cm² and has a landing to channel ratio of 1:1. The power densities at various operating temperatures are determined experimentally. The testing is done on the PEMFC for three different temperatures: 50, 60 and 70°C. The output power at a particular cell voltage has been found to increase as the temperature increases. The maximum power obtained is 23.01 W at 0.48 V when the cell operating temperature is 70°C. In order to characterize the nafion membrane, a scanning electron microscope analysis is also performed and the results are reported in the present paper.

1. Introduction
Today, the world is mostly dependent on fossil fuels for meeting its energy demands. Fossil fuels are non-renewable and their use has serious detrimental effects on the earth's environment. Among the alternative sources of energy fuel cells are very promising. Fuel cells are electrochemical devices, which can produce electricity by electrochemical reactions between the hydrogen fuel and oxygen or another oxidizing agent. The various types of fuel cells are proton exchange membrane fuel cells, molten carbonate fuel cells, direct methanol fuel cells, solid oxide fuel cells, phosphoric acid fuel cells and alkaline fuel cells. The PEMFCs offer greater advantages over others due to their lower operating temperature, less running cost and increased lifetime.

The various components of a PEMFC are a) end plates b) current collector plates c) polymer electrolyte membrane d) gas diffusion layer and e) bipolar plates. Unlike the battery, fuel cells need a continuous supply of fuel and oxidizer for the production of electricity. Higher initial investment and the complications involved in the storage of hydrogen are the major drawbacks for the implementation of fuel cells for power generation.
Following are the chemical reactions involved in the operation of PEMFC:

At the anode: \( \text{H}_2 \rightarrow 2\text{H}^+ + 2e^- \quad (1) \)

At the cathode: \( \frac{1}{2} \text{O}_2 + 2\text{H}^+ + 2e^- \rightarrow \text{H}_2\text{O} \quad (2) \)

Cell reaction: \( \text{H}_2 + \frac{1}{2} \text{O}_2 \rightarrow \text{H}_2\text{O} \quad (3) \)

2. Literature Review

Several numerical as well as experimental investigations have been done on various flow fields of PEMFCs. Still, a lot of work needs to be done on fuel cells for their useful applications in our day to day lives. Wang et al. [1] investigated various operating features like pressures and temperatures, anode and cathode humidification. They also carried out numerical studies and verified that their numerical results with reference to their experimental outcomes. They reported that, with proper humidification the performance of a PEMFC would increase with the increasing operating temperature. In their work Carton and Olabi [2], studied the various flow fields such as serpentine, maze and parallel types for low temperature PEMFCs. Various experiments were carried out on these three flow channels in order to determine the reaction of the fuel cell to output current, voltage, power and also their efficiency. It was found that the serpentine flow channel exhibited better performance characteristics and polarization curve compared to other two flow fields.

Karthikeyan et al. [3] observed that the power density of PEMFC decreased with increase in cross-sectional area. They also found that the performance of a PEMFC stack depended on the temperature management and the distribution of fuel in the flow channel. Kanezaki et al. [4] focused their attention towards the effective water removal in a PEMFC. They conducted numerical studies on the influence of cross-leakage flow through a PEMFC. It was reported that, in a PEMFC with serpentine flow channel, cross-leakage through the electrode reduced the concentration over potential and helped to effectively remove the water formed in the fuel cell. Chang and Hung [5] studied the influence of channel depth and flow rates on the performance of a PEMFC. They reported that to maintain necessary pressure in order to push the reactant into the flow field and to have a sufficient water balance, an appropriate flow rate was required for shallow channels. Ararimeh and Sastry [6] studied the effect of baffles on various flow channels. They reported that when baffles are added to various flow field designs, the performance of the PEMFC improved.

Rostami et al. [7] numerically studied the effect of bend sizes in serpentine flow fields of PEMFC. They carried out various numerical studies by changing the bend sizes from 0.8 mm to 1.2 mm. They found that 1.2 mm bend size serpentine flow channel had better electrochemical properties due to better catalyst contact area and also due to uniform temperature distribution. Khazaei and Sabadabafan [8] investigated the influence of flow channel design and relative humidity of a rectangular PEMFC with active area of 24.8 cm\(^2\). They established the effect of water management in the performance of a PEMFC. They developed a three-dimensional PEMFC of various serpentine flow fields and studied the flow patterns of the inlet gases on the fuel cell performance. They also found that the flow channel design had much influence over the performance of a PEMFC compared to the directional properties. A serpentine geometry having three tapered channels and a diverging channel at the cathode side was proposed by Wang et al. [9]. They reported that the design would enhance the oxygen transport rate within the channel and thus the current density.

A three-dimensional computational model with various sizes, shapes and patterns of bipolar plates with serpentine flow channel was developed by Boddu et al. [10]. They reported that square bends had higher pressure drop than curvilinear bends. Also, it is seen that more uniform distribution of inlet gases occurred when the cross-section area was decreased. Teccani and Zuliani [11] studied the influence of flow field on the performance of a PEMFC. They compared the results of serpentine and parallel flow fields. The results showed that the flow field having a higher number of serpentine step had better performance in terms of power density.
3. Experimental Setup

The experimental setup of a fuel cell test station has mainly five parts: a computer, temperature control system, flow rate control system, humidifier and an electronic load system. The computer stores the various values of current, voltage, power density and inlet flow rate of hydrogen and oxygen. The temperature control system is used to vary the temperature of the fuel cell. A calibrated thermocouple is inserted into the graphite plates, in order to measure the temperature of the fuel cell. The flow rate control system has hydrogen, oxygen and nitrogen stored in special cylinders for supply to the fuel cell. High purity hydrogen is supplied to the anode side of the PEMFC and medical grade oxygen is supplied at the cathode side. Nitrogen is used so as to flush the excess water and residual gases formed in the fuel cell during the reaction. If the hydrogen and oxygen are supplied without proper humidification the membrane electrode assembly (MEA) may suffer damages. So a humidifier is used to humidify the inlet hydrogen and oxygen supplied to the fuel cell. The electronic load system is employed to obtain the various current and voltage loads. The load system has a 600 W maximum power output, 500 V maximum voltage and 120 A maximum current. A photograph of the fuel cell test station is shown in figure 1.

![Figure 1. A photograph of the fuel cell testing station used in the present study](image)

The flow channel is made of graphite plate with a total area of 100 cm². The active area of the fuel cell selected for the present experimental work is 50 cm². The landing to channel ratio considered is 1:1. The diagram of the serpentine flow channel used is shown in figure 2.
Figure 2. Design of the 50cm² bipolar plate.

The fuel cell has a membrane electrode assembly through which the exchange of proton takes place. Nafion membrane is used as the binder to hold the gas diffusion electrodes (GDE) together. A scanning electron microscope image of the Nafion membrane used in the present study is shown in figure 3.

Figure 3. A 850x magnified image of the Nafion membrane.

3.1 Experimental Procedure
The values of current, voltage, and power of the fuel cell are recorded during the testing process. Oxygen and hydrogen gases are humidified using a humidifier at various temperatures. Calibrated thermocouples and heating coils are used to measure and vary the temperature respectively. The voltage developed is recorded for a particular current. A computing device is used to record current density, power density and the power developed, with the help of a testing apparatus. The flow rate,
line pressure, line temperature, humidity values and supply temperatures of hydrogen and oxygen gases respectively are recorded throughout the experiment. An electronically varying load testing apparatus is set to 1 V and 50 A parameter limits. Relevant readings are noted for temperatures of 50, 60 and 70ºC.

4. Results and Discussion

4.1 Effect of temperature on current density
Polarization curves are plotted with cell voltage along the Y-axis and current density along the X-axis for temperatures of 50, 60 and 70ºC. The polarization curve at 70ºC is shown in figure 4. From the figure it can be observed that the maximum current density of 0.96 A/cm² is obtained for a cell voltage of 0.48 V. The cell potential decreases as current density increases.

![Polarization curve at 70ºC.](image)

The polarization curve at 60ºC is plotted and is shown in figure 5. From the graph it can be inferred that the maximum current density of 0.88 A/cm² is attained for a cell voltage of 0.48 V. There is a slight decrease in the maximum current density with temperature.
The polarization curve at 50ºC is shown in figure 6. From the graph it can be seen that the maximum current density of 0.80 A/cm² is attained for a cell voltage of 0.48 V. From the figures 4 to 6, it is clear that current density increases with increase in temperature for a particular cell voltage.

Figure 5. Polarization curve at 60ºC.

Figure 6. Polarization curve at 50ºC
4.2 Effect of temperature on power

The variation of power with cell voltage for the three temperatures are given in table 1. From the table it is inferred that the power decreases as the cell voltage increases.

| Sl. No | Cell Voltage (V) | Power at 50°C (W) | Power at 60°C (W) | Power at 70°C (W) |
|--------|------------------|-------------------|-------------------|-------------------|
| 1      | 0.47             | 20.65             | 21.60             | 22.88             |
| 2      | 0.48             | **19.18**         | **21.09**         | **23.01**         |
| 3      | 0.50             | 16.47             | 18.47             | 17.97             |
| 4      | 0.55             | 9.87              | 12.62             | 13.72             |
| 5      | 0.60             | 4.77              | 5.97              | 8.97              |
| 6      | 0.65             | 1.91              | 3.21              | 5.16              |

Operating range of the fuel cell is the ohmic region and the voltage varies between 0.40 and 0.50 V. From the table 1 it is observed that the peak power output values occur between these voltages. The maximum power output of 23.01 W is obtained at 0.48 V and 70°C. At 0.48 V and 50°C the power output is 19.18 W. The deviation when temperature rises from 50 to 70°C is 20%. Similarly, deviation between power at 50°C and 60°C is 10%. Better performance is due to the increase in the rate of reaction when temperature is on the increase.

5. Conclusions

In the present work, experimental investigations are conducted on a 50 cm² active area PEMFC. The main conclusions obtained from this investigation are given below.

- The power output at three different temperatures and cell voltages are obtained. From the present study it is seen that for a particular voltage as the temperature increases power level also increases.
- From the cell voltage and power, it can be inferred that as the temperature is increased from 50 to 70°C the power output increases by 20%. Increase in the temperature will improve the rate of chemical reaction. So, at 70°C electrochemical reaction and its rate will be high when compared with those at lower temperatures and therefore gives the maximum power value.

The insights developed from the present experimental studies may be used for further improvement in the design of proton exchange membrane fuel cells.

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