Midterm I

Team 16

Design and development of optimized flow channels for an alkaline membrane fuel cell (AMFC) educational kit

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ABSTRACT

The goal of the fuel cell project is to investigate the performance of a proposed alkaline fuel cell membrane (AMFC) and optimize it for an education kit for high school and college level laboratory fuel cell functional demonstration. This investigation involves learning from the flaws of the current fuel cell kit and finding new ways of improving the performance of the fuel cell. An understanding of how flow channels affect performance will contribute a key factor in the new design of the fuel and oxidant delivery components. Senior design group 16 members have previously chosen roles, responsibilities and have emerged with a code of conduct that we are diligently going to follow. A lot of background research has been carried out by the group members on how the design will be carried out. A list of goals and objectives were created to achieve optimum success. Design constraints have also been identified and are related to budget, resources available, and process product generation. A methodology for how this design problem will be solved has been outlined and a schedule of how tasks relevant to the described methodology will take place throughout the semester. This need assessment will serve as a vital foundation for how the design will be at the end of the project.

1. Introduction

Advancements in the development of fuel cells have been slow relative to other power generation systems like combustion engines, wind power, and hydropower. The highly demand of more clean and sustainable power generation brought a new focus in the development of fuel cells. In practical application, fuel cells operate at lower efficiencies than the expected value. Therefore, most researchers are dedicated to improving their performance. With the development of computer based software and knowledge in fluid dynamics, a previously developed cellulose-based AMFC prototype flow configurations will be studied and modified.

2. Project Definition

2.1 Background Research

The fuel cell was invented in 1839 by a British professor William Grove. His fuel was made of a series of cells made with a dilute solution of sulphuric acid and pairs of test tubes of hydrogen and oxygen. Grove observed that the ratio of consumption of the hydrogen to oxygen was 2:1. The volume ratio is an agreement with the simple reaction equation of hydrogen and oxygen to produce water. Since the invention of the first fuel cell, other types of cells has emerged this includes:

1) Proton Exchange Membrane (PEM)
2) Phosphoric Acid Fuel Cell
3) Alkaline Fuel Cell (AFC)
4) Direct Methanol Fuel Cell

2.2 Fuel Cell Application

Fuel cells have been used for power generation for over two decades and are an attractive alternative source of energy due to their high efficiencies and non-polluting operation. They have been used to power automobiles, spacecrafts, and some power plants. Some portable fuel cells have also been developed for use in powering of electronic devices for camping, yachting, traffic monitoring, medical treatment, and warfare. [1] In general, fuel cells produce electricity and can power any device or equipment that runs on electricity. Once again, the main advantage of fuel cell application is that it does not emit pollutants and other greenhouse gasses that are harmful to the environment.

2.3 Fuel Cell Operation

The purpose of a fuel cell is to convert chemical energy into electrical energy. The fuel cell provides an electrical current to an external circuit, providing on-demand power and requiring no moving parts. This is achieved by taking advantage of oxidation and reduction reactions, which release and capture electrons, respectively. The diagram of a standard alkaline fuel cell can be found below in figure 1. [2]

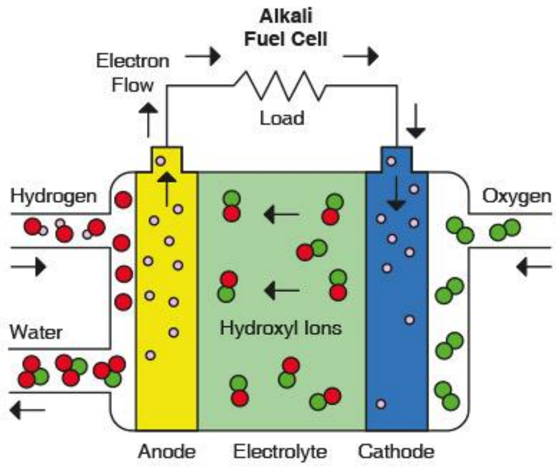

Figure 1: A diagram depicting an alkaline fuel cell [3]

The diagram above shows how the alkaline fuel cell functions. On the left side of figure one, hydrogen gas is supplied into the fuel cell. Once hydrogen gas enters the fuel cell, it begins to diffuse into the anode, which is highlighted in yellow. The anode is an electrical conductor which allows for a flow of electrons. The anode must not only conduct electrons but must also contain a catalyst for the oxidation reaction. The anode in an alkaline fuel cell is usually made of carbon which is coated with either platinum or palladium. These two metal are highly conductive of electricity and act as a catalyst for the oxidation and reduction reactions. This is due to the high porosity of the metals microstructure, which allows for efficient diffusion of hydrogen and oxygen into the microstructure. The faster this diffusion process can take place, the most efficient power generation can occur. To the right of the anode is the electrolyte soaked membrane (seen in green). From this membrane, hydroxyl ions supplied from the electrolyte solution also diffuse into the anode. The hydroxyl ions react with the hydrogen gas. This reaction is the oxidation reaction, and its balanced chemical equation can be found below in equation 1. [4]

$$2H_2 + 4OH^- \rightarrow 4H_2O + 4e^- \quad (1)$$

From equation 1 seen above, we can see the how the first half of the process works. As the hydrogen gas (H_2) diffuses through the anode, the two hydrogen atoms which make up the hydrogen gas, break apart. One of these atoms bonds with one hydroxyl ion. This reaction results in one water molecule and one excess electron. The water is expelled out of the anode, and eventually out of the fuel cell, and the electron flows out of the anode and through the external circuit. This electron flows from the anode to the cathode (seen above in figure 1 in blue) because of electric potential. The anode is electropositive, and the cathode is electronegative. This simply means there is an excess of electrons at the anode, and a shortage of electrons at the cathode. The cathode is constructed the same as the anode, which is described above. Oxygen gas supplied into the fuel cell (which can be seen on the right side of figure 1), diffuses into the cathode, and a reduction reaction occurs. The balanced reduction reaction that occurs at the cathode can be seen below in equation 2. [4]

$$O_2 + 2H_2O + 4e^- \rightarrow 4OH^- \quad (2)$$

The hydroxyl ions (OH^-) produced in equation 2 then flow through the membrane from the cathode to the anode. Currently, two possible configurations of membranes exist. One is the static electrolyte configuration. In this configuration, the membrane is usually either asbestos or the more complex Alkaline Anion Exchange Membrane (AAEM), which is ammonium based. These membranes are soaked in a highly concentrated electrolyte solution such as potassium hydroxide (KOH). This electrolyte solution is responsible for the flow of ions. In the flowing configuration, the membrane consists of some form of a matrix microstructure, which allows the electrolyte to circulate freely. The static configuration is generally safer in vehicular applications. However, these materials tend to be more toxic. More specifically, ammonia cause acute toxicity when inhaled or digested, and asbestos is a well-known carcinogen. Research is still attempting to develop a safe and efficient membrane. One possibility that is still being tested is a cellulose-based membrane. [4]

One important aspect governing fuel cell efficiency are the flow channels which provide fuel to the anode and the oxidizer to the cathode. Very little actual research has been done to test the best way to supply these gasses to the fuel cell. Ideally, the flow channels will be designed to produce maximum diffusion of both hydrogen and oxygen through the corresponding electrodes. The flow channels must also be designed to facilitate the removal of water vapor from the surface of the anode, which is the byproduct of the oxidation reaction occurring within the anode. Theoretically, a perfectly designed flow channel would be able to supply equally concentrated gas over the entire surface of the electrode while having the least amount of pressure drop. If the gas is not equally concentrated over the entire surface of the electrode, the current density will be uneven within the electrode, and will not produce optimal results. One consequence of having an uneven distribution of current within the electrode is uneven heat distribution. This could potentially affect the longevity of certain components in the fuel cell. This could also lead to a poor evacuation of water vapor. Likewise, if the head loss is too significant due to the complexity of the design, diffusion through the electrode will be slowed drastically. High pressure drops caused by head loss could also result in stagnation within the flow channels, which would have similar results as previously mentioned.

2.4 Advantages and Drawbacks

There are several advantages to using alkaline fuel cells. Generally, fuel cells only emit pure water. If contained and managed properly, the fuel cell can also prove to be a source of clean water in addition to providing clean energy. Furthermore, fuel cells are quiet. Also, when compared to other types of fuel cells, alkaline fuel cells offer relatively high current density. This is due to the fact that the alkaline solution allows for quicker chemical reactions than acidic membrane fuel cells. It is also due to the fact that an alkaline fuel cells can safely operate at temperatures ranging from 100° to 120°C, which is much higher than other fuel cells. Higher temperatures facilitate faster chemical reactions and increased diffusion rates. [3]

The main drawback to using an alkaline fuel cell is a phenomenon known as carbon dioxide poisoning. This occurs when the fuel being used is not pure. An example would be using air instead of pure oxygen. When carbon dioxide enters the fuel cell, carbonates form. These carbonates block and clog the pores in the anode and cathode. This blocking slows the rate at which diffusion occurs until it eventually stops the process altogether. The chemical reaction which causes this phenomenon at the anode and cathode can be seen below in equations 3 and 4, respectively. [4]

$$CO_2 + 2KOH \rightarrow K_2CO_3 + H_2O \quad (3)$$

$$2OH^{-} + CO_2 \rightarrow CO_3^{-2} + H_2O \quad (4)$$

The formation of these carbonates, potassium carbonate (K_2CO_3) and carbon trioxide (CO_3^{-2}), create a need for pure hydrogen gas and pure hydrogen gas in order to allow the fuel cell to remain efficient for long periods of time without maintenance. Purifying and collecting these gasses is a relatively complicated and sometimes expensive process. The best way to obtain pure oxygen is to use cryogenics. If air is cooled to -183°C, pure oxygen will liquefy, and it can then be collected and returned to a gaseous state. This method, however, is expensive and complicated. A simpler method to collect pure hydrogen is to use electrolysis in order to separate water into pure hydrogen and pure oxygen. A diagram of this process, as well as the chemical reactions involved, can be found below in figure 2. [6]

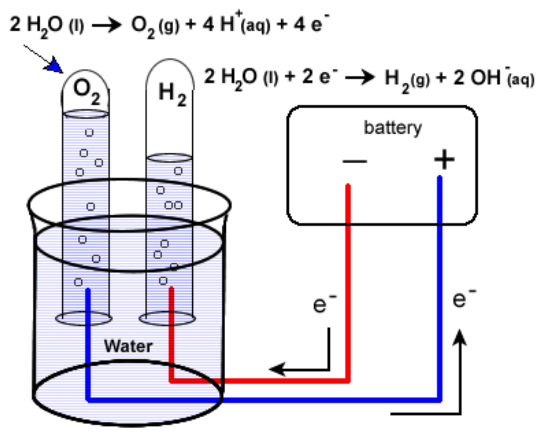

Figure 2: A diagram showing the electrolysis of water into hydrogen gas and oxygen gas [6]

The figure above shows a relatively safe and inexpensive way to produce pure fuel for an alkaline fuel cell. This method is one that could be easily used in order to power an at home fuel cell kit. As seen in the diagram, electrons leaving the battery from the negative terminal create a negative electrode in the water. This causes a reduction reaction (electrons gained) of H_2O, and hydrogen gas escapes where it is collected. The blue wire then becomes an effective positive electrode or cathode, and H_2O is oxidized. This releases pure oxygen gas which can be collected. It is important to note that pure water is a very poor conductor. This is due to the fact that pure water molecules have no free electrons to transfer electrical current. This slows down the process of electrolysis. In order to speed up this process, salt or any other common water soluble electrolytes can be added to the water. [6]

2.5 Need Statement

The project is being sponsored and advised by Florida State Professor Dr. Juan Ordonez. The project will include and demonstrate various experiments of testing different flow diagrams to show students the correlation between flow systems and efficiency in AMFC single cell. The fuel cell and all necessary parts will be in one portable kit that can be easily transportable. A previous educational fuel cell kit has been made and is located at the CAPS lab at Florida State University. This project will take this fuel kit and redesign it with the addition of exchangeable flow channel plates that contain different flow configurations. The team eventually plans to deliver a fully functioning AMFC educational kit that will be commercialized as a marketable product.

"The current AMFC setup does not effectively allow students to test the effects of flow configurations on fuel cell performance."

2.6 Goal Statement and Objectives

"Deliver a functioning educational alkaline membrane fuel cell kit that demonstrates the effects of flow configurations on the fuel cell's performance by the end of spring 2017 semester."

The main objectives that have been addressed from assessing the need statement are listed below.

- Improve the design of an alkaline membrane fuel cell (AMFC) educational kit for high school and college level laboratory demonstration.
- Include multiple flow configurations to test performance
- A standard operation procedure and a product specification sheet included in the kit

- A series of demonstration experiments will be designed and conducted
- Develop a model for commercialization of the kit.

2.7 Constraints

The proposed functionality of the fuel cell requires multiple components such as delivering pure Oxygen and Hydrogen to the system. As mentioned in the background research a method of electrolysis will be used to create pure Oxygen and Hydrogen. This method requires an outside power source such as a battery to make the process possible. A customer requirement was to have all components to fit inside the fuel cell kit resulting in a desire of fewer components. Electrolysis method requires more components of the system, resulting in new problems in making storage in the kit more difficult. Size and weight from the HOQ have shown that this is a major constraint due from the need statement to deliver a mobile kit. Any part of the system that requires extra parts or components will create problems of keeping this desire satisfied.

Safety is another constraint noticed from assessment. The fuel kit product will be used as a learning tool to deliver to students on how fuel cells function and what parameters affect functionality. The system will deal will pressurize gasses and electrical components being used in a classroom setting putting safety at a high priority. This puts constraints on material selection and assembly to ensure that the system is safe during operation. The material selection also impacts the resistance to weather where oxidation or material failure can occur. It is desired for the kit to be durable during its lifespan for safety and practical reasons.

3. Design and Analysis

3.1 Design Components

3.1.1 Fuel Cell Components

The kit will contain all necessary components required to assemble the fuel cell. This includes all necessary nuts, bolts, washers, an anode, a cathode, an electrolyte solution, an electrolyte membrane, and three different sets of endplates which will contain different flow configurations . All nuts, bolts, and washers will be made of stainless steel to promote longevity and prevent corrosion. The electrolyte solution will consist of potassium hydroxide (KOH) concentrated at 40%. The endplates will be made of Aluminum 2024, and will contain the three different flow configurations. Aluminum 2024 will allow the fuel cell to be lightweight, and will also prevent corrosion. These different flow configurations will provide the user with a means to experiment. The flow channels can be swapped out by the user, and fuel cell power and current output can be compared. The different fuel cell configurations used will contain fundamental differences in how they deliver hydrogen and oxygen to the inside of the fuel cell. This will allow the user to clearly see how these differences effect the fuel cell.

3.1.2 Electrolysis Components

Compressed hydrogen and oxygen are extremely dangerous and expensive. Because of this, keeping these gases within the fuel cell kit is impractical. The kit will instead contain a kit for producing, capturing, and delivering these gases to the fuel cell. This will make the kit safer and cheaper. The method being used is known as electrolysis. Electricity will be used to separate the water molecule into pure hydrogen and oxygen gas. The gas will then flow from the water source to the inside of the fuel cell flow configuration. This will be done using a DC power supply, two flasks, two collection cups, and gas lines. A DC power supply will convert 110V AC power from the wall into a safe and useable power that can power electrolysis. It was decided that using a battery to complete this task would make the kit too heavy and expensive. The flasks, collection cups, and gas lines will then be used to hold the water, trap the gas produced by electrolysis, and finally move the gases from the flasks to the fuel cell. The gases will be driven to the fuel cell by pressure which will build up as the electrolysis process takes place. Gas lines must be tight fitting in order to prevent leaking.

3.1.3 Kit Components

The final design of this project will include everything needed to assemble and test a working alkaline membrane fuel cell. This will allow users of the kit to gain hands on experience and learn the fundamentals about how a fuel cell operates and what aspects influence their performance. The kit will include an instruction manual that will list the steps required to assemble the fuel cell, as well as different experiments that can be conducted by the user. The current design will require no tools to assemble. Traditional nuts will be replaced with wing nuts to prevent the usage of a wrench. This will eliminate unnecessary components contained in the kit. The kit will also contain a multimeter which will allow the user of the fuel cell to measure current and voltage output. Everything will be housed in a polymer briefcase sized carrying case which will offer durable protection to the components in the kit.

3.2 Effects of Different Configurations on Cell

Ultimately, the main idea behind testing different flow configurations is the optimization of diffusion. Diffusion is the driving force in producing power and maximizing efficiency in a fuel cell. Diffusion takes place at the anode and cathode, and allows the reduction and oxidation reactions to take place, respectively. This process is effected by three different factors. These factors include gas distribution, pre, and wastewater management.

Gas distribution is important for several reasons. To start, evenly distributed gas will ensure that diffusion is occurring at an even rate across the entire anode/cathode. If the gas is not evenly distributed, diffusion will occur faster in some spots than others. This causes an uneven current density which reduces overall power output. Additionally, this will cause uneven heating of the fuel cell. In extreme cases, poor thermal management can lead to warping and degradation of the fuel cell.

Pressure drop is also an important factor when studying diffusion within a fuel cell. A flow configuration that contains complicated flow regimes could potentially result in high minor losses. Minor losses in fluid flow are caused by characteristics such as sharp edges, bends, entrances, and decreasing diameter in the flow regime. These minor losses cause a pressure drop. Pressure is important in diffusion because as pressure becomes higher, gas molecules tend to become more excited. This type of behavior maximizes the molecules contact with the fuel cell. This inevitably increases diffusion. If pressure drop is too high, the gases will not flow autonomously through the flow channels. This would mean that the fuel cell would require a pumping method to force the gases through the fuel cell. This is undesirable because it would increase the weight, size, and overall complexity of the kit.

Wastewater management is another aspect which effects diffusion rates in a fuel cell. As the fuel cell operates, hydrogen and hydroxyl ions undergo an oxidation reaction which leads to the formation of water and extra electrons. This water vapor must be effectively removed from the flow channels to prevent the buildup of condensed water. If water begins to condense inside the fuel cell, it will prevent gas from contacting the surface of the anode. This would result in an obvious reduction of diffusion. It is for this reason that the flow channels be designed to facilitate the removal of water vapor from the fuel cell.

3.3 Design Concepts

This fuel cell kit will not only provide a hands-on learning experience behind the construction of a fuel cell, but it will also offer an insight into the aspects which effect fuel cell performance. More specifically, diffusion. This will be done by containing at least three different fuel cell flow configurations, for a total of six end plates. The three configurations that are currently being analyzed are the parallel, serpentine, and interdigitated flows. Users can configure the fuel cell, allow it to run, and measure the fuel cells performance using the multimeter. Then, the user can disassemble the fuel cell, and reconstruct using a different flow configuration. This enables the user to run the fuel cell and compare the results. Each configuration has different positive and negative aspects on the efficiency of the fuel cell. For example, a serpentine style flow configuration is shown in Figure 3.

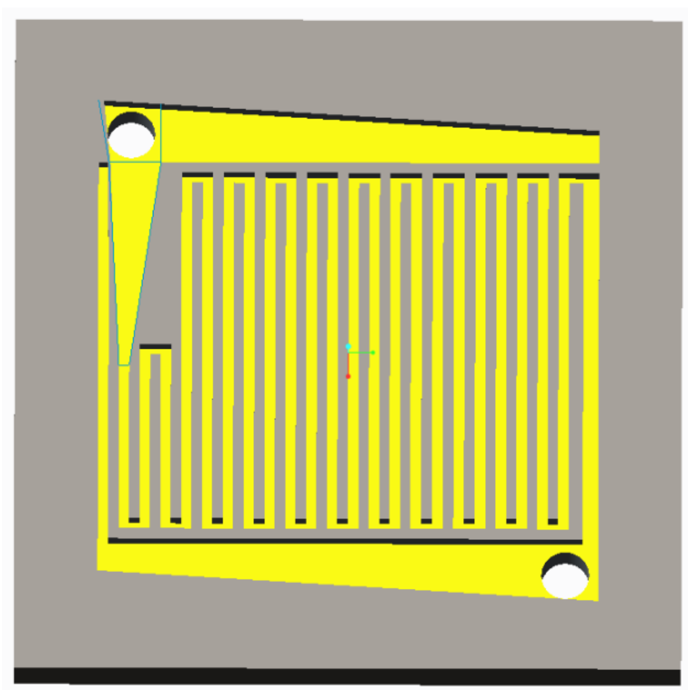

Figure 3: Team 16 3D model of serpentine flow configuration

The model above has the same dimensions in order to fit in the housing of the current fuel cell (drawings can be found in Appendix A). By observing the flow configuration, some assumptions have been made from the flow path of the fluid. The fluid flows through one path and is continuous; along the path, the gas becomes less concentrated as it diffuses through the electrode. This can cause a reduction in current density, and a reduction in fuel cell efficiency. Another note that has been made from the continuous flow is that this allows for areas to eliminate to stagnant flow [7].

The interdigitated flow configuration is the other alternate plate that will be used to compare for testing as shown in Figure 4.

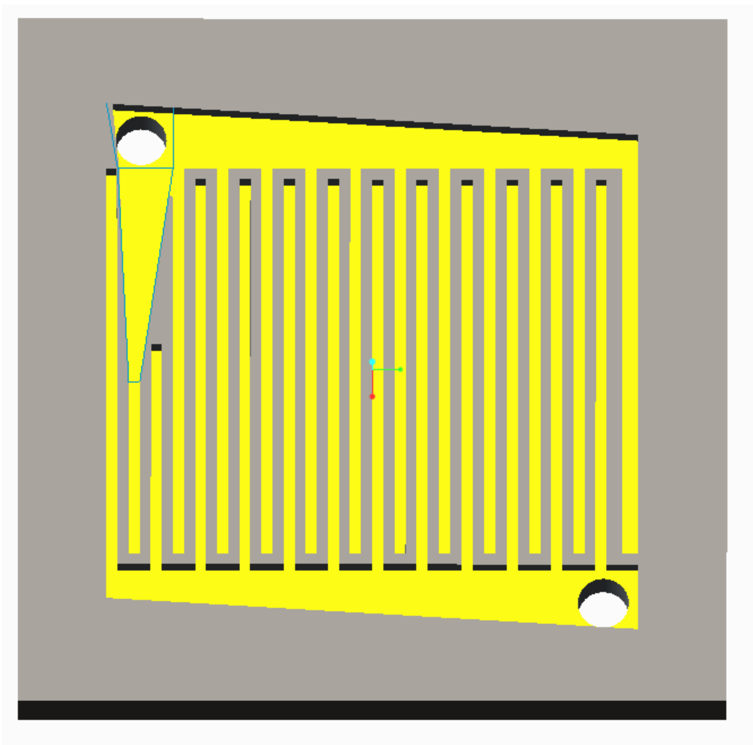

Figure 4**:** Team 16 3D model of interdigitated flow configuration

The interdigitated configuration flow path is not continuous as seen above. Fluid may flow through multiple paths, which allows for a more evenly distributed spread of gas within the fuel cell. The inlet and outlet channels are not connected which forces the flow to laterally diffuse over the ribs through the electrode. This can cause forced convection, which results in a higher heat transfer rate and a higher fuel cell efficiency [7]. The pressure drop may be higher in this configuration due to the non-continuous flow, the fluid needs to be pushed over the ribs resulting in the higher energy losses through the configuration. This could impact the functionality of the fuel cell kit due to the possible addition of a pump to overcome this high energy loss. The parallel configuration is already included in the current kit and can be seen in Figure 5.

Figure 5: Current parallel flow configuration

The parallel configuration can be seen as the most simplistic design from the serpentine and interdigitated designs. The flow can flow through multiple paths allowing for a lower pressure drop due to flow not being forced. Other observations from the configuration above is possible fluid buildup in the extra free space by the inlet and outlet channels.

3.4 Testing of Designs

When designing, and testing the fuel cell and the different flow configurations, pure hydrogen and oxygen gas will be used to power the fuel cell. This will provide a control to compare the function and efficiency of the flow configurations provided in the fuel cell test kit. Several tests will be performed. The first test conducted will be measuring power and current output. This will be done by connecting a multimeter to the fuel cell and allowing it to operate. The different outputs can then be compared. This test will be completed to ensure that each flow cell configuration works with the fuel cell.

A second test that will be conducted is measuring pressure drop. This can be done by measuring pressure at both the entrance and the exit of the endplate. As the pressurized gas travels through the endplate, it will experience various minor losses, and eventually a pressure drop. This pressure drop will reveal the efficiency of the flow regime within the endplate. If a pressure drop is too great, the flow configuration will be redesigned to prevent malfunction of the fuel cell.

The third and final test which will be conducted is thermal imaging. The fuel cell will be allowed to operate for an extended period, and will be recorded with a thermal imaging camera. The distribution of heat within the fuel cell will reveal distribution of current density. For instance, if the fuel cell is noticeably warmer in one area than another, it will be clear that diffusion is not occurring evenly within the flow regime. If the problem is too severe, the flow configuration will have to be redesigned.

4. Methodology

The first step is to conduct series of experiments on the parallel flow configuration available to us from the previous team that worked on an alkaline fuel membrane fuel kit in the Centre for Advanced Power Systems (CAPS) building to determine its uniform current density, reactant distribution over a large area, and its head loss. The next step is to design two flow configurations, which are the serpentine and interdigitated flow configuration, utilizing the CAD software for visual purposes as well as part drawings. Then we meet with our project adviser Dr Ordonez about the flow configurations to seek his approval or modifications on the flow configurations. A Design prototype is then made to understand the different configurations from a technical point of view, to gather requirements that are more accurate and to have a general idea of the costs involved.

The flow configurations will now be manufactured according to the budget allocated to the project in the machine shop. Testing will then be carried out on the current density, reactant distribution, head loss, diffusion rate and the power generated from the serpentine and interdigitated flow configuration that will be designed comparing it with the parallel flow configuration that we already have in the CAPS building which will enable the team to come to a conclusion on the most efficient flow configuration. In order to prevent exceeding the $1,000 budget, price will be weighed in every decision to make sure the team makes the best decision between performance and costs. Items which will be used in the flow configuration will be quoted to ensure the lowest possible price was obtained, thus using the team's budget efficiently. A good representation of the methodology is shown below in Figure 6.

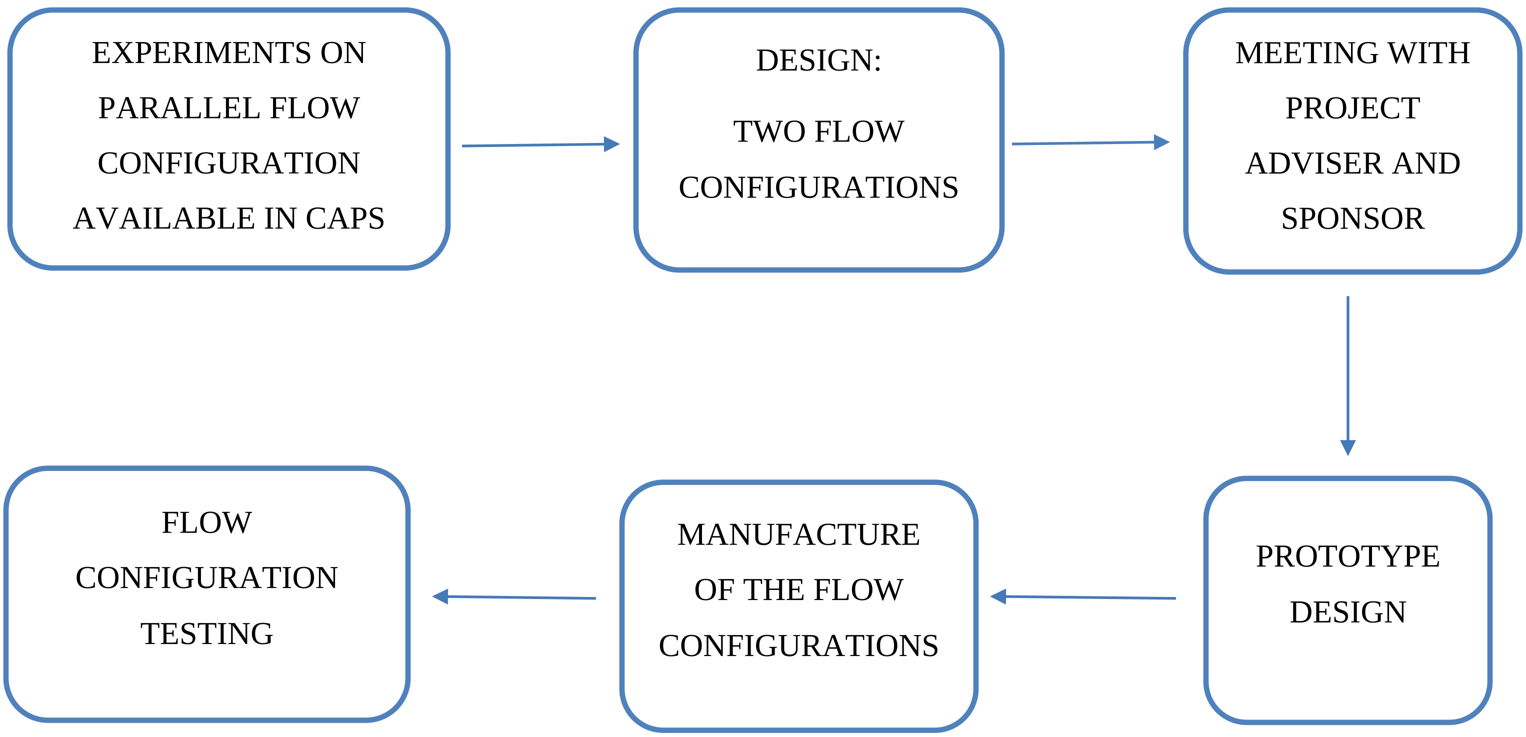

Figure 6: Flow pattern of methodology to approach goal

5. Schedule

The methodology above has kept the team on a track of what must be completed in steps in order to reach our goal of prototype testing. The team needs data from the parallel, serpentine, and interdigitated designs. Comparisons can be made and more research can be done in order to get a more in depth understand to how certain configurations respond during application. The final prototype kit will then be made by the end of the semester with a detailed experimental booklet included. The ultimate goal by the end of spring 2017 is to develop a new unique configuration that is optimized in all aspects that improve efficiency based on studied properties. This will be the forth configuration plate that will eventually be added to the kit resulting in a unique kit that is specially designed by Team 16. In Figure 7, a Gantt chart is used to help organize Team 16's process on the project. This will help the team reach goals and stay on track in order to complete what is desired.

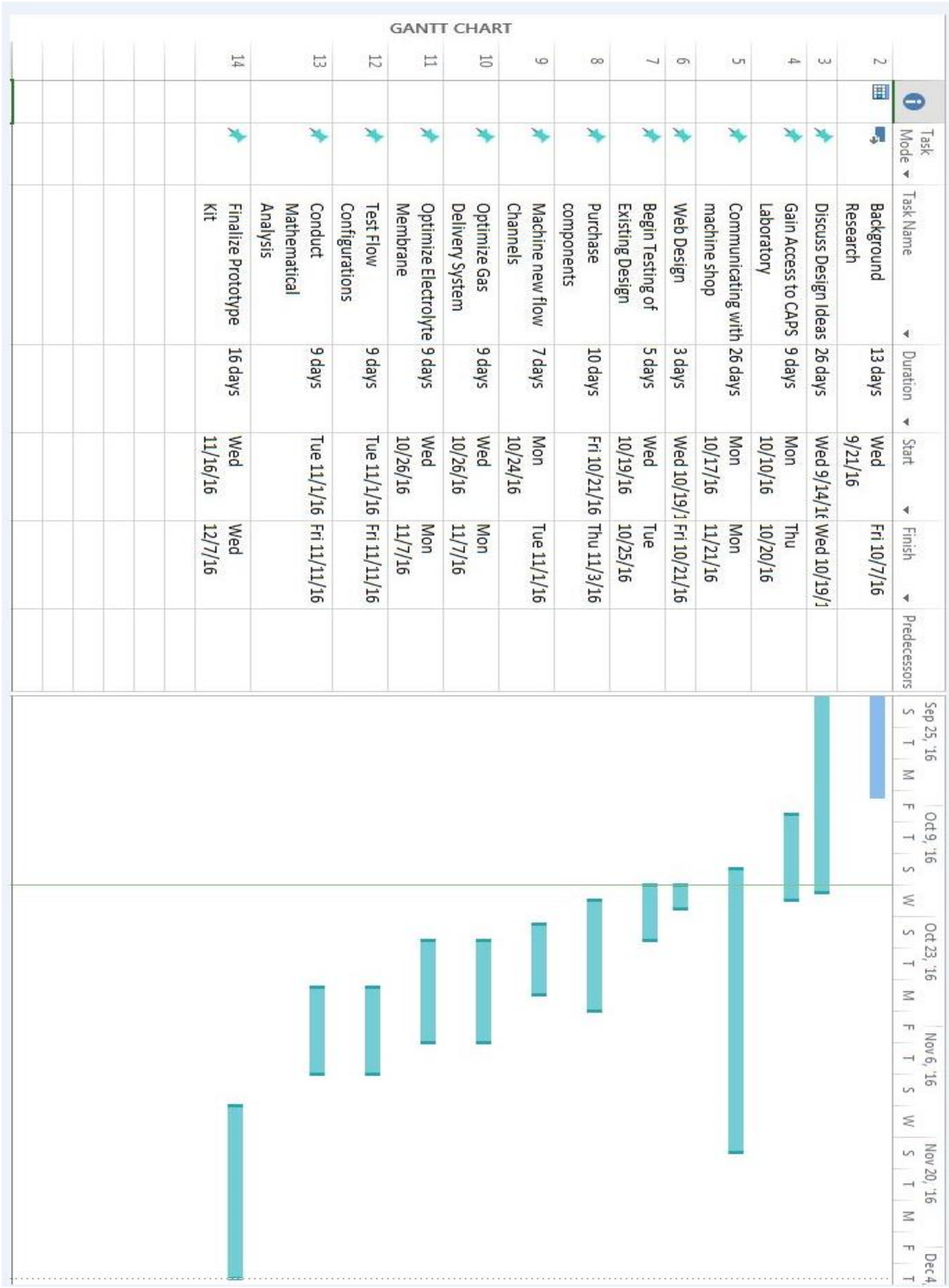

Figure 7: Team 16 Gantt Chart

6. Marketing

Part of the sponsor's goal for the project is develop commercialization of the fuel cell kit. The kit has demonstrated an opportunity for Team 16 as entrepreneurs. Ideas such as developing a fuel cell kit is determined to be a good opportunity to be manufactured on the market. Alternatives energy is a high interest in today's society due to global warming. The targeted consumers of Team 16's fuel cell kit have been high schools, university labs, and science centers. Since the kit will include demonstrational experiments, it is a good learning tool. The kit will engage students on a more interesting level about learning how an alkaline fuel cell works. When people are engaged in learning, they retain information more efficiently. The kit will include all necessary parts and be easily assembled and portable. The case will be relatively lightweight and compactable resulting in a simplistic learning tool. Team 16 finds it important to gain interest of alternative energy to people and therefore bringing a fun, easy way to learn about how an alkaline fuel cell works.

7. Conclusion

An alkaline fuel cell is a device that uses a source of fuel, such as hydrogen, and an oxidant to create electricity from an electrochemical process in which its electrolyte is alkaline e.g. potassium hydroxide (KOH). These cells were costly at the beginning stages but different research focusing on their optimization reduced that cost. Alkaline Fuel Cells in the market today have a power output of 300 Watts to 5kW per cell with an efficiency of about 70%. The only by-products are heat and water. They are very stable and can operate for several thousand hours within the temperature range of 90-100 C.

The objective of this project is to test different flow configurations of an alkaline membrane fuel cell (AMFC) and determine all components of the configuration that effects the overall efficiency. The fuel cell will be used for an educational tool for high school and college level laboratory demonstrations. The kit will contain four different flow configurations, the parallel, serpentine, interdigitated, and Team 16's own configuration. Special experiments will be conducted and written in a booklet that will also be contained in the kit. The Team will also develop a model for commercialization of the kit to sell on the market to STEM institutions.

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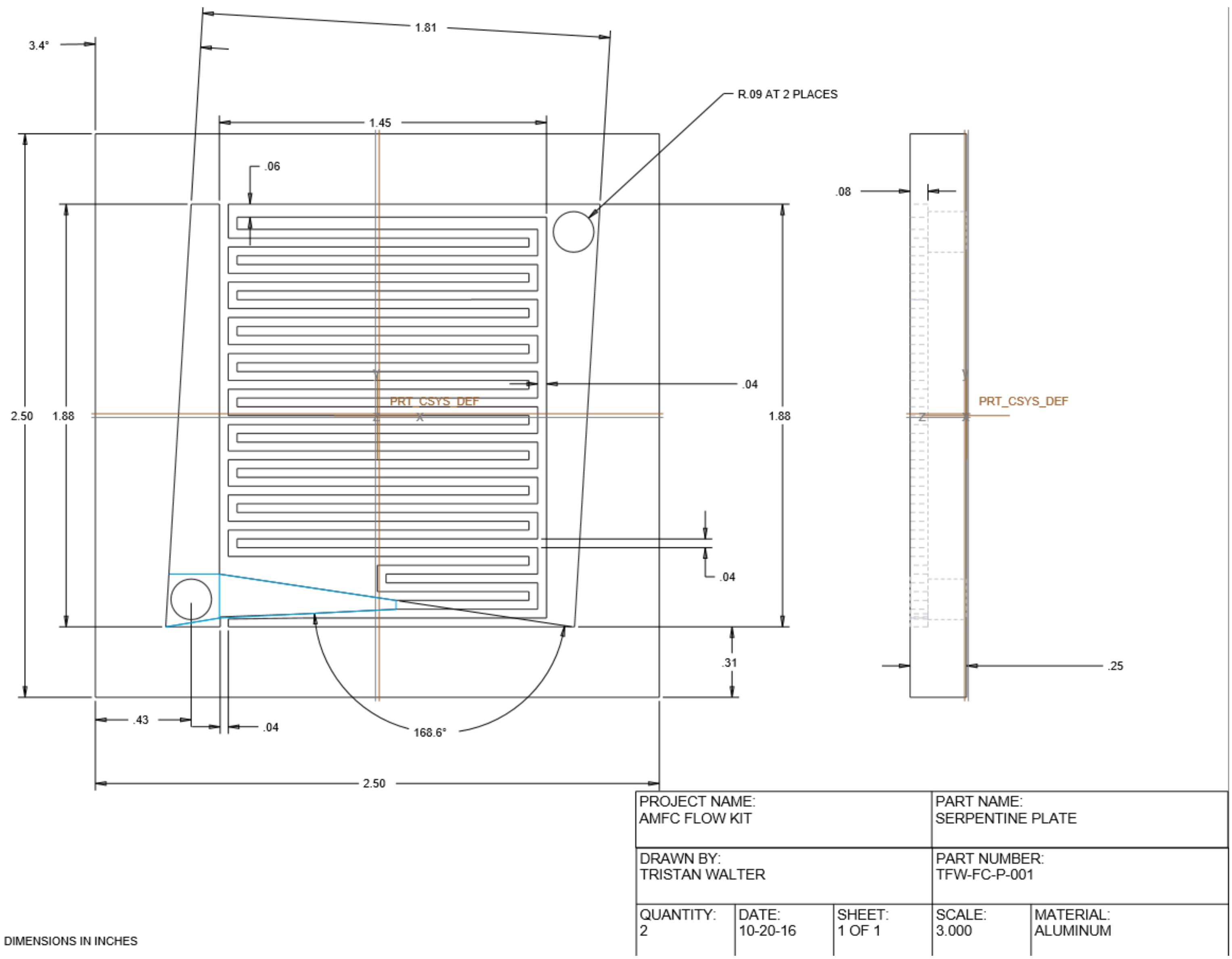
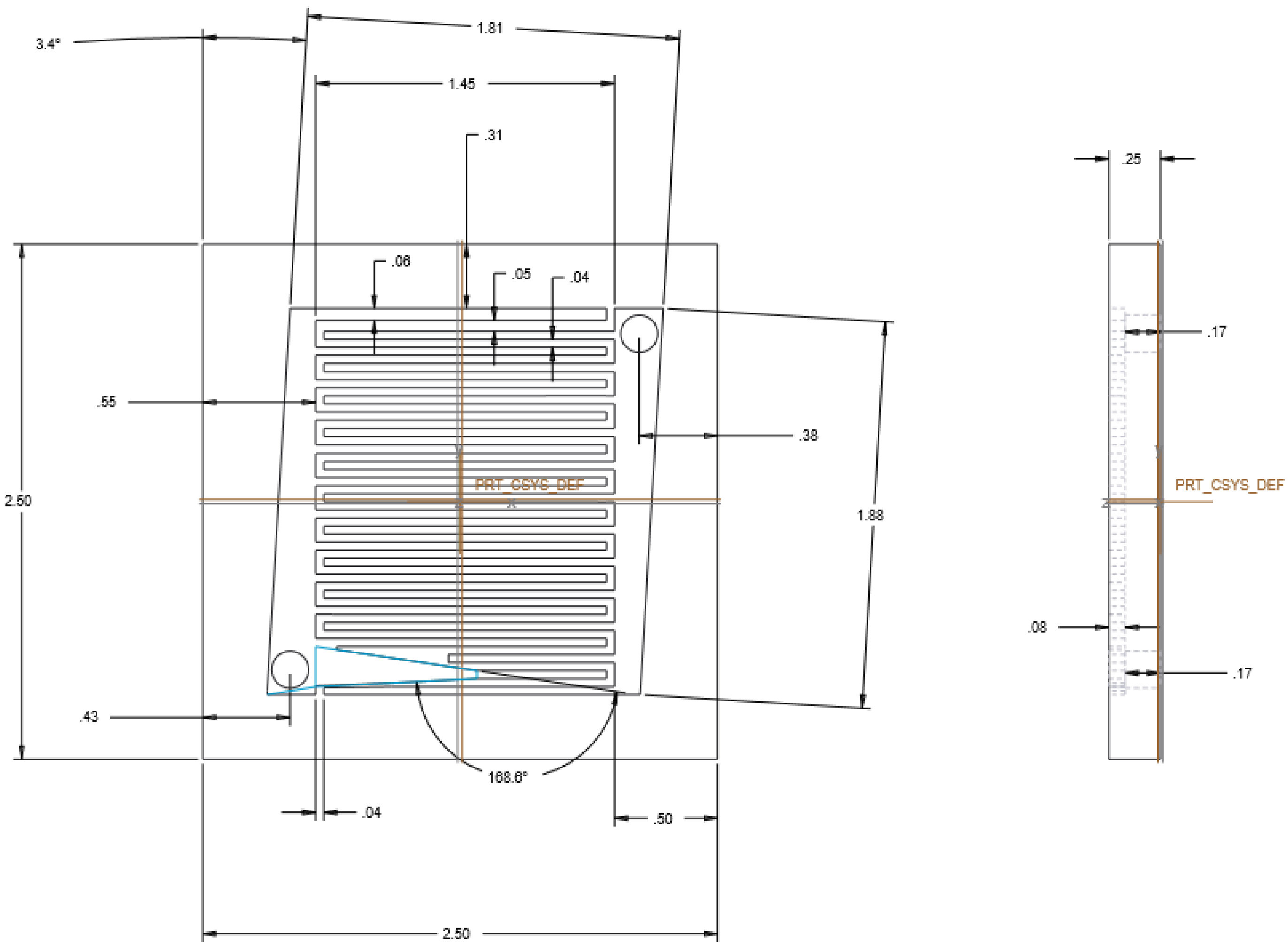
Appendix A



CAD of Serpentine Design



PROJECT NAME: AMFC FLOW KIT			PART NAME: INTERDIGITATED PLATE	
DRAWN BY: TRISTAN WALTER			PART NUMBER: TFW-FC-002	
QUANTITY: 2	DATE: 10-20-16	SHEET: 1 OF 1	SCALE: 3	MATERIAL: ALUMINUM

DIMENSIONS IN INCHES

CAD of Interdigitated Design