Performance Analysis of Various Types of PEM Fuel Cells

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Abstract

Proton exchange membrane (PEM) fuel cells are important to chemical engineering due to its ability to produce clean sustainable energy from hydrogen and oxygen. In this experiment, different types of PEM fuel cells (i.e. single membrane with pure H_2 and air, double membrane fuel cell with pure H_2 and O_2, and methanol fuel cells with 3% methanol solution and air) were tested from 1-110 Ω in increments of 5 Ω to obtain voltage and current. On the other hand, the single membrane fuel cell with pure H_2 and pure O_2 was tested from 1-55 Ω in increments of 1 and 5 Ω to obtain voltage and current. From analyzing the data, the power curves and coefficients from the polarization curves were obtained for each fuel cell. The data collected shows that the double membrane with pure O_2 and pure H_2 produced the highest power and efficiency compared to the rest of the fuel cells. This is as expected as the double membrane fuel cell has more surface area for the protons to permeate through, and using pure O_2 leads to more reduction. Although the collected data does follow previous literature trends, several improvements can be made. For example, using a more reliable decade resistant box would allow for more accurate data collection, and more testing at lower resistances for the fuel cells would capture more data for the polarization curves. Thus, better results and more concrete conclusions can be drawn if these recommendations are considered.

1 Introduction

Proton exchange membrane fuel cells are one of the many types of fuel cells being researched for applications in chemical engineering. PEM fuel cells are important because they are able to produce clean sustainable energy by using H_2 as the fuel and O_2 as the oxidizer. The fuel passes a catalyst down the anode which ionizes the fuel; the ions then pass through the electrolyte layer of the membrane in the fuel cell to the cathode. At the same time, current passes through the external circuit. At the cathode, the ions react with the external current and oxidizing agent to produce water. With the growing increasing need for clean sustainable energy production, PEM fuel cells could be a possible solution. However, even since it's inception in the 1960s by the General Electric Corporation there is still much needed research to be done such as its performance and cost before it can be widely adopted.[1] Despite this, PEM fuel cells have been seen as feasible options in multiple industries such as the automotive and residential. For instance, PEM fuel cells have been researched in the automotive industry due to its ability to power cars while producing no polluting emissions.[2] However, due to its lower performance there is still much needed research before this can replace combustion engines.[2] In regards to the residential sector, PEM fuel cells have been researched as uninterruptible power sources.[3] Although this idea has potential to provide uninterruptible clean sustainable energy, it is still not implementable due to the high costs.[3] As shown, PEM fuel cells are capable of providing clean and sustainable energy, but there is still much research that is required before they become widely used.

2 Background

The performance of a PEM fuel cell is dependent on various parameters such as the gas flow rate, the design of the membrane, the parameters of the environment such as the temperature, humidity, and the air quality.[4] The performance of the PEM fuel cell can be optimized such that the PEM fuel cell can produce more energy and do so for a longer period. Of the parameters

that were mentioned previously, only a few have a significant effect on the performance of the PEM fuel cell.

To begin with, the membrane itself that allows for the proton exchange to occur is an important aspect of the performance of the PEM fuel cell. PEM fuel cells use what is known as a catalyst coated membrane.[5] The kind of catalyst and the structure of the membrane is what can be designed and modified to the application of the PEM. Surface area can be increased, depending on the structure of the membrane, thereby improving the proton conduction of the PEMs; however, the literature on the topic of increasing surface area is less researched because of the difficulty manufacturing nano and micro structured membranes.[5]

Additionally, increasing the range in which the PEM can operate effectively and improving the operating efficiency in a certain range is also a design aspect that can be modified to improve the overall performance of the PEM. Research is currently being done on PEM fuel cells integrated in low duty vehicles where the performance of the different kinds of PEM fuel cells are being analyzed.[4,5] The structure and the shape of the PEM affects the surface area, the extent of performance and the temperature range of the performance, consequently requiring a balance between how the PEM is designed with regards to temperature and humidity, and surface area interaction.

Furthermore, simulations are done to gather preliminary data on how a PEM may perform in certain circumstances. Simulation data can be collected and compared to experimental data to determine if the experimental data adheres to expected results. When modeling PEMs, various assumptions are made such that the data collected is representative of how a PEM will perform. A paper from Min et al. simulated a PEM fuel cell operating at different temperatures with a constant humidification temperature, and a fuel cell operating at a constant operating temperature and at different humidification temperatures.[6] By simulating the PEM preliminary data can guide researchers towards how to further experiment with a PEM in an actual experiment.

Here in this experiment, data was collected on 4 different configurations of PEM fuel cells.

Current and voltage were measured at different resistances for each of the experimental setups. The characteristics and performance of each of the PEM fuel cells were determined by producing polarization curves and performance curves. The polarization curves were produced by using the model determined in Kim et al.[7] The performance curves were produced using the model provided by Benzinger et. al.[8] Each of the performance curves were analyzed and compared to determine what kinds of characteristics produced a high performing PEM fuel cell.

3 Theory

The objective of this lab was to compare the performance and the characteristics of each of the 4 different configurations of PEM fuel cells.

The equation

$$E = E_o - b\log(i) - Ri - m\exp(ni) \tag{1}$$

from Kim et al. was used to model the characteristics of a PEM fuel cell.[7] E_o is defined as,

$$E_o = E_r + b\log(i_o) \tag{2}$$

where E_r is the reversible potential of the cell and i_o and b are the Tafel parameters for O_2 reduction.[7] In this experiment, Kim et. al. provides experimentally determined values for E_o.[7] The use of Equation 2 was limited only to using the experimentally determined values and understanding of Equation 1. To continue, R is defined as the resistance which causes a linear variation of E with i, m and n are constants that account for the mass-transport overpotential, i is the current density, and E is defined as the cell potential.[7]

The equations used to model the performance of the PEM fuel cell are,

$$P = I \times V \tag{3}$$

and

$$\xi = \frac{P}{P_o} \tag{4}$$

where ξ is the fuel cell conversion efficiency, V is the measured voltage, I is the current, and P_o is the power if there were no internal resistances.[8] P_o is defined as,

$$P_o = \frac{V_b^2 R_L}{(R_{int} + R_L)^2} \tag{5}$$

where V_b is the voltage of the fuel cell, R_L is the resistance measured from external load, and R_{int} is the internal resistance of the fuel cell which in this case is zero.

4 Methods

An electrolyzer was used to separate water into hydrogen and oxygen and store them into storage tanks. These tanks were then connected to the various types of fuel cells, single and double membrane with pure O_2 and pure H_2, and ultimately vented out to the atmosphere. The methanol fuel cell and single membrane with pure H_2 and air fuel cell did not require this. The methanol fuel cell only requires 3% methanol solution poured into the fuel cell and air to function properly. Also, the single membrane with pure H_2 and air fuel cell only needed the pure H_2 feed line, but not the pure O_2 feed line. Before experimenting with the fuel cells, three purges were done in order to ensure that the fuel cells were ready to be tested. Purging was done by closing the lines from the storage tanks to the fuel cell, waiting until O_2 and H_2 filled the storage tanks, and then opening the lines. After purging, the fuel cells were connected to an external circuit comprising of a decade resistance box and multimeter. The decade resistance box was varied from 1-110 Ω in increments of 5 Ω for the single membrane with pure H_2 and air, the double membrane, and the methanol fuel cell; the single membrane with pure H_2 and pure O_2 was varied from 1-55 Ω in increments of 1 and 5 Ω. The resulting current or voltage was measured for each fuel cell. To measure current, the decade resistance box and multimeter was

set in series. To measure voltage, the decade resistance box and multimeter was set in parallel. Readings were then taken once the mutltimeter reached steady state.

5 Results and Discussion

The two major results that were obtained from the data were the polarization ("characteristic") curves and its coefficients as well as the power performance curves of the various different fuel cells. The characteristic curves originate from Kim et al. whereas the power performance curves originate from Benziger et al.[7,8]

The figure below displays the characteristic curve of the single membrane fuel cell with H_2/pure O_2 vs. one with H_2/air. Equation 1 was used to perform the fit to the data collected

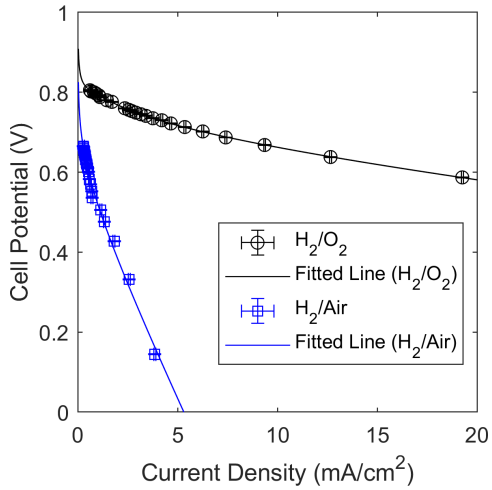

Figure 1: The figure above demonstrates the cell potential of the H_2/pure O_2 and H_2/air fuel cells vs. current density.

and the coefficients that were obtained are previously listed in the theory section.[7] A clear trend is shown here almost similar to the one displayed in the Kim et al. paper. The H_2/O_2 fuel cell has significantly more cell potential than the H_2/air fuel cell. This is because there's exceptionally less concentration of O_2 in the air in comparison to using pure O_2. Namely, there is about 21% O_2 in the air. Since there's less O_2 in the air for it to react with the electrons and H^+ ions from the anode, less voltage and current is to be expected. However, there is a stark

difference in the coefficients that were calculated using nonlinear regression, which are listed in the table below. For the H_2/O_2 fuel cell, all 5 coefficients were able to be calculated; for

Table 1: Coefficients obtained from nonlinear regression for each of the fuel cells using Equation 1 from Kim et al.[7]

Fuel Cell	E_o (mV)	b (mV/dec)	R ($\Omega \cdot cm^2$)	m (mV)	n ($cm^2\,mA^{-1}$)
Single (H_2/O_2)	808 ±4	92 ±10	5.4 ±0.5	59 ±20	-1.7 ±0.6
Single (H_2/Air)	619 ±30	123 ±50	100 ±20	N/A	N/A
Double (H_2/O_2)	1583 ±5	164 ±20	13 ±1	N/A	N/A
Methanol	189 ±60	300 ±70	170 ±80	N/A	N/A

the H_2/air fuel cell, only 3 of the coefficients were able to be calculated. This is because the data collected for the H_2/air fuel cell did not sufficiently capture the drop off at high current density. The exponential term in that equation is intended to model the high current density region. As mentioned previously, the H_2/O_2 fuel cell data contained some lower resistance values that the H_2/air fuel cell did not capture, which explains why this high current density drop off couldn't be captured. Moreover, the decade resistance box was also instrumental in the calculation of the coefficients since setting the resistance values allowed for the collection of current and voltage. It was faulty at times, which was evidenced by the fact that the current or voltage values would change dramatically. These reasons apply not only for the H_2/air fuel cell but also the double membrane and methanol fuel cells as well. As a result, only 3 of the coefficients were able to be gathered for the fit equation. Additionally, the single fuel cell coefficients differ from those of the Kim et al. paper. This is because the operating conditions of the experiment differed from those in the Kim et al. paper.[7] Namely, the temperatures in the Kim et al. paper were at 50 and 70°C, while this lab was just at room temperature (25°C).[7] As a result, it should be expected that the coefficients would vary depending on these conditions. For the power performance curve shown in Figure 2, the trends are also as expected. Firstly, the shape of the curves match those that were reported in previous literature.[8] Furthermore, the power and the fuel conversion efficiency for the H_2/O_2 fuel cell are much greater than those of the H_2/air fuel cell. Just like what was mentioned earlier, this is because there's much

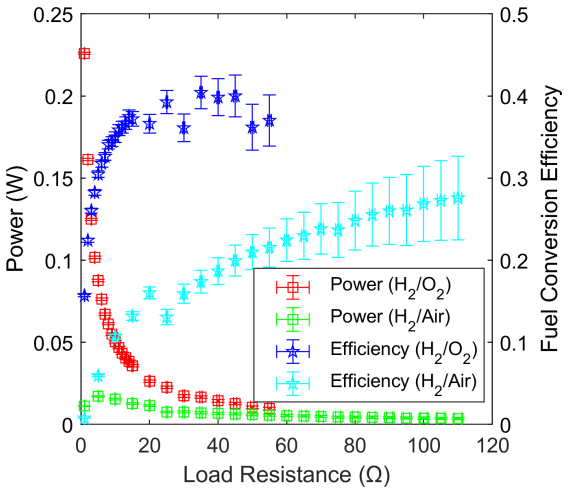

Figure 2: The figure above displays the power and fuel conversion efficiencies of the H_2/pure O_2 and H_2/air fuel cells vs. resistance.

less O_2 in the air which means that less electrons and H^+ ions are reacting with it. Thus, there would be less current, which leads to less power according to Equation 3.

The next relationship that was examined was the one between the single membrane fuel cell and the double membrane fuel cell. The respective figure for the characteristic curve is shown in Figure 3, and the trend displayed is as expected. Here, the double membrane fuel

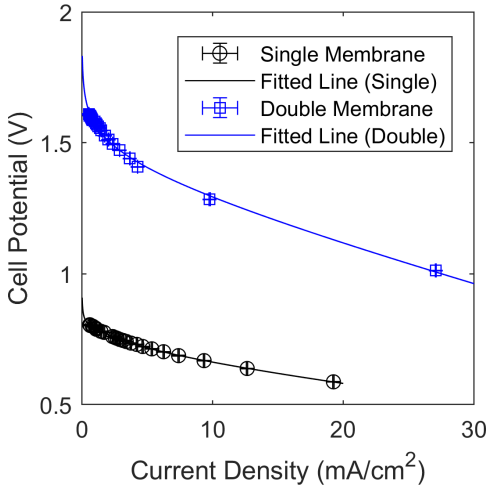

Figure 3: The figure above demonstrates the cell potential of the single and double membrane fuel cells vs. current density.

cell is shown to have a higher cell potential and current density than the single membrane fuel cell. This can be explained by the fact that the double membrane has a higher surface area,

which allows for more protons (H^+) to permeate through the electrolyte. Consequently, this allows for more current and voltage. Once again, the coefficient values for the two fuel cells differ. As seen in Table 1, all 5 coefficients are present for the single membrane fuel cell. But, only 3 are present for the double membrane fuel cell. As mentioned previously, this is because the data for the double membrane fuel cell did not capture the drop off at high current density. The coefficients for the double membrane fuel cell are much greater in value than those for the single fuel cell. This is expected since the double fuel cell allows for more voltage to be produced and thus a higher resistance. In regards to the power performance curve in Figure 4, the trend and shape displayed is also as expected. Particularly, the double membrane fuel cell generally has a higher fuel conversion efficiency and power compared to the single membrane fuel cell. Again, this can be explained by the fact that the double membrane has twice the surface area of a single membrane, which allows for more current and voltage. This then allows for more power since power is directly related to current as seen in Equation 3.

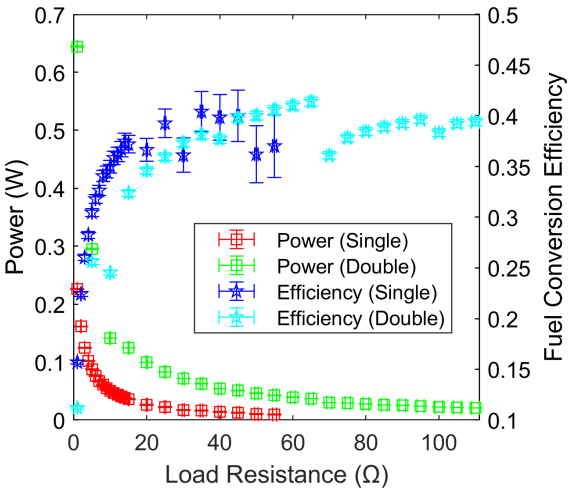

Figure 4: The figure above displays the power and fuel conversion efficiencies of the single and double membrane fuel cells vs. resistance.

Finally, the methanol fuel cell was compared to the regular fuel cell in order to analyze its relationship. In particular, the 3% methanol fuel cell was compared to the single membrane fuel cell. The characteristic curve is shown below in Figure 5. The trend displayed is sensible since the methanol fuel cell acted alone without the help of an electrolyzer. The regular fuel

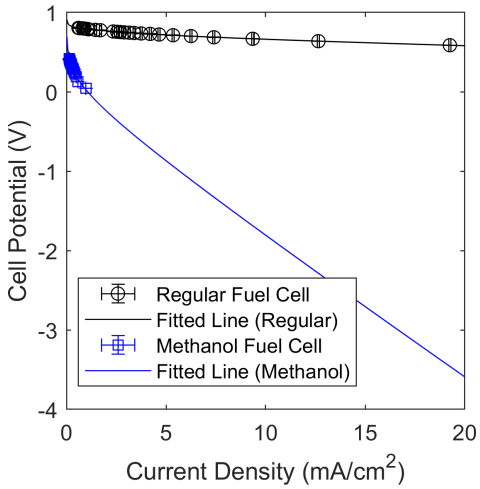

Figure 5: The figure above demonstrates the cell potential of the regular and methanol fuel cells vs. current density.

cell used H_2 as the primary fuel source and an electrolyzer to separate the H^+ and O^{2-} ions in water apart from one another. In the case of the methanol fuel cell, the H^+ ions were generated when the methanol was oxidized. As a result, the regular fuel cell has more cell potential than its methanol counterpart since H_2 and its ions were directly acquired from the environment rather than having to be generated through an oxidation process. Referring to Table 1, the coefficients for each cell again differ from one another in the sense that the single membrane fuel cell was able to retain all 5 coefficients while the methanol fuel cell only had 3. As was

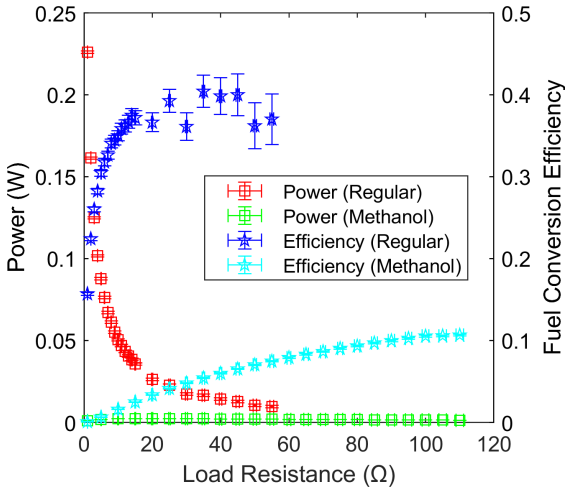

Figure 6: The figure above displays the power and fuel conversion efficiencies of the single and double membrane fuel cells vs. resistance.

the case for the other fuel cells, this can be explained by the fact that the data for the methanol fuel cell didn't capture the drop off at high current density. For the power performance curve shown in Figure 6, the trend and shape are also sensible since it shows that the regular fuel cell has a greater power and fuel conversion efficiency than its methanol counterpart. Since there was less voltage for the methanol fuel cell, there was less current for it as well, leading to it having less power.

6 Conclusions

By testing the various types of fuel cells, the power curve and coefficients of the polarization curve for each fuel cell was obtained. As seen in Table 1, only the coefficients for the single membrane with pure H_2 and pure O_2 was able to all be determined. This is due to the fact that this fuel cell was tested at more lower resistances than the others. Thus, this fuel cell was able to capture the high current density drop off and all the coefficients were able to be obtained. In addition, some of the coefficients for the fuel cells were either close to what is expected from literature or drastically different, partially due to a faulty decade resistance box. In contrast, the power curves followed similar trends seen in literature. From the polarization and power curves, the double membrane fuel cell produced the highest power and efficiency compared to the rest of the fuel cells. This is as expected as the double membrane has more surface area for the protons to permeate through and using pure O_2 would lead to more reduction occurring. Although the conclusions made are expected from literature, further improvements could be made to reinforce them. For instance, testing at lower resistances would allow for the capture of the high current density drop off for all fuel cells, and using a more reliable decade resistance box would lead to accurate voltage and current readings. If these recommendations were taken into consideration, it would give better results and reinforce the conclusions made.

Bibliography

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(2) Mohiuddin, A. et al. Investigation of PEM fuel cell for automotive use. *Iium Engineering Journal* **2015**, *16*, 69–78.

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(5) Paul, M. et al. Microstructured Membranes for Improving Transport Resistances in Proton Exchange Membrane Fuel Cells. *International Journal of Hydrogen Energy* **2020**, *45*, 1304–1312.

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(7) Kim, J.; Lee, S.; Srinivasan, S. Modeling of Proton Exchange Membrane Fuel Cell Performance with an Empirical Equation. *Journal of the Electrochemical Society* **1995**, *142*, 2670–2674.

(8) Benziger, J. et al. The power performance curve for engineering analysis of fuel cells. *Journal of Power Sources* **2006**, *155*, 272–285.

Appendix

1. Challenges for PEM fuel cell membranes

    - Author(s): Beuscher, U.; Cleghorn, S.J.C.; Johnson, W.B.
    - Year published: 2005
    - Journal name: International Journal of Energy Research
    - 1-3 major accomplishments of this paper:
        (a) Gives the history of PEM fuel cells including its inception and recent advancements made to make PEM fuel cells better.
        (b) Discusses the challenges and limitations of PEM fuel cells, such as cost and durability, before they can be widely used as a power source.

2. Investigation of PEM fuel cell for automotive use

    - Author(s): Mohiuddin, A.K.M.; Rahman, A.; Chemani, M.F.; Zakaria, M.B.
    - Year published: 2015
    - Journal name: Iium Engineering Journal
    - 1-3 major accomplishments of this paper:
        (a) Discusses the possibility for PEM fuel cells as an alternative to combustion engines due to its ability to produce clean sustainable energy.
        (b) Concludes that more research is required because performance is too low.

3. Design of a PEM fuel cell system for residential application

    - Author(s): Gencoglu, M.T.; Ural, Z.
    - Year published: 2009
    - Journal name: International Journal of Hydrogen Energy
    - 1-3 major accomplishments of this paper:

(a) Discusses the possibility for PEM fuel cells as an uninterruptible power source for residential homes.

(b) Concludes that more research is required in order to bring costs down so that PEM fuel cells could be widely used in residential homes.

4. A Parametric Study of PEM Fuel Cell Performances

   - Author(s): Wang, L.; Husar, A.; Zhou, T.; Liu, H.
   - Year published: 2003
   - Journal name: International Journal of Hydrogen Energy
   - 1-3 major accomplishments of this paper:

     (a) When a certain amount of humidification is provided the PEM fuel cell can improve by increasing the operating temperature.

     (b) By increasing the pressure of the PEM fuel cell, the performance of the fuel cell will increase because there is an increase in the exchange of current density and the reactant gas partial pressure.

5. Microstructured Membranes for Improving Transport Resistances in Proton Exchange Membrane Fuel Cells

   - Author(s): Paul, M. T. Y.; Saha, M. S.; Qi, W. L.; Stumper, J.; Gates, B. D.
   - Year published: 2020
   - Journal name: International Journal of Hydrogen Energy
   - 1-3 major accomplishments of this paper:

     (a) Using a hot embossing process, cylindrical features were embossed into Nafion that enabled the tuning of the depth features that were integrated into membrane electrode assemblies that finally were incorporated into PEM fuel cells.

(b) The use of the hot embossed cylindrical features onto PEMs imporves fuel cell performance at hot conditions.

6. Dynamic Simulation of a Stationary Proton Exchange Membrane Fuel Cell System

- Author(s): Min, K.; Kang, S.; Mueller, F.; Auckland, J.; Brouwer, J.
- Year published: 2009
- Journal name: Dynamic Simulation of a Stationary Proton Exchange Membrane Fuel Cell System
- 1-3 major accomplishments of this paper:

(a) A MATLAB-Simulink simulation of a PEM fuel cell was developed and produced data that predict experimental data