The Mechanization and Analysis of a Proton Exchange Membrane Hydrogen Fuel Cell Stack

Prepared by:
Amelia Cantwell

Faculty Advisors:
Dr. Thomas Montoya
REU Site Director, Department of Electrical and Computer Engineering

Professor Scott Rausch
Interim Department Head, Department of Electrical and Computer Engineering

Dr. Alfred Boysen
Professor, Department of Humanities

Program Information:
National Science Foundation
Grant NSF # EEC-1359476

Research Experience for Undergraduates
Bringing Us Together: Improving Communications and Lives
Summer 2016

South Dakota School of Mines and Technology
501 E Saint Joseph Street
Rapid City, SD 57701

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Abstract

The mechanization and analysis of a proton exchange membrane hydrogen fuel cell stack project involves the assembly, analysis, and safe operation of a fuel cell stack. The purpose is to better understand fuel cell technology and gain experience with building a functional fuel cell. Steve Gates, a South Dakota School of Mines and Technology alumnus initiated the fuel cell project in 2015. Summer 2015 REU intern Julia Theisen continued Gates' work. This project was a continuation of the work of both Gates and Theisen on a Ballard® PEM hydrogen fuel cell and a Matheson® gas monitor for safe operation of the stack. It was found that the fuel cell stack requires extensive work on its power electronics system, showing that the project is still a work in progress. Many other improvements and data are needed before the fuel cell can safely and effectively run. Advancements were made on both the stack's fuel subsystem and an external safety system for the environment in which the stack is to be operated. The project was well documented to provide a smooth transition to future students working on the project.

I. Introduction

Background

Proton exchange membrane fuel cells (PEMFCs) work by converting chemical energy to electrical energy. This can be understood by understanding the distinct parts of the membrane electrode assembly (MEA). The MEA is composed of a proton exchange membrane (PEM) in the center, two catalyst layers, two gas-diffusing electrodes (GDEs), and two bipolar plates on the outside. First, the PEM is a semi-permeable membrane that allows only protons (H^+) to pass through; electrons cannot pass through the PEM, so they are forced to exit the cell to be used for the current. Second, the catalyst layers are thin layers on both sides of the PEM that are responsible for the essential chemical (redox) reactions. The reaction at the anode breaks down hydrogen molecules (H_2) into electrons and protons (oxidation); the reaction at the cathode forms water from oxygen molecules (O_2) and the electrons and protons formed from the anode oxidation reaction. The required gases to complete the fuel cell chemical reaction are oxygen gas and hydrogen gas. The oxygen comes from air and the hydrogen is the fuel for the cell, in the form of compressed hydrogen gas. These reactions are depicted below.

$$2\ H_2 \rightarrow 4\ H^+ + 4e^- \qquad \textit{(anode)}$$

$$4\ H^+ + 4e^- + O_2 \rightarrow 2\ H_2O \qquad \textit{(cathode)}$$

Third, the gas diffusing electrodes (GDEs) consist of a gas diffusing layer (GDL) and a very thin micro-porous layer. The gas diffusing layers are the anode and cathode of the MEA. The micro-porous layer provides a smooth surface between the catalyst and the GDE and balances water release and retention. The GDEs are responsible for facilitating the movement of gas into the catalyst layers and removing product water. Fourth, the bipolar plates distribute and transport gas across the cell, serve as coolants, prevent leakage, and provide electrical conduction and physical strength between adjacent cells. A PEMFC *stack* consists of many MEAs stacked one after the other, providing an amount of power proportional to the number of cells. An MEA diagram is illustrated in Figure 1.

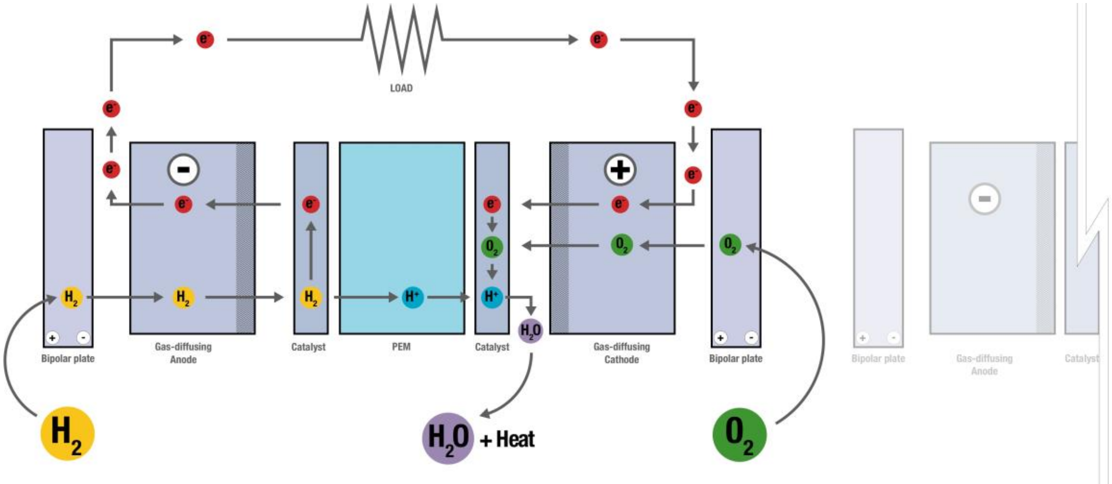

Figure 1: Membrane Electrode Assembly Diagram

The research project involved the use of a Ballard® hydrogen PEMFC, 18-cell, platinum catalyst membrane that is capable of producing roughly 800 W of power. The PEMFC stack consists of three major subsystems: fuel, oxidant/coolant and electrical/ power/energy. The fuel subsystem (Figure 2) delivers hydrogen to the stack at specified parameters and removes impurities at the anode via gas purges. The oxidant/coolant subsystem’s (Figure 3) two purposes are to provide oxygen (O_2) to the stack and to cool the stack to maintain the proper temperature. The electrical/power/ energy subsystem (Figure 4) draws current from the stack and delivers power to the load. This subsystem includes a power electronics system, which is an Arduino® Uno microcontroller with code that controls the current drawn from the stack given a specified current, voltage and power.

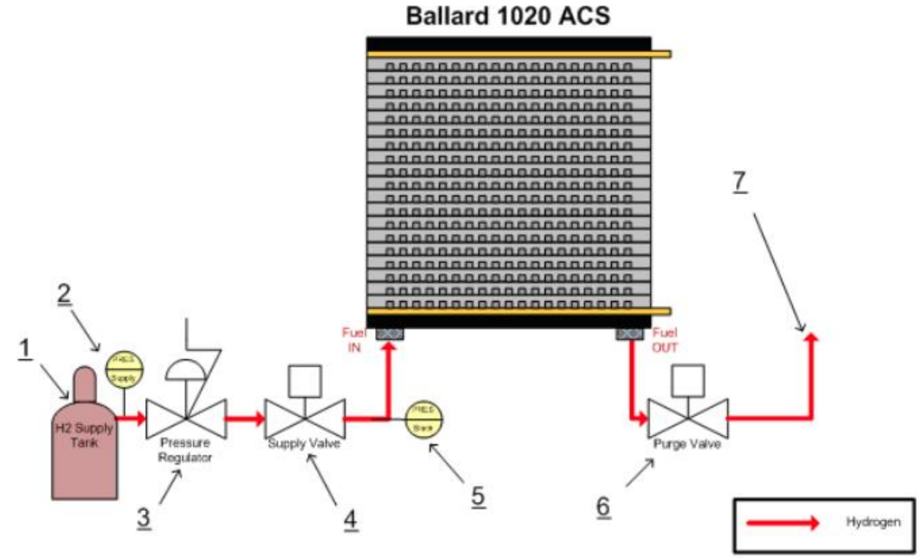

Figure 2: Fuel Subsystem

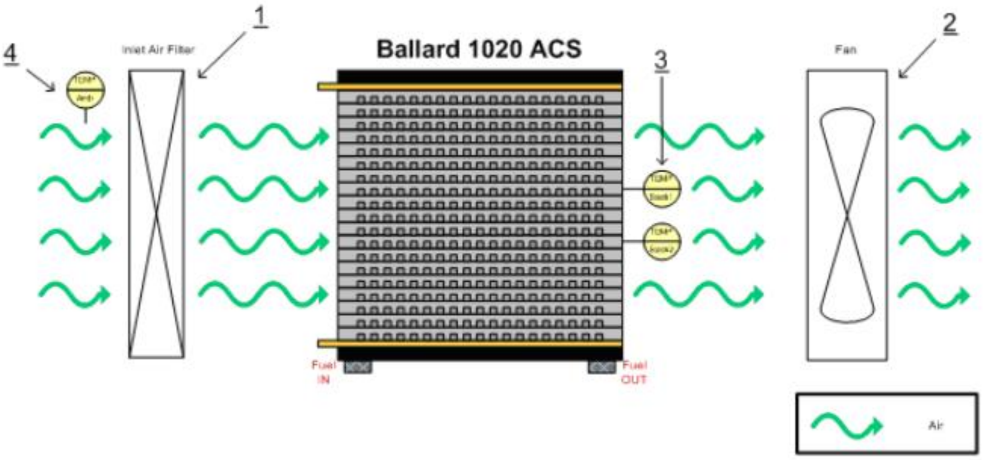

Figure 3: Oxidant/Coolant Subsystem

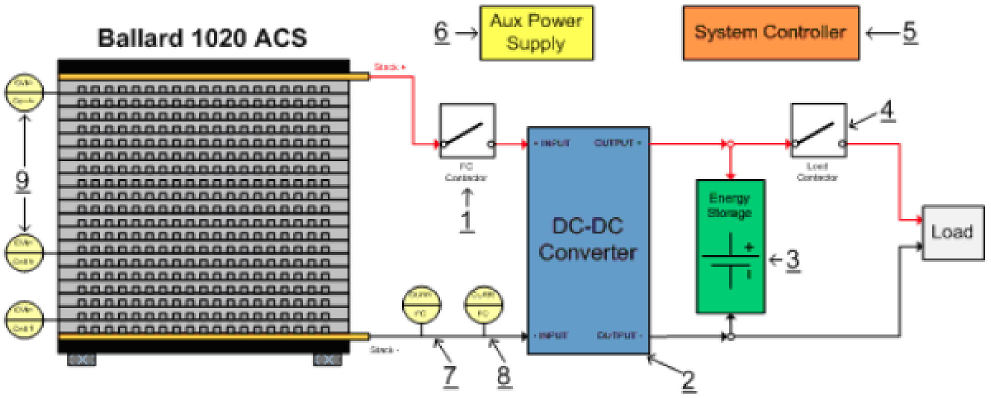

Figure 4: Electrical/Power/Energy Subsystem

Objectives

The first general objective of this project was to prepare an overall safe environment for the operation of the fuel cell stack. The more specific objective for this was to calibrate, set up, and install a gas monitor for the laboratory in which the fuel cell will be operating. This is necessary for the safe operation of the stack because hydrogen gas is very flammable and is hazardous at high concentrations. The second general objective was to deliver 800 W of energy to a dummy load. The more specific objective for this was to assemble the fuel subsystem and deliver hydrogen gas to the stack.

II. Broader Impact

The use of hydrogen fuel is very sought after as an energy source. The search for efficient clean energy is on the rise, and hydrogen fuel is a promising type of clean energy. Currently 81% of energy used by the United States comes from fossil fuels, which primarily consist of oil, coal, and natural gas. These energy sources are non-renewable and are shown to produce greenhouse gases. Hydrogen, on the contrary, is very abundant, renewable, and considered clean because its waste is purely water. This means hydrogen fuel is more eco-friendly and potentially cheaper. Hydrogen fuel cell vehicles (HFCVs) are of particular interest. HFCVs are more efficient and shown to be longer lasting and quieter than gasoline, diesel, or electric vehicles. Clearly, hydrogen fuel cells have many ideal qualities that make them a significant topic of interest. Unfortunately, there are still many issues with hydrogen fuel cells, the first being that although elemental hydrogen is abundant, hydrogen gas (H_2) does not exist in Earth’s atmosphere. Therefore, hydrogen gas must be chemically produced, compressed, and stored before it may be used as fuel. This compression and storage uses energy from fossil fuels, making it neither cost-effective nor energy-efficient. This issue can be resolved by the use of other renewable energy sources to make and store the hydrogen, of which new methods are being explored and improved. The second major issue with PEMFCs is their expense. The initial cost of just the PEM stack is very high, which is undesirable for consumers and manufacturers. In time, cheaper methods of manufacturing fuel cell stacks will likely to be found, however at the moment it is an obstacle. The third major issue is the safety concerns with using hydrogen gas in HFCVs. Hydrogen gas is hazardous, especially when transported on roads. Research into making hydrogen gas safer to transport is being done to solve this issue. There are other smaller issues concerned with using hydrogen fuel cells, but the three main problems are the energy efficiency of producing hydrogen fuel, the price of the PEMFCs, and the safety concerns of transporting hydrogen gas in HFCVs.

III. Procedure

Materials and Equipment

- Ballard® FCGen® 1020ACS Fuel Cell Stack/FCVelocity®
- Arduino Uno microcontroller
- Grade 5 (99.999%) H_2 gas
- Teflon (PTFE) tubing (5/16” OD and ¼” OD)
- Purge valves
- Matheson® Tri Gas Monitor *Gas Scanner 2C*
- RKI Instruments® Combustible Gas Transmitter 4-20 mA detector head
- RKI Instruments® Oxygen Transmitter 4-20 mA detector head
- Matheson® Calibration kit including calibration cup, tubing, adjustable flow

regulator and calibration gas cylinders:
    - 50% LEL Hydrogen gas cylinder
    - 20.9% Oxygen/Balance Nitrogen gas cylinder
    - 100% Nitrogen gas cylinder
- Voltmeter
- Tool kit including Allen wrenches and screwdrivers

Procedures

1. Analysis of Existing Systems

The fuel cell project began in 2015 by SDSM&T alumnus Steve Gates for his senior design project. The project was continued in the summer of 2015 by REU intern Julia Theisen. Gates made significant progress on the Ballard® fuel cell stack, while Theisen made progress on the gas scanner and documenting her work. The first month of the 2016 REU program was spent analyzing the work done by Gates and Theisen, reading the Ballard® fuel cell and Matheson® gas scanner operation manuals, recording notes/instructions in the logbook, and ordering necessary parts.

2. Calibration and Operation of Gas Scanner

The first priority for the project during the 2016 REU program was to operate the gas scanner that is able to detect hydrogen and oxygen gas levels. The monitor was assembled and wired by Theisen, but was not fully operational because the detector heads required calibration. Theisen wired channel 1 for the oxygen detector head and channel 2 for the hydrogen detector head.

For the calibration of the detector heads, a calibration kit and gas calibration cylinders were ordered. The gas scanner system input program was used to change the two channels because they had been opposite of their respective detector heads. Channel 1 was set to measure oxygen % at a full scale of 25% and channel 2 was set to measure LEL hydrogen % at a full scale of 100%. The calibration was performed at the detector heads.

The hydrogen detector calibration first required setting a zero reading using a zero-air cylinder, which is the 20.9% oxygen/balance nitrogen gas cylinder. The calibration cup, tubing, and regulator were assembled to the cylinder and detector head, allowing gas to flow at 0.5 liters per minute (LPM). A voltmeter was used to measure in mV while adjusting the zero potentiometer with a flat blade screwdriver, in order to get a correct reading of 0% LEL hydrogen. Secondly, the hydrogen detector head calibration required setting a response reading using a 50% LEL hydrogen calibration gas cylinder. The procedure for the response reading was the same as that for the zero reading, except the span potentiometer was adjusted in order to get a correct reading of 50% LEL hydrogen. Repeating this process to double-check the calibration proved helpful.

The oxygen detector calibration was similar to that of the hydrogen detector. The difference is that the first calibration required setting a fresh air reading using the zero-air cylinder. The calibration cup, tubing and regulator were assembled to the cylinder and detector head, allowing gas to flow at 0.5 LPM. A voltmeter was used to measure in mV while adjusting the span potentiometer in order to get a correct reading of 20.9% oxygen. Secondly, the oxygen detector head calibration required setting a zero reading using a 100% nitrogen calibration gas cylinder. The procedure for the response reading was the same as that for the fresh air reading except the zero potentiometer was adjusted in order to get a correct reading of 0% oxygen. Repeating this process to double-check the calibration proved helpful.

3. Fuel Subsystem

The following work on the fuel cell stack began with the completion of the fuel subsystem. Rough designs of the fuel subsystem were made in the student logbook, in order to assemble and chose a proper location in the laboratory. The required Teflon tubing, valves, and hydrogen gas for the fuel subsystem were ordered. The Teflon tubing was subsequently connected from the hydrogen gas tank to the anode fuel-in, and another out of the cathode fuel-out ports. Purge valves were added to the tubing system, following the Ballard® manual instructions. A shelf was built to raise the stack to the height of the hydrogen gas tank, with proper holes to feed tubing to the stack.

Safety: Before delivering hydrogen to the stack, SDSM&T campus safety measures had to be met and approved. The approval from the health and safety manager was denied until further investigations have been made into the nature of hydrogen fuel cells and the ventilation in the Electrical and Computer Engineering Building.

4. Documentation

The procedures and additional information described were well documented. The documentation includes clearly outlined procedures, data, problems that occurred, descriptions of the Ballard® and Matheson® manuals, and photographs of equipment. These are located in both a student logbook and a binder. The documentation of the REU project was intended to facilitate the process of continuing this project by future students.

IV. Results

1. Calibration and Operation of Gas Scanners

The Matheson® gas scanner was successfully calibrated at the detector heads. The gas monitoring system is prepared to detect hydrogen and oxygen gas levels in the room and activate alarms when hydrogen concentrations are too high or oxygen levels are too low. This gas monitoring system was not installed above the hydrogen gas tank and stack due to the impermanence of the stack location.

2. Fuel Subsystem

The fuel subsystem was fully assembled and connected to the hydrogen gas via Teflon tubing. Hydrogen gas was not delivered to the fuel cell stack because the campus safety measures were not approved. However, the fuel cell stack is now prepared to accept hydrogen gas. Additionally, a location in a different laboratory room in the Electrical and Computer Engineering Building was proposed and tentatively approved. This location is one of the outer rooms of the building, meaning it has windows. The fuel cell laboratory should have either a window or a pipe vent to the roof; this is necessary in order to ventilate hydrogen gas to the atmosphere, which prevents gas buildup in the laboratory. Once the fuel cell is located to a permanent laboratory with safe ventilation, hydrogen fuel may be supplied to the stack.

3. Documentation

The operation manuals, books, papers, binders, logbooks and other materials were labeled for organization. Detailed hand-written notes on the operation manuals were taken in the student lab notebook. These should be used as easy reference when continuing the project. Photographs of the fuel cell stack assembly and the calibration process were printed, clearly labeled, and added to the student binder. The procedure accompanying the calibration was described in the student logbook, as well as the work on the hydrogen fuel cell. All the parts that were ordered or used were described in the logbook. Tests were performed on the fan to measure voltage, current, fan rotational speed, wind speed and wind volumetric flow. These data were organized in a table, graphed, and provided in both the student logbook (data table only) and the student binder.

V. Discussion

The original intended goal of the mechanization of the PEM fuel cell stack was to deliver 800 W of power to a dummy load. While much progress was made, the goal was not achieved. The next steps will prepare the stack to produce 800 W of power, but it is not near completion. Midway through the project, the goal was updated to the delivery of hydrogen fuel to the stack; this required completion of the fuel subsystem assembly. One primary issue preventing this new goal to be met is the lack of proper environmental safety measures for hydrogen delivery to the stack. The campus safety management department did not approve the laboratory room in which the fuel cell stack was assembled, so no hydrogen could be used. Although the utilization of hydrogen was not accomplished, the fuel subsystem was successfully assembled and ready to run when hydrogen utilization is permitted. The 800 W of power necessary may be delivered to a dummy load once the other subsystems of the stack are assembled correctly. Despite the failure of original goal to be met, much progress was made on the fuel cell stack. Due to the extensive documentation, the project will have a smooth transition to future students, allowing them to continue its work with ease. The progress made will better prepare future students to complete the goal of delivering 800 W of power.

VI. Conclusion

Summary

The work that alumnus Steve Gates and REU intern Julia Theisen have contributed to the fuel cell project should be included in the summary of the overall project. Gates was responsible for the conception of the project, the initial assembly of the stack and development of Arduino® Uno code for the electronics. Gates added the fans, pressure sensors and purge valves to the stack and made rudimentary electrical connections to them. Gates was the developer of the electronics system, which was arguably the most important contribution he made, being as the electrical/power subsystem is the most complex. The Arduino® code has not been tested and does not include power electronics for controlling current drawn from the stack. Although Gates did not finish the electronics, he made major progression and provided his code so it may be improved upon in the future. This electronics system Gates developed was an Arduino® code to read thermistor and pressure data, and to control the fans and the valve contactor. Theisen contributed to the project by starting the safety system. She ordered the Matheson® Gas Scanner 2C and the two detectors; she then made the electrical connections on the gas scanner and detector heads. She ordered the calibration kit along with other parts, and made significant contributions to the documentation of the project.

The proton exchange membrane fuel cell project saw much improvement. The two main areas of the project that have made great progress are the safety system and the fuel subsystem. Additionally, thorough documentation has been provided for future students. The safety precautions have been well understood and are nearly complete. The fuel subsystem has been completely assembled and ready to be utilized with hydrogen gas. The safety precautions that have been accomplished include the installment of a gas scanner for hydrogen and oxygen gas concentrations in the room, contact with campus safety management, the understanding of proper ventilation for and the future location of the stack. The fuel subsystem parts that have been completed include connection of Teflon (PTFE) tubing to the anode and cathode in and out ports, connection of the tubing to the hydrogen gas tank, and the integration of valves, purge valves, and pressure regulators. The oxidant/coolant subsystem has been partially analyzed by taking measurements of the fans' parameters. This will also be useful in future work on the oxidant/coolant subsystem and the power electronics. In conclusion, documentation has been made to be very useful; additionally safety measurements and fuel delivery are on their way to completion and may be finished in short time.

Future Work

Due to the safety system and fuel subsystem having made considerable improvement, they should be finished soon, as those tasks are the closest to being done. In addition to the successful completion of the fuel subsystem and a safe environment for the stack, the electrical/power subsystem requires the most work. The oxidant/coolant subsystem is relatively simple, but must also be improved upon. One aspect is the absence of an inlet air filter that increases the quality of the oxygen entering the stack, thereby preventing damage from poor quality air. The collected fan data should be analyzed and used when determining the temperature settings for the Arduino® code. Additional data of the parameters of stack operation should be measured and analyzed for the same purpose including stack voltage, current, temperature and pressure, ambient temperature, hydrogen gas pressure, and individual cell voltage. A recommended parameter to measure is individual cell voltage using a cell voltage monitor (CVM). The individual cell voltages are recommended because irregularities in individual cell voltage that cause damage to the stack can be missed by overall stack voltage monitoring. The electrical/power subsystem requires the most work in order to fully operate the PEMFC stack. Gates stated that a power electronics system must be added, which has still not been done. The Arduino® code must be tested and improved, as it has not been proven to work yet, and is still missing significant features.

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Acknowledgements

The funding for this research came from the National Science Foundation. Special thanks to advisor Professor Scott Rausch for his guidance and assistance with the project, Dr. Thomas Montoya for organizing this research experience and Dr. Alfred Boysen for his critique in writing and speaking.