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

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Abstract

Fuel cell technology is a strong candidate for future alternative energy, and is thus being researched and developed by many different groups for various purposes. The purpose of this study was to explore the reality of working with fuel cell technology by continuing the work of South Dakota School of Mines and Technology alumni Steve Gates, whose senior design project was the mechanization of a Ballard® Proton Exchange Membrane (PEM) Hydrogen Fuel Cell Stack. At the completion of Gates' project, the mechanization of the stack was not complete, thus this study focused on completing the unfinished aspects of making the stack functional, along with assessing the strengths and weaknesses of the stack. This required implementing tubing for gas/liquid flow, reviewing and finalizing the system electronics that Gates applied for sensing, adding power electronics so that the stack output is properly managed, and implementing a gas monitor for safe operation of the stack.

It was found that the stack system required more development than was available during the time period of this project. Therefore the following developments were made to the stack system: existing circuitry was labelled, documented, reorganized, and mobilized; an external gas monitoring system was wired and the necessary calibration kit was purchased and ordered; the microcontroller was updated; a new pressure sensor was integrated into existing circuitry; and multiple fixes and replacements were made to circuitry due to storage/travel damage. In conclusion, though highly effective in producing clean energy, this Proton Exchange Membrane hydrogen fuel cell stack requires complex and diverse systems in order to be operated safely and optimally.

1. Introduction

Background

There are several different types of hydrogen fuel cells, but they all follow the same basic process [5], which can be seen in Figure 1. The three main components of a fuel cell are the two electrodes and the electrolyte [2]. The electrode on the hydrogen side of the electrolyte is called the anode because it is negative, and the electrode on the oxygen side of the electrolyte is called the cathode and is positive [2].

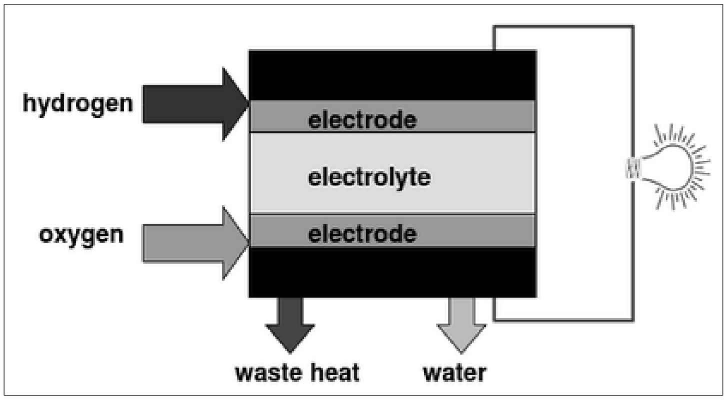


Figure 1. Basic diagram of a hydrogen fuel cell process [2]

Hydrogen fuel cells are typically categorized by the electrolyte used [5]. One of the most promising contenders for future fuel cell implementation is the Proton Exchange Membrane (PEM), or Polymer Electrolyte Membrane, Fuel Cell (PEMFC), which uses a proton conducting polymer membrane as an electrolyte [2]. This membrane allows the protons of hydrogen atoms to pass through, but holds back the electrons, which then travel along the electrically conductive electrode and outside the cell to produce current for some load, then reenter the cell on the other side of the membrane, where they meet the protons again and the oxygen that has been introduced to the cell, creating water electrochemically and flowing out of the cell due to excess oxygen flow [2]. A more detailed diagram of this process can be seen in Figure 2.

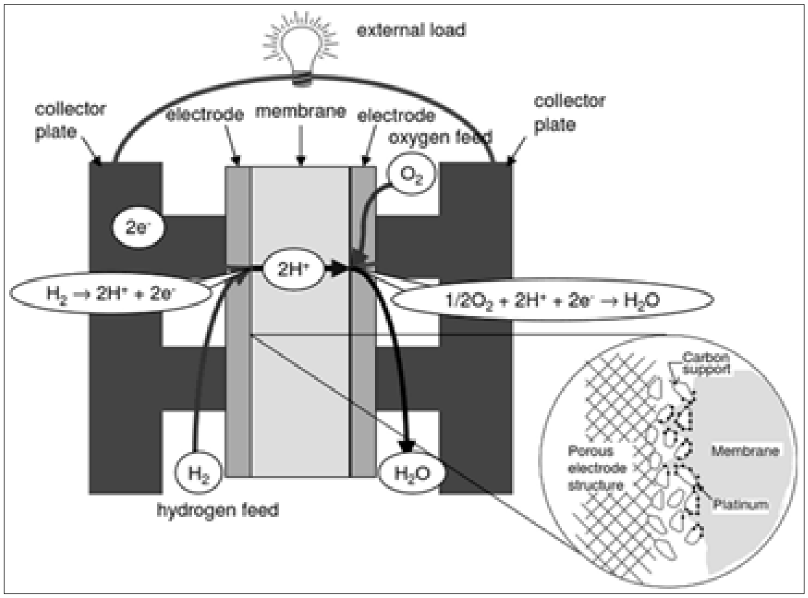


Figure 2. Diagram of a PEM fuel cell process [2]

Each fuel cell only produces about 1 Volt (V), so the cells are connected in series to increase their output, which is called a stack [2]. For this project, a Ballard Power Systems Inc. FCGen-1020ACS 5117418 stack, which has 18 PEM fuel cells in series, was chosen by Professor Scott Rausch for its cost efficiency and power output. Figure 3 shows a picture of this model.

Figure 3. Ballard® FCGen-1020ACS 5117418 PEM fuel cell stack [1]

Steve Gates, a South Dakota School of Mines and Technology alumni worked on the mechanization of this stack as his senior design project, which ended in May 2015. Because hydrogen is a highly explosive gas, there are many requirements and specifications to meet before a hydrogen fuel cell stack can be safely operated. Gates spent his senior year designing and constructing the mechanical and electrical systems necessary to meet all of those requirements and due to time constraints was unable to finish before he graduated.

Objectives

The objective of this project was to complete the mechanization of the stack so that it can be operated safely and to analyze its ability to produce energy efficiently as a potentially large-scale alternative energy source. Beyond meeting these technical goals, this project was to be well documented in order to allow students to continue and improve upon this system in the future, both for learning purposes and for optimized energy production.

Developmental Plan

Meeting this objective required analyzing the existing systems, making changes and additions, and testing the fuel cell. Once the fuel cell could be turned on, voltage, current, and power data would need to be gathered and analyzed to determine statistics for the stack's efficiency, which could be compared to those of other energy sources to determine how fuel cells measure up and what steps are necessary to widely implement them.

2. Broader Impact

As one of the most promising prospects for clean energy, hydrogen fuel cell technology is being researched and explored by various groups, from the world's top automotive industries to undergraduate and even high school students [4]. Despite the development of new technology in the past few decades, there are still several issues preventing fuel cell systems from advancing to widespread implementation, and scientists and engineers must continue to create safer, more efficient solutions so that the world's current dependency on unclean energy sources can be replaced. A few of the main issues with hydrogen fuel cells are their large size, the high expense and lack of infrastructure for necessary materials, the unclean methods currently used to supply hydrogen, and the danger incurred when storing and using hydrogen gas [4]. As students and researchers gain experience with existing technology, there is more opportunity for development in these areas. Companies can invent more efficient ways to produce the necessary monitoring systems unique to hydrogen fuel cells, chemists can discover safer and cleaner ways of producing and storing hydrogen, engineers can design systems that take full advantage of fuel cell stacks, and so on, leading to a future shift in the world's primary source of energy.

The documentation of this project will allow the faculty and students at the South Dakota School of Mines and Technology to participate in the exploration of this pioneering technology and to benefit from higher efficiency energy production. It is the author's hope that her work and its continuation at this school would contribute to the development of PEM hydrogen fuel cell systems and result in the use of cleaner energy.

3. Procedure

Analysis of Existing Systems

One of the most challenging but critical aspects of continuing Gates' work, which consumed the majority of the time on this project, was analyzing the existing systems, those that Gates implemented. Once the existing systems had been realized, only then could the necessary changes be accurately found and made. The Ballard Product Manual and Integration Guide outlines four main subsystems within an operational fuel cell stack system [1]. They are stack enclosure/mounting, oxidant/coolant, fuel, and electrical/power electronics/energy storage [1]. For this project, the subsystems have been slightly redefined to better describe the four physical, distinctive systems implemented and/or planned. They are stack enclosure/mounting, tubing, circuits, and power electronics. Here, each of these subsystems will be described –including how they relate to the original, Ballard subsystems– and its initial state at the start of this project will be analyzed.

The first subsystem is *stack enclosure/mounting*, which is one of the original Ballard-defined subsystems. According to Ballard, this subsystem serves to hold the stack in place, allow air from the fan(s) to adequately move through the stack, and protect the stack from outside contact that could be damaging [1]. As redefined for this specific project, this system also includes the fan(s), an element originally included in the oxidant/cooling subsystem by Ballard. Because Gates incorporated two fans into the mounting structure he designed and built, the fans have been included in this subsystem. The fans serve to deliver both oxidant for the chemical processes within the cells and coolant to maintain a healthy temperature for stack operation. A block diagram of the mechanical architecture for the stack can be seen in Figure 4. Figure 5 shows Gates' design for a mounting structure, designed with SketchUp software and built from ¼" Lexan (polycarbonate). Gates' product can be seen in Figure 6, with the stack and fans included, although Figure 7 shows that the entire system is not connected. With the exception of the base, the structure is kept from direct contact with the stack by closed-cell weather stripping.

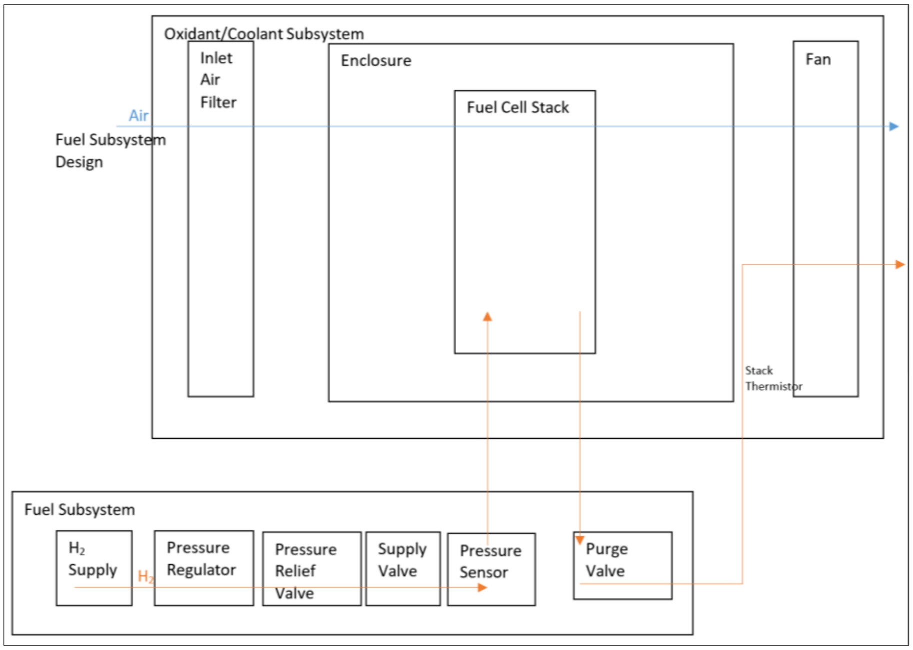


Figure 4. Gates' mechanical block diagram [3]

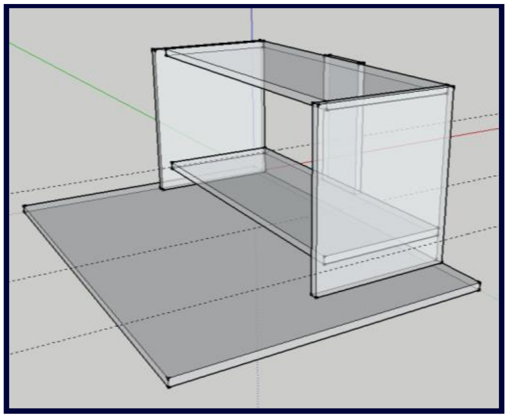


Figure 5. Gates' SketchUp model of a stack enclosure/mounting system [3]

Figure 6. The stack enclosure/mounting fixture with the stack and fans mounted [3]

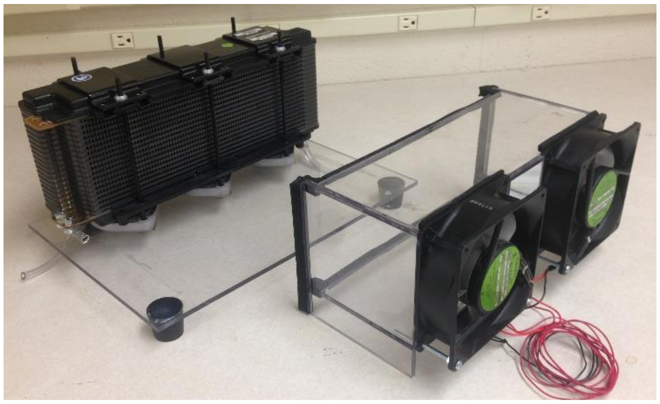


Figure 7. The enclosure/mounting fixture has two unconnected parts [3]

While the stack and fans were mounted with the appropriate material, the enclosure did not meet all requirements and specifications given by Ballard, such as to protect the stack from outside contact and the implementation of an inlet air filter.

The next subsystem is *tubing*, which primarily involves the fuel subsystem outlined by Ballard, intended to deliver hydrogen fuel to the stack at the appropriate pressure and flow and to periodically purge impurities from the stack anode [1]. While Gates did not implement a full tubing system, he did attach some nylon tubing to the stack (visible in Figures 6 and 7) and to various unattached pressure regulators. He very clearly specified in his report that this tubing was purely superficial, intended primarily for aesthetics and rudimentary design, and that because this tubing was nylon, it MUST be removed and replaced, due to the fact that nylon can react violently with hydrogen [3]. Teflon or PVDF tubing is recommended for use with hydrogen [1]. A source/supplier of the proper hydrogen fuel also needed to be determined.

The third subsystem is *circuits*, a broad category encompassing Gates' electrical systems, which included both hardware and software. This is the most complex and wide-reaching subsystem, used to monitor and control temperatures, pressures, flow, etc. so that the stack can operate safely and optimally. Gates' block diagram for the electrical architecture is shown in Figure 8, and his software flow control diagram can be seen in Figure 9.

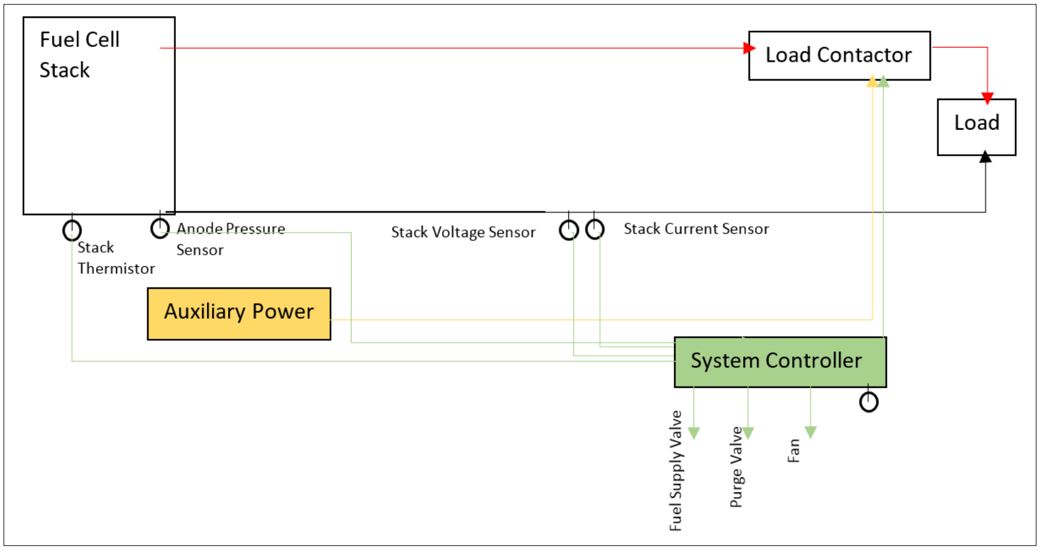


Figure 8. Gates' electrical block diagram [3]

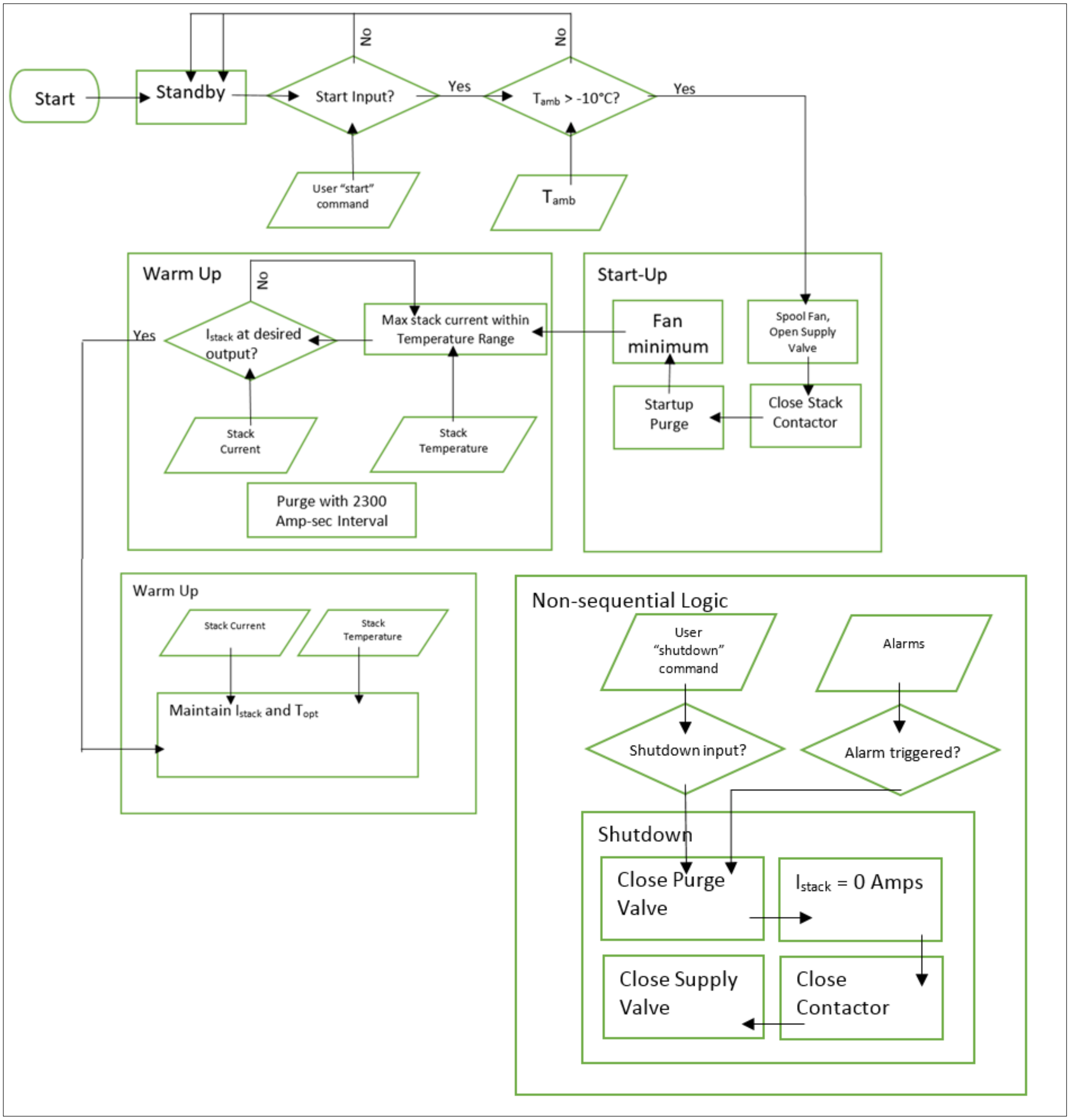


Figure 9. Gates' software flow control diagram [3]

Gates designed and assembled three subcircuits to interface with an Arduino Uno that would control the fans and valve contactor, along with reading thermistor and pressure data and other tasks. Gates' schematic for these three subcircuits and their connections to the microcontroller is shown in Figure 10.

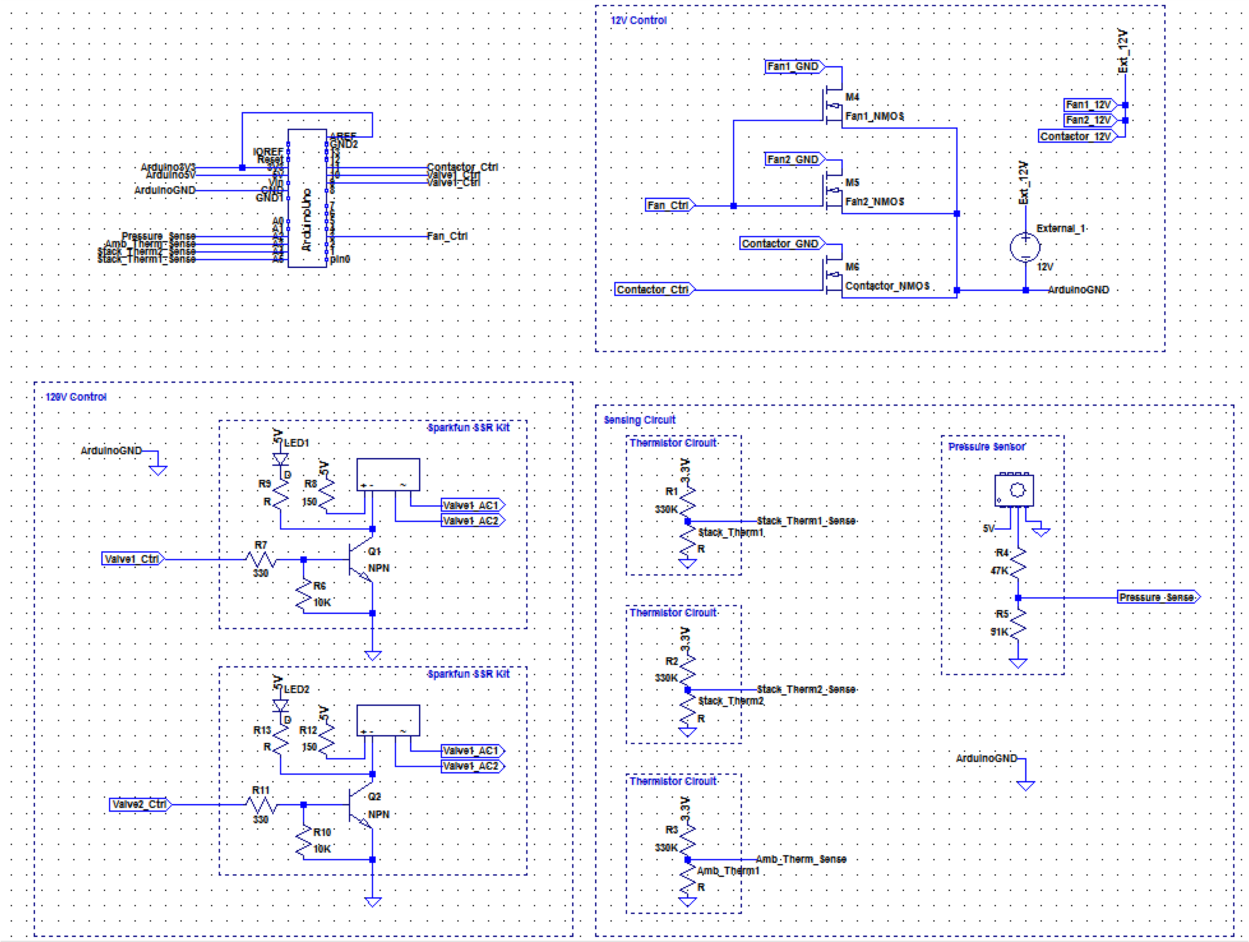


Figure 10. Gates' subcircuits and microcontroller schematic [3]

Though these subcircuit designs were satisfactory to Gates and primarily operated as intended, the pressure sensor implemented by Gates was an absolute pressure sensor, while a gage pressure sensor was needed, and the Arduino Uno used by Gates did not have standard fuse settings. These needed to be replaced in order for the circuitry to function correctly. Additionally, various repairs needed to be made to circuit connections, due to damage incurred during storage and travel.

Power electronics is the last category, and was nonexistent in Gates' system and therefore need to be designed and implemented to properly manage the output of the stack.

In addition to these four subsystems, a GasScanner 2C external gas monitor from Matheson Tri-Gas and two gas detector heads –one for hydrogen and one for oxygen– were included, unassembled, with the other hardware.

Changes and Additions

Developments to the PEMFC stack system were made as time and resources allowed. As mentioned previously, the majority of time was spent reading the necessary materials to determine the state of the system and to assess what was needed. Progress in each of the four subsystems will be discussed.

Although no additional structure was created for *stack enclosure/mounting*, a source for additional Lexan was found. McMaster-Carr offers a variety of sizes at www.mcmaster.com and came at the recommendation of a professor. In addition, due to developments in the *circuits* subsystem, the stack was made more mobile, and documentation of circuitry has made it much easier to mount in conjunction with the stack in the future.

There was no development of the *tubing* subsystem, as designing tubing would depend heavily on how the stack is enclosed and mounted, along with the position of the circuitry. It is expected that the necessary hydrogen fuel (99.95%) will be supplied by the SDSM&T Chemistry Department.

With several smaller-scale needs, the *circuits* subsystem was advanced in multiple ways. The most notable visible change is that the circuitry was carefully disassembled as much as possible, then laid out on a piece of poster paper in order to be reassembled in a more organized fashion and labelled for quicker and more clear identification of parts. Figure 11 compares the system near the beginning of the project to its more organized set-up at the completion of the project. The system was also placed on a cart, increasing mobilization.

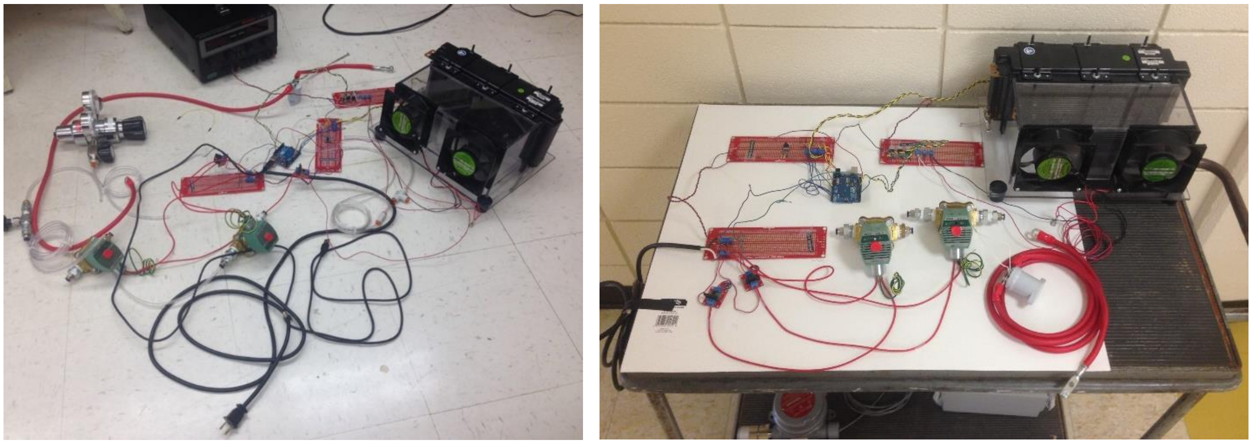


Figure 11. System before (left) and after (right) reorganization and adjustments

In addition to this reorganization and mobilization, the absolute pressure sensor was removed and a gage pressure sensor integrated in its place. A new Arduino Uno microcontroller replaced the one with faulty fuse settings, and the various necessary fixes to damaged connections were made.

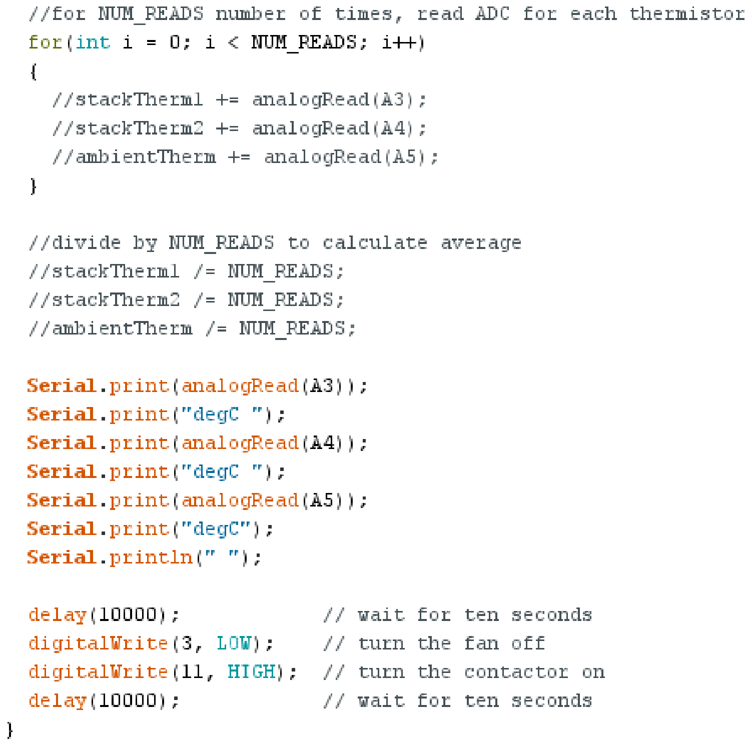
Again due to restraints in time, *power electronics* were not implemented, however a stack contactor is already implemented into the circuitry to connect to a load.

For the external gas monitoring system, the necessary cabling was purchased and wiring was completed for AC power and both detector heads. The GasScanner 2C was successfully turned on, indicative of correct wiring, however the detector heads required calibration. After research and consultation, a calibration kit was ordered from Matheson Tri-Gas. Unfortunately, the consultation and ordering process, combined with the lengthy shipping time, prevented the calibration of the detector heads. The kit and fully wired monitoring system are prepared for the opportunity to calibrate the detector heads, at which point the system will be fully operational, warning the user of a breach of lower explosive limit (LEL) hydrogen and/or a lack of appropriate oxygen.

Testing

Because the fuel cell stack was not “turned on” the anticipated testing phase, regarding measuring the voltage, current, and power outputs of the stack, was not conducted. However, the fans, stack contactor, and thermistors were tested by writing a short program for the Arduino Uno to toggle the fans and contactor, integrating Gates’ code to serially read the thermistor data. Once the microcontroller was properly connected and powered, the fans and contactor toggled as desired, verifying their operation status, and the thermistor data was successfully displayed. However, the thermistor data was clearly incorrect, display temperatures typically ±tens of thousands of degrees Celsius, indicating an error in the code or an issue with the thermistors. Figure 12 displays the code used.

```
 #define NUM_READS 5

  int stackTherm1 = 0;
  int stackTherm2 = 0;
  int ambientTherm = 0;

  //lookup table used to convert ADC value directly to temperature without taxing computation on CPU
  static const int16_t g_Temp[256] = {198,126,111,102,95,90,86,82,79,76,74,71,69,67,66,64,62,61,60,58,
    57,56,55,53,52,51,50,49,49,48,47,46,45,44,43,43,42,41,41,40,39,38,38,37,37,36,35,35,34,34,33,32,32,
    31,31,30,30,29,29,28,28,27,27,26,26,25,25,24,24,23,23,23,22,22,21,21,20,20,19,19,19,18,18,17,17,17,
    16,16,15,15,15,14,14,13,13,13,12,12,12,11,11,10,10,10,9,9,9,8,8,7,7,7,6,6,6,5,5,5,4,4,4,3,3,2,2,2,1,
    1,1,0,0,0,-1,-1,-1,-2,-2,-3,-3,-3,-4,-4,-4,-5,-5,-5,-6,-6,-6,-7,-7,-8,-8,-8,-9,-9,-9,-10,-10,-10,-11,
    -11,-12,-12,-12,-13,-13,-13,-14,-14,-15,-15,-15,-16,-16,-16,-17,-17,-18,-18,-18,-19,-19,-20,-20,-20,
    -21,-21,-21,-22,-22,-23,-23,-23,-24,-24,-25,-25,-25,-26,-26,-27,-27,-27,-28,-28,-29,-29,-29,-30,-30,
    -31,-31,-31,-32,-32,-33,-33,-33,-34,-34,-35,-35,-36,-36,-36,-37,-37,-38,-38,-38,-39,-39,-40,-40,-41,
    -41,-41,-42,-42,-43,-43,-43,-44,-44,-45,-45,-46,-46,-46,-47,-47,-48,-48,-48,-49};

int ADC_to_degC(int adc)
{
  //shift ADC from 10-bit to 8-bit for 256-value lookup table
  //return value from lookup table
  return g_Temp[adc >> 2];
}

// the setup function runs once when you press reset or power the board
void setup()
{

  pinMode(3, OUTPUT);  // initialize digital pin 3 as an output.
  pinMode(11, OUTPUT); // initialize digital pin 11 as an output.

  //Arduino Uno is fused to DIV8 for frequency
  //This sets the prescaler to divide system clock by 8
  //also fused to 8MHz
  //these 4 lines change prescaler to 1, making it 8MHz
  //recommended to get Uno with proper fuses or ICSP (e.g. JTAGIce3) to change fuses
  CLKPR = (1 << CLKPCE);
  CLKPR = 0;

    //we average NUM_READS number of ADC values, so initialize to zero
  stackTherm1 = 0;
  stackTherm2 = 0;
  ambientTherm = 0;

  //set analog reference to external. This pin is tied to 3.3V. We use this for ADC reference voltage
  analogReference(EXTERNAL);

  // initialize serial communication at 9600 bits per second
  Serial.begin(9600);
}

// the loop function runs over and over again forever
void loop()
{
  digitalWrite(3, HIGH);   // turn the fan on
  digitalWrite(11, LOW);   // turn the contactor off
```



```
  //for NUM_READS number of times, read ADC for each thermistor
  for(int i = 0; i < NUM_READS; i++)
  {
    //stackTherm1 += analogRead(A3);
    //stackTherm2 += analogRead(A4);
    //ambientTherm += analogRead(A5);
  }

  //divide by NUM_READS to calculate average
  //stackTherm1 /= NUM_READS;
  //stackTherm2 /= NUM_READS;
  //ambientTherm /= NUM_READS;

  Serial.print(analogRead(A3));
  Serial.print("degC ");
  Serial.print(analogRead(A4));
  Serial.print("degC ");
  Serial.print(analogRead(A5));
  Serial.print("degC");
  Serial.println(" ");

  delay(10000);            // wait for ten seconds
  digitalWrite(3, LOW);    // turn the fan off
  digitalWrite(11, HIGH);  // turn the contactor on
  delay(10000);            // wait for ten seconds
}
```

Figure 12. Test code for toggling fans and contactor and serially reading thermistor data

4. Results

Subsystems

Each of the four subsystems, *stack enclosure/mounting*, *tubing*, *circuits*, and *power electronics* was assessed and developed as much as possible. While there are still features left to be developed before the stack is fully operational, the stack circuitry was repaired, updated, labelled, and reorganized, allowing for better understanding of parts and increased mobilization. The subcircuits were also tested, proving that the Arduino Uno, fans, contactor, and thermistors are all operational, and demonstrating the need to further investigate the existing microcontroller programming and thermistors.

Safety

An extra safety measure, the GasScanner 2C with oxygen and hydrogen detection, was successfully wired and turned on. The necessary calibration kit for accurate detection has been purchased and ordered, and has arrived on location.

Documentation

In addition to this report, detailed documentation of the existing subsystems and the GasScanner 2C has been compiled and organized so that the future recipients of this project may more easily become acquainted with the project and thus resume work on the stack quickly and with a clear understanding of the existing systems.

5. Discussion

As is clear throughout this report, the total mechanization and analysis of a PEMFC stack was beyond the scope of the time and resources available for this project. Stack systems are complex and require highly detailed development in multiple disciplines, such as mechanical, electrical, and computer engineering. Despite the magnitude of the desired outcome, there were many smaller-scale elements of this project that were realistically accomplished in just eight weeks. Ideally, the mechanization and analysis of this stack would be completed by a team of no less than two people over the time period of at least two semesters, however any work done on the stack is a worthwhile contribution and there are manifold opportunities for students to learn about PEMFC technology and the necessary developments to accompany it. In order for this stack to become operational and for hydrogen fuel cell technology to develop for efficient future use, students, professors, and companies must continue to study the intricate details of fuel cells themselves and the systems that accompany them.

6. Conclusion

Summary

Several significant contributions were made to the stack system, including updating and documenting the subsystems created by Gates and implementing an external gas monitoring system as a secondary safety measure to be installed near the stack. Because the mechanization of the stack is such a large task, it will continue to be the work of students in the future until the system is complete, and then students will have the opportunity to analyze the stack's performance, utilize the power output, and continue to improve upon the mechanical, electrical, and computer components of the system.

Recommendations

It is recommended that this project next be assigned to no fewer than two students at a time with mechanical, electrical, and/or computer engineering education. As revealed by both Gates and the author, this project requires a great deal of time. While it is beneficial to transition the project between students from year to year, it is important that students new to the project have adequate time to become familiar with all of the materials they have inherited so that they can effectively continue the work done before them.

Future Work

In order to make the stack operational, several aspects of the mechanization must be completed. A structure for the enclosure/mounting of the stack must be constructed to meet all of the requirements and specifications listed in the Ballard manual. Individual cell voltage monitors should be implemented to measure the voltage of each individual cell and avoid severe damage to the stack, which could be missed by monitoring only the overall stack voltage. An inlet air filter should be installed, as shown in the design in Figure 4. It is recommended that a printed circuit board replace the existing circuitry to decrease size and increase mobility. An appropriate tubing (Teflon or PVDF) system must be designed and constructed for the flow of fuel and byproduct. A power electronics system must be designed and implemented to manage the output from the stack. Finally, hydrogen fuel must be obtained to feed to stack.

These contributions, along with careful review of existing systems and an evaluation to assure that all of the necessary requirements and specifications have been met, will allow students in the future to use the stack to produce power. Professor Rausch intends to use the system to power a golf cart, and students will be challenged to find other applications. Overall, students will continue to benefit from the opportunity to work on the Proton Exchange Membrane hydrogen fuel cell stack and the ability to use the system for energy.

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