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Novel design and manufacturing strategies for portable air-breathing proton exchange membrane fuel cells

Sriram Praneeth Isanaka
Missouri University of Science and Technology, sihyd@mst.edu

Department: Mechanical and Aerospace Engineering

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NOVEL DESIGN AND MANUFACTURING STRATEGIES FOR PORTABLE AIR-BREATHING PROTON EXCHANGE MEMBRANE FUEL CELLS

by

SRIRAM PRANEETH ISANAKA

A DISSERTATION

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Approved by

Frank Liou, Advisor
Joseph W. Newkirk
Ashok Midha
Xiaoping Du
K. Chandrashekara

PUBLICATION DISSERTATION OPTION

This dissertation consists of the following three articles that have been submitted for publication as follows:

Paper I, Pages 23 - 59 have been submitted to the JOURNAL OF ELECTROCHEMICAL CONVERSION & STORAGE.

Paper II, Pages 60 - 86 have been published in the JOURNAL OF MANUFACTURING SYSTEMS.

Paper III, Pages 87 - 114 have been submitted for publication in the INTERNATIONAL JOURNAL OF HYDROGEN ENERGY.

An appendix has been added for purposes normal to dissertation writing to detail supplementary and unpublished data.

ABSTRACT

The purpose of this dissertation is to study the importance of design novelty and advanced manufacturing and assembly practices towards portable air-breathing proton exchange membrane fuel cells. Traditional proton exchange membrane fuel cell designs have always been based on prismatic shapes and expensive materials like graphite and steel. The novel design strategies theorized as part of this research though have led to the creation of working prototypes with unconventional form factors, materials and manufacturing methods. The benefits include improved reactant flow characteristics, superior power densities, reduced cost, and simplified manufacturing and assembly complexity as compared to conventional proton exchange membrane fuel cell designs.

The proof of these improvements will be provided as numerical, analytical and experimental data over the forthcoming sections. Materials including polycarbonate and stainless steel have been employed to improve power densities. Solvent welding has been employed as an assembly practice in place of conventional fastening mechanisms to promote leak proof sealing. Additive manufacturing practices have also been employed to promote manufacturing ease. The benefits of these new ideologies in some cases have included ten-fold increases in power densities, coupled with an eighty percent reduction in the number of components and weight. All of these advantages of the new designs have been verified using working prototypes that were manufactured in-house. These advantages could make them exceedingly attractive, portable energy solutions.

ACKNOWLEDGMENTS

The course of my doctoral study has been long, rigorous and enlightening. During this period I have evolved as a person both professionally and personally. I would like to thank all the people who helped me become the person that I am today.

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Last but in no way the least, I would like to thank my family for their patience and confidence in me. My parents (I. Ramesh Reddy, & J. Pushpalatha Ramesh), sister (I. Lakshmi Priya), uncle (J. Vijaya Bhaskar Reddiar), and grandparents (C. Jayaram Reddiar, T. Sudharsanamma, I. Rajagopal Reddy and Y. Aadhilakshmamma) have always encouraged me to earn the first doctorate in our family. Hopefully it won't be the last.

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LIST OF ABBREVIATIONS

SYMBOL	DESCRIPTION
PEMFC	Proton Exchange Membrane Fuel Cell
PEM	Polymer Electrolyte Membrane
ASA	Axis Symmetric Architecture
CAD	Computer Aided Design
CNC	Computer Numerical Control
SS	Stainless Steel
FEM	Finite Element Methods
FEA	Finite Element Analysis
3D	Three Dimensional
MEA	Membrane Electrode Assembly
AFRL	Air Force Research Labs
ISC	Intelligent Systems Center
DOE	Department of Energy
GPS	Global Positioning System
GDL	Gas Diffusion Layer
H2	Hydrogen
AM	Additive Manufacturing
FDM	Fused Deposition Modelling
ABS	Acrylonitrile Butadiene Styrene
PTFE	Poly Tetra Fluoro Ethylene (Teflon)

SECTION

1. INTRODUCTION

The fuel cell is an electrochemical device that enables the direct and efficient conversion of chemical energy stored in the fuel along with oxidant into electrical energy. The types of fuel cells currently under research include

- Polymer electrolyte membrane fuel cell (PEMFC)
- Direct Methanol fuel cell (DMFC)
- Solid Oxide Fuel cell (SOFC)
- Molten Carbonate Fuel cell (MCFC)
- Phosphoric Acid Fuel cell (PAFC)
- Alkaline Fuel cell (AFC)

A typical Proton exchange membrane fuel cell (PEMFC) design is comprised of a proton-conducting polymer membrane (the electrolyte), that separates the anode and cathode sides. On the anode side, hydrogen diffuses to the anode catalyst where it dissociates into protons and electrons. These protons often react with oxidants causing them to become what is commonly referred to as multi-facilitated proton membranes. The protons are conducted through the membrane to the cathode, but the electrons are forced to travel in an external circuit (supplying power) because the membrane is electrically insulating. On the cathode catalyst, oxygen molecules react with the electrons (which have traveled through the external circuit) and protons to form water. The main components of a fuel cell are:

- MEA (Membrane electrode assembly)
- GDL (Gas diffusion layer)
- PEM membrane
- Bipolar plates
- Gaskets
- Endplates

The PEM (Proton Exchange Membrane) is sandwiched between two electrodes which have the catalyst embedded in them. This ensures that the electrodes are electrically insulated from each other by the PEM. The membrane being electrically insulating only allows the transport of the protons from the anode to the cathode through the membrane but forces the electrons to travel externally to the cathode. Commonly used materials for these electrodes are carbon cloth or Toray carbon fiber paper. Platinum is one of the most commonly used catalysts; however other platinum group metals have also been researched. Ruthenium and platinum are often used together as catalysts in place of platinum. Iridium and its oxides along with nickel have also been used in cases. Due to the high cost of these and other similar materials, research is being undertaken to develop catalysts that use lower cost materials. These high costs are still a hindering factor in the wide spread economical acceptance of fuel cell technology.

For a given membrane electrode assembly (MEA), the power density of a fuel cell stack can be significantly increased by reducing the profile of the bipolar plates. A key prerequisite for many power applications is the production of compact and lightweight PEMFC stacks which may be achieved with novel design strategies and the appropriate selection of materials. Proton exchange membrane (PEM) fuel cells are a potentially significant power source for transportation and portable electronics. One of the most significant barriers to the adoption of PEM fuel cells is the high cost and weight of the current graphite bipolar plate technology.

Bipolar plate, which accounts for 40-50% cost and 60-80% weight of the whole fuel cell stack, is an important part in Proton Exchange Membrane (PEM) fuel cell. The main functions of bipolar plate include carrying current away from each cell, distributing gas fuel within the cell, and providing support for Membrane Electrode Assembly (MEA). The Department of Energy (DOE) has proposed a technical target of bipolar plates for the year 2010 in which the main requirements are electrical conductivity >100 S/cm and flexural strength >25 MPa.

Based on interactions, it was found that the customer for this project, the US Air Force, had the following requirements:

- 5W output to charge mobile applications
- Economical (Sub 100 $)
- Light weight (under 2 lbs)
- Efficient (5 – 6 recharges) per canister
- Long working life (> 1000 hours) per fuel cell module
- Portable. (Small enough to be carried in the soldier’s vest)
- Aesthetic. (Functionally adept and pleasing to the customer)
- Reliable (Work without problems in a variety of temperature and humidity ranges)
- Air breathing, without the use of a fan
- Ease to use

Based on the customer requirements, studies were conducted into multiple areas including

- Materials
    - Graphite
    - Metals (Aluminum, Copper, Stainless Steel)
    - Plastics
- Design
    - Flow field and manifold designs
    - Shape and package designs
- Sealing
    - Permanent adhesion
    - Temporary fastening
- Manufacturing methodology
- Assembly methodology

The results from this work are elaborated in the forthcoming sections and have also been included as part of the journal publications presented in this dissertation.

2. RESEARCH APPROACH

Initial strategy for the PEM fuel cell was to study various designs and shapes of conventional prismatic fuel cell designs. This was pursued to determine the benefits of unconventional shapes on the ease of manufacturing and assembly complexity. Figure 2.1 and Figure 2.2 show some examples of the shapes investigated. The designs were modelled with the purpose of simulating their flow characteristics in FLUENT, therefore only the flow channels were modeled.

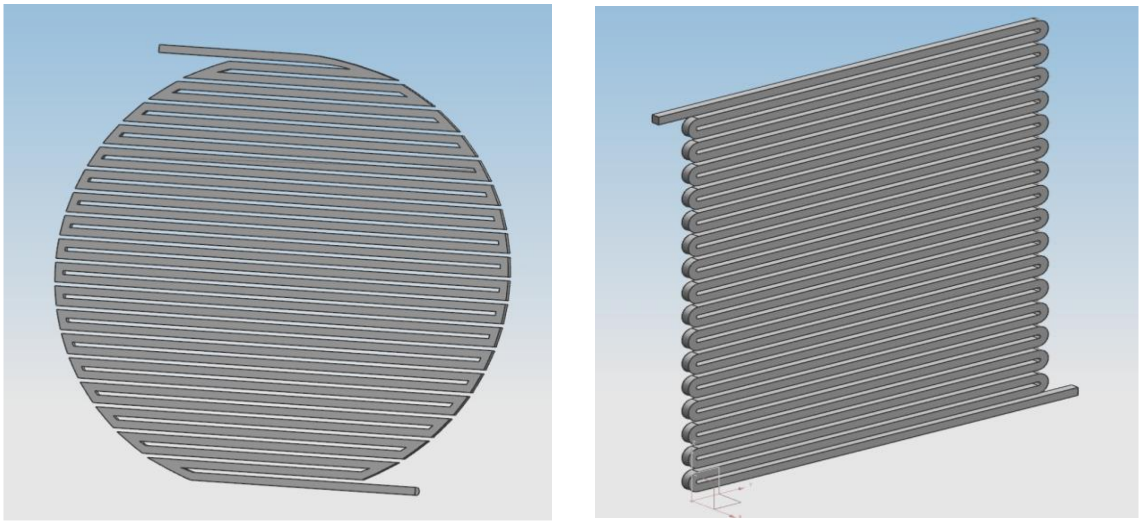

Figure 2.1: Different concepts for initial investigation of conventional design strategies, (a) Circular plate design, (b) Square plate

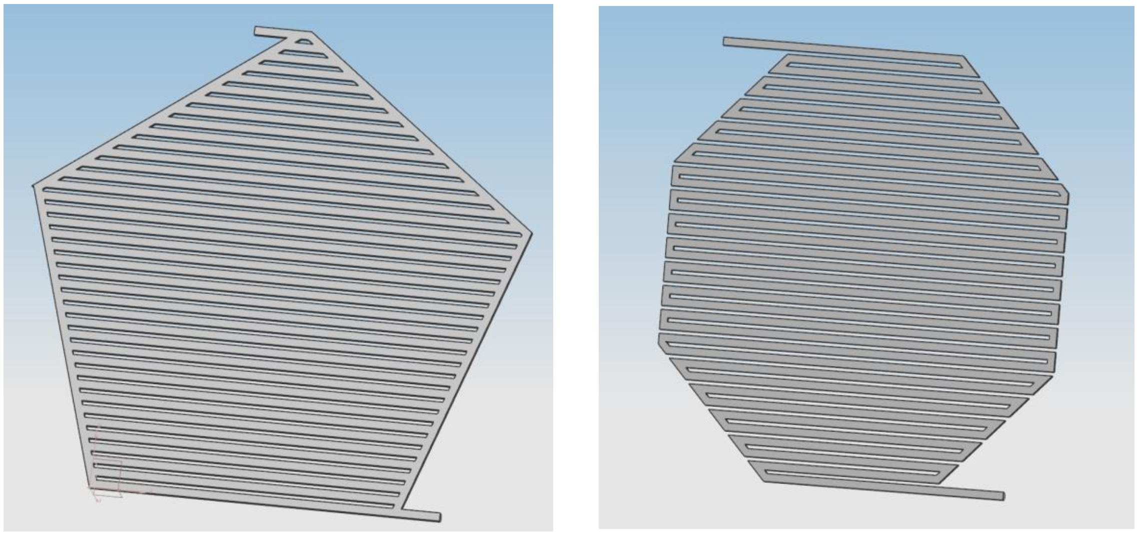

Figure 2.2: Different concepts for initial investigations (contd.) ((c) Hexagonal plate, (d) Octagonal plate

2.1.CHANNEL CROSS-SECTION

The cross-sections of the fluid flow channels of the conventional plate design are typically rectangular or square, even though other configurations like triangular, and semi-circular have been explored. Literature has shown that in the case of small and portable fuel cells, the flow channel dimensions range from 1 to 2mm in width, and depth as low as 1mm, so as to minimize the fluid pressure loss due to friction. The land width (i.e. the un-machined section between two adjacent channels) was also considered as this is the area that attracts the electrons from the reactions taking place in the MEA. If the plates have large land widths, then the active area of the MEA available for absorption of the reactant gas is reduced which in turn reduces the performance of the fuel cell. Reduction in the land width ensures that the surface area for the collection of electrons is reduced. Therefore, when designing the active area of the plate, a balance between the areas under the flow sections and the land sections is vital. The most common method of manufacturing the fluid flow channels on the plates requires the engraving or milling of the flow channels onto the plate’s surface. It also has been found that having larger channel size causes the reactant gas to have a turbulent flow which is to be avoided as it would interfere both in the flow of the gas through the channels as well as the absorption of the gas into the MEA.

2.2.FLOW-FIELD LAYOUTS AND CHANNEL DISTRIBUTION

The purpose of the flow field is to evenly distribute the reactants across the entire surface of the membrane, and provide support for the membrane. Over the course of a few decades investigators have developed a variety of designs to serve these purposes. This section details some of the designs that have been used and their merits and demerits. They include:

- Pin-type flow field
- Parallel/Straight flow field
- Serpentine flow field
- Multiple Serpentine flow fields
- Inter-digitated flow fields
- Mixed flow field designs

Pin-Type Flow Field **-** The flow field in this type of design is formed by many pins arranged in a regular pattern. These pins are usually cubical or circular in cross-section. In these types of designs there is a low reactant pressure drop. However, reactants flowing through such flow fields tend to follow the path of least resistance and energy loss which may lead to the formation of stagnant areas, thus causing uneven reactant distribution, inadequate water removal and thereby causing poor fuel cell performance. Also large areas of the catalyst on the membrane will not be exposed to fuel thereby wasting valuable membrane area. A pin type design is shown in Figure 2.3.

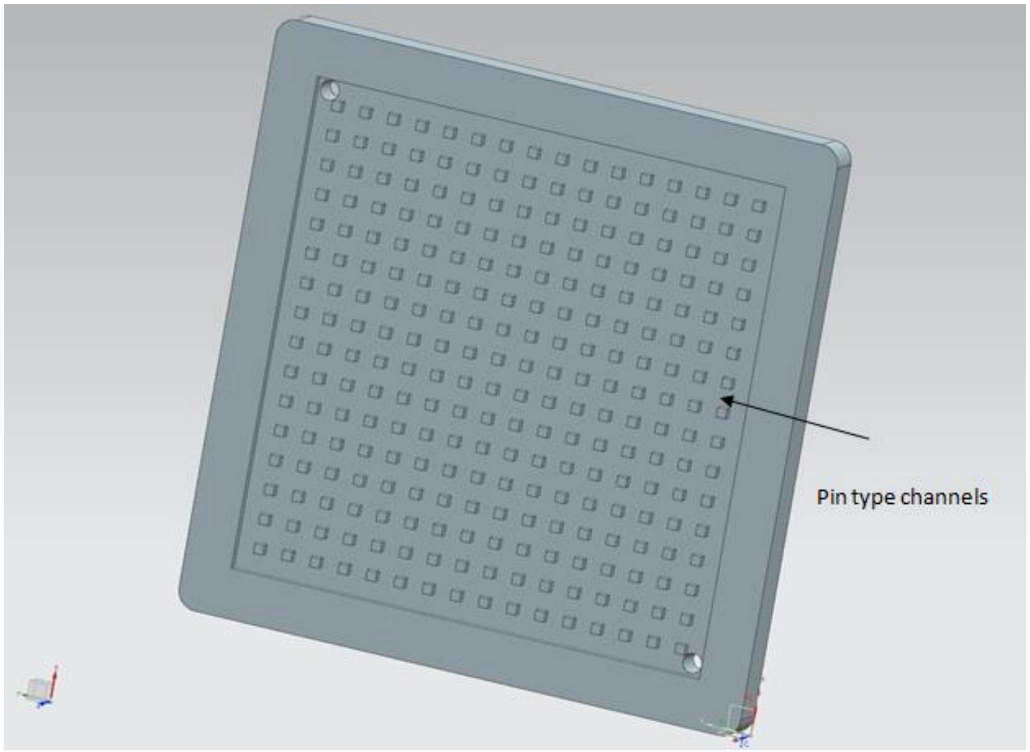

Figure 2.3: Flow plate with pin-type flow field design

Parallel/Straight Flow Fields - This type of flow field design (an example of which is shown in Figure 2.4) entails the gas flow field plate having a number of parallel flow channels which are also connected to the gas inlet and exhaust. This design while an improvement over pin-type, still exhibits stagnant regions of low flow velocity. This phenomenon is more pronounced when the inlet and exit are not located at the corners of the flow section. This leads to poor gas flow distribution, moisture accumulation and inadequate water removal, whereby the performance of the fuel cell is affected. Another aspect in this type of design is that there is low pressure loss in the flow channels due to their being small in length. Location of inlet and outlet in this design is important and good distribution of gases occurs only where they are located in the corners diagonally opposite to each other.

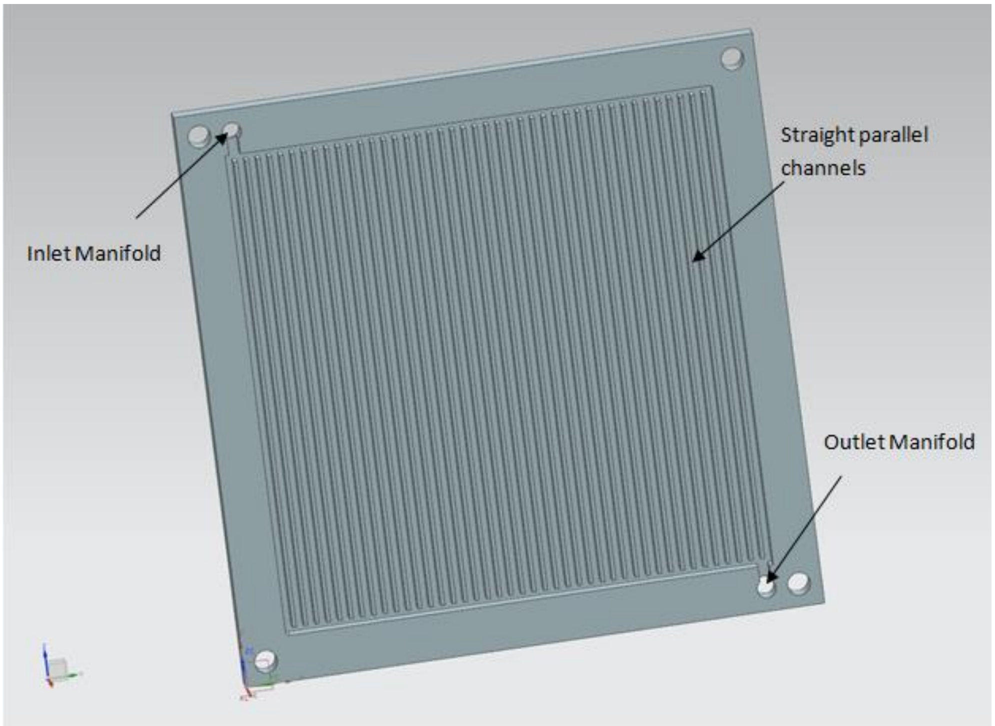

Figure 2.4: Flow plate with straight/parallel type flow field design

Serpentine Flow Field Designs - This design can be explained as a continuous flow section having an inlet at one end and an outlet at the other end, and follows a serpentine path with multiple 90^{o} bends altering the flow direction. This type of serpentine flow field forces the reactant gases to flow across the entire active area of the plate which in turn eliminates the stagnant areas caused by improper gas distribution. However, due to the relatively long flow path, a large pressure drop along the channels from the inlet to the outlet is induced which in certain cases (large flow plates) might be undesirable. An example is shown in Figure 2.5. One of the common problems in a single serpentine channel is that these long winding flow channels are more prone to getting blocked due to the formation of water droplets in the channels especially at higher current densities.

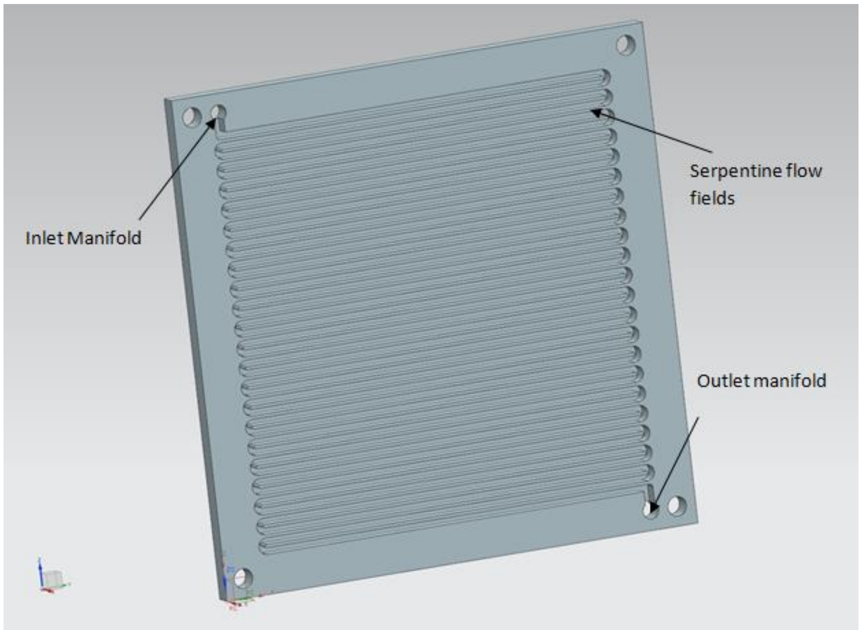

Figure 2.5: Plate with single serpentine flow field design

Therefore, for a higher current density operation or a large active area, it would be better to have multiple serpentine channels instead of a single channel. This reduces the length of the flow sections and thereby the pressure drop which in turn would help in the water management. Here, even if one channel is blocked, the fuel cell can still operate due to the presence of the other channels albeit with a lower efficiency. A multiple flow field design is shown in Figure 2.6.

Inter-Digitated Flow Field Design - All the previous designs investigated incorporated continuous flow channels from the inlet to the exit. Unlike the others, in this design the reactant gases flow from the inlet manifold to the outlet manifold via molecular diffusion through the gas diffusion layer where it also undergoes the required electrochemical reaction and generates electrons. One issue with this type of design is that molecular diffusion is a slow process which in turn would cause large concentration gradients of the reactants across the GDL's.

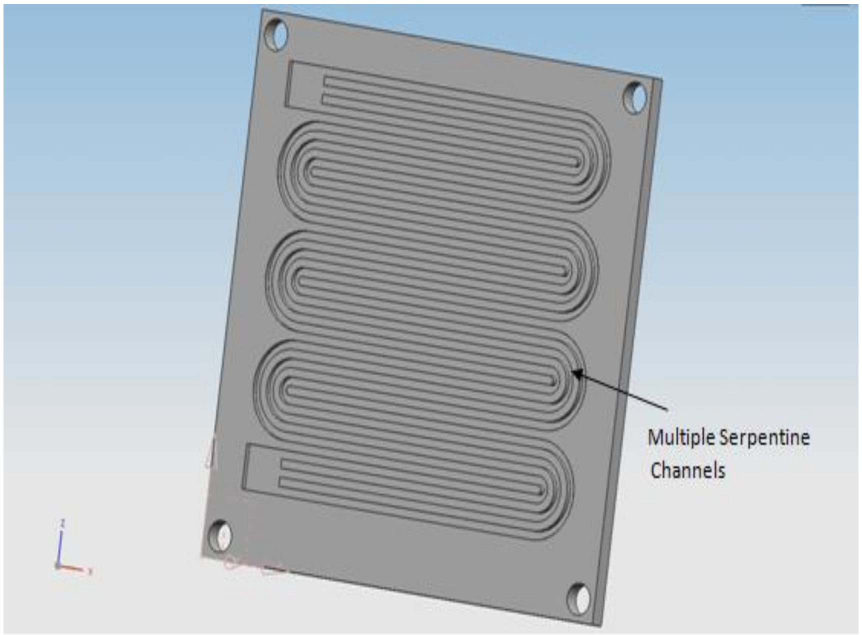

Figure 2.6: Plate with multiple serpentine flow field design

An inter-digitated system consists of dead ended channels on the active surface area. The channels are not continuous from the inlet manifolds to outlet manifolds. The reactant gases are made to diffuse under pressure through the MEA to reach the other channels connected to the outlet manifold thus developing a convection velocity in the MEA which would help in the removal of water formed. Therefore this type of design is effective in preventing flooding caused due to water formation and also provides better fuel cell output owing to increased reactant availability and usage. The mechanism can be better understood using Figure 2.7.

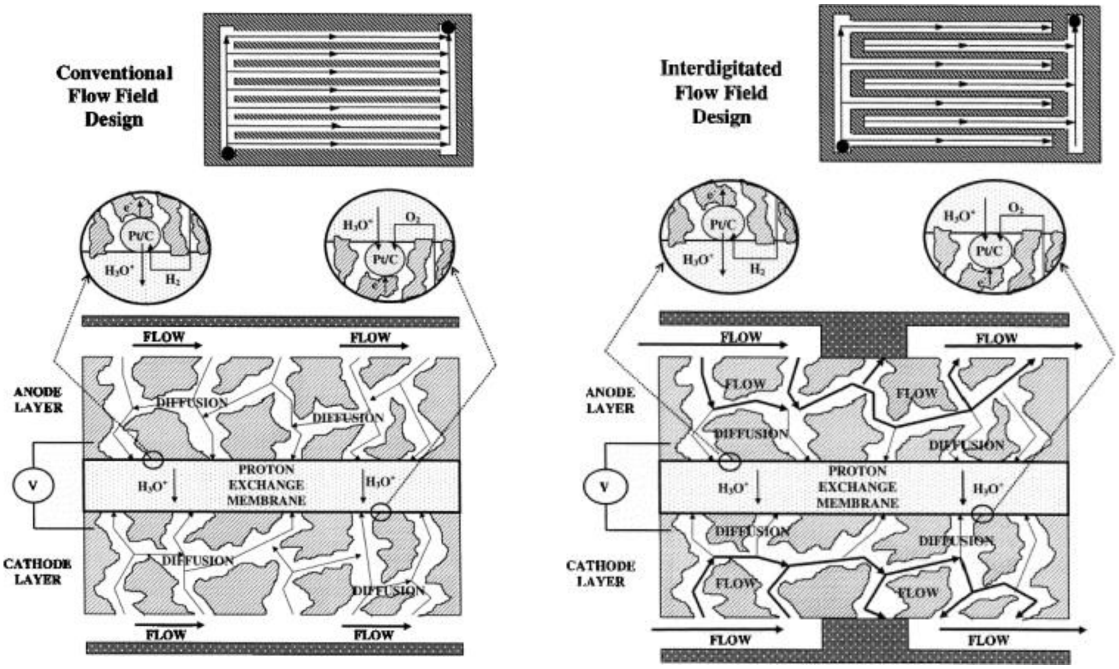

Figure 2.7: Mechanism of inter-digitated flow field design

2.3.A STUDY OF MATERIAL SAVINGS

One of the main goals for this project was minimization of the cost of the fuel cell and one avenue where this was possible was the reduction in the amount of material used in the manufacture of the flow plates. It was theorized that removing material in unwanted areas would reduce weight and material usage thereby reducing cost. As an example, the square plate shown in Figure 2.8 was modified to reduce weight as shown. In this case, material savings of about 16.5% were achieved.

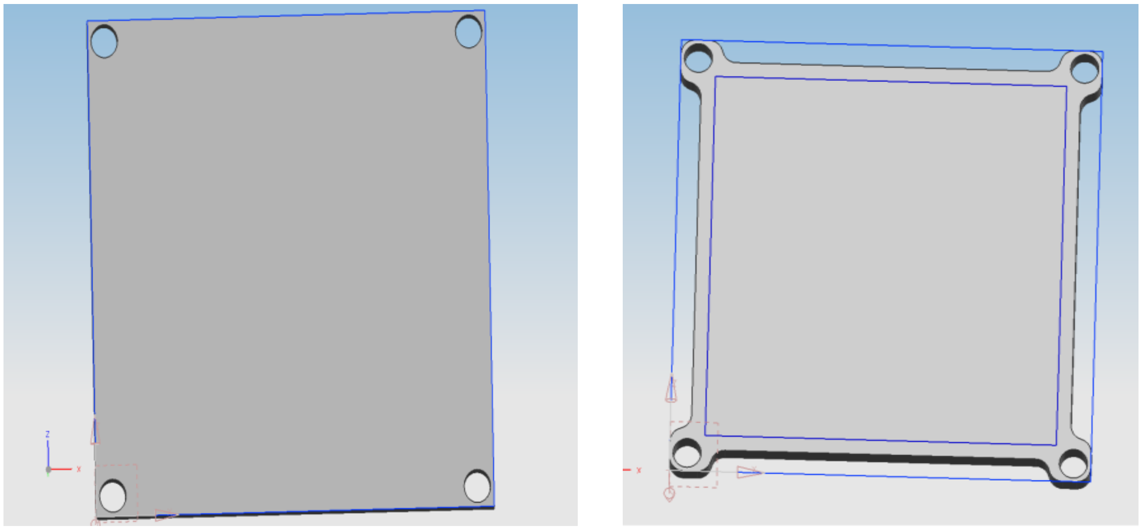

Figure 2.8: Material savings in a square bipolar plate

Multiple Serpentine Flow Field - After designing the plate and incorporating a multiple serpentine fuel flow channel design onto it, the same was successfully manufactured by an industrial partner, Megamet Solid Solutions (Figure 2.9). Upon experimental investigations of this design severe leakage of the reactant gas was noticed.

This plate was difficult to clamp and seal due to the non-availability of the extraneous area around the fluid flow sections for the purpose of including gaskets. The ears designed for the bolts proved insufficient and tended to break when too much force was employed to clamp the plates together.

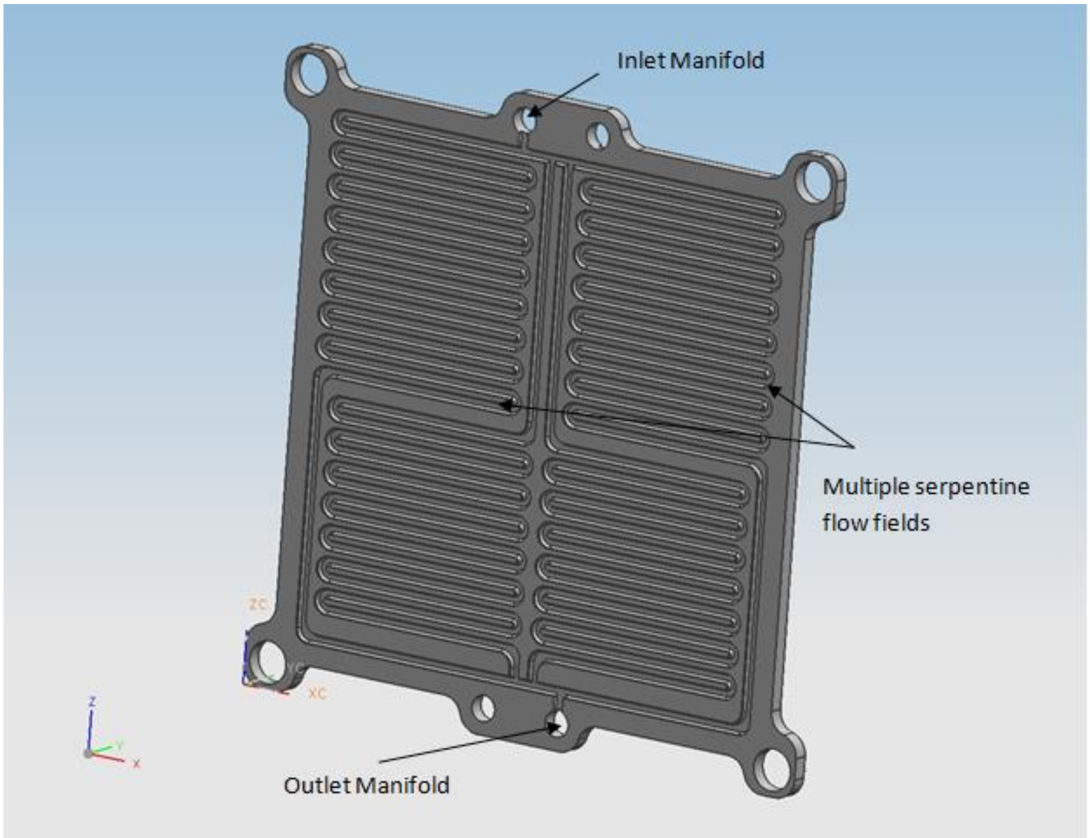

Figure 2.9: Bipolar plate with multiple serpentine flow fields

Although it produced significant material and cost savings, removal of the excess material proved detrimental to this project. It produced prototypes that systematically leaked hydrogen and thereby were unable to reach peak performance. Instead, carving grooves in the extraneous area for the purpose of placing the gaskets would help prevent leaks and also to make the plates structurally sound to withstand the clamping forces involved.

3. DESIGN STRATEGIES FOR SMALL PRISMATIC DESIGNS (HYBRID INTER-DIGITATED FLOW FIELDS)

The design indicated in Figure 3.1 incorporates the use of an exhaust channel totally isolated from the flow field channels of the bipolar plate and also a separate groove for the gasket, and includes all the lessons learnt from the literature and preliminary investigations. This design follows the same theory as that of the inter-digitated design. The major targets of this design were to improve, the sealing of the plates, the fuel distribution and the manufacturing ease. As seen Figure 3.2, the plate has a conventional straight/parallel flow field design but without the direct access to the outlet manifold. The reactant gas flows through the flow fields and into the MEA by molecular diffusion and then flows out into the exhaust groove and the outlet manifold.

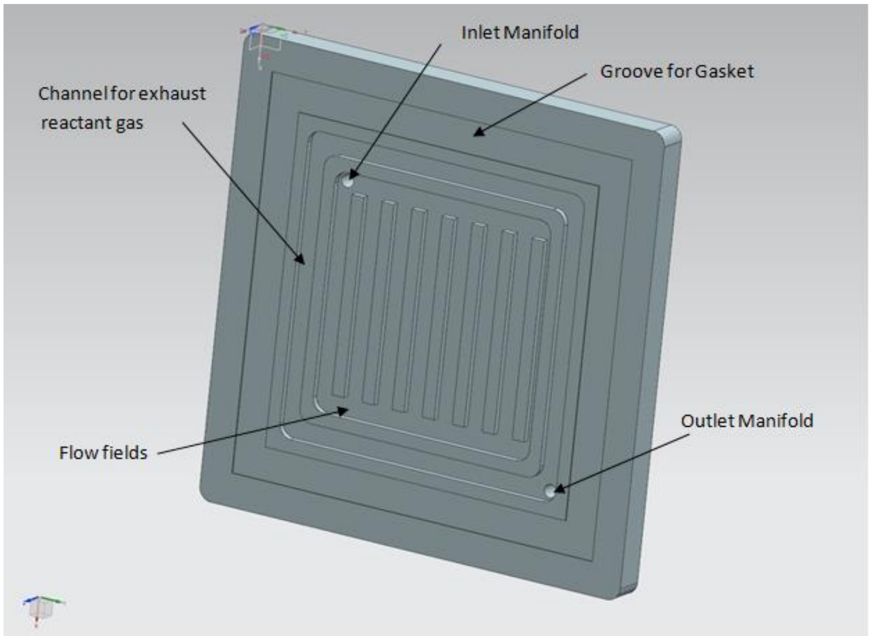

Figure 3.1: Hybrid Inter-digitated

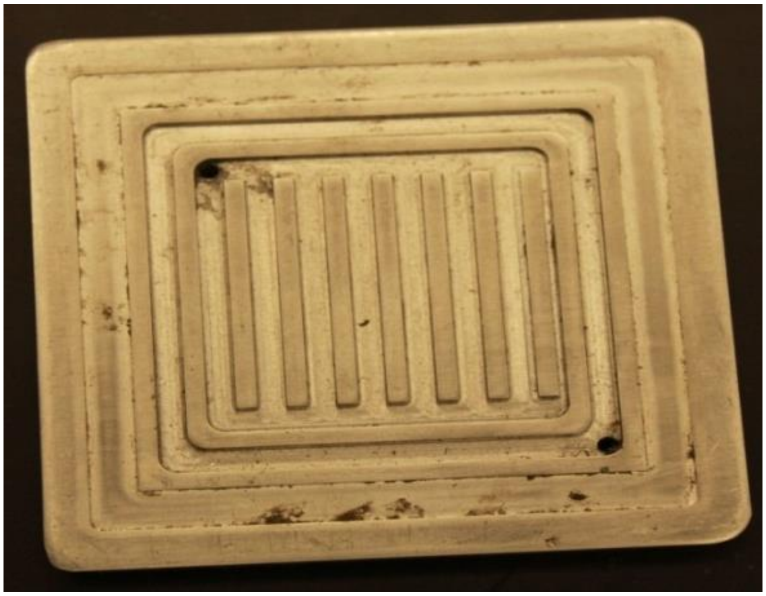

Figure 3.2: Machined prototype

This design increases the active area available for diffusion when compared to the inter-digitated design and also provides improved sealing as compared to the previous designs due to the polished surface and the dedicated groove for the gasket around the active area. The groove for the gasket is lesser in depth than the thickness of the gasket to ensure that on compression, the gasket (due to its elasticity) would flow outwards and fill all the gaps between contact surfaces and ensure sufficient sealing. Also to ensure proper fit and sealing between all the components, namely the bipolar plates and the clamp plates, all the contact surfaces were polished using sandpaper having grit size of 600, 800, 1000, 1500, 2000 and 2500. With the help of the gasket groove, exhaust groove and by improving the surface finish of the plates, a superior sealing was achieved.

3.1.ALTERNATE DESIGN IDEAS

While improvements to the conventional flat plate designs show promise, the logistics behind assembling and maintaining a seal along with the design and the manufacturing constraints involved, pose significant challenges. As an alternative, cylindrical designs as shown in Figure 3.3 were investigated.

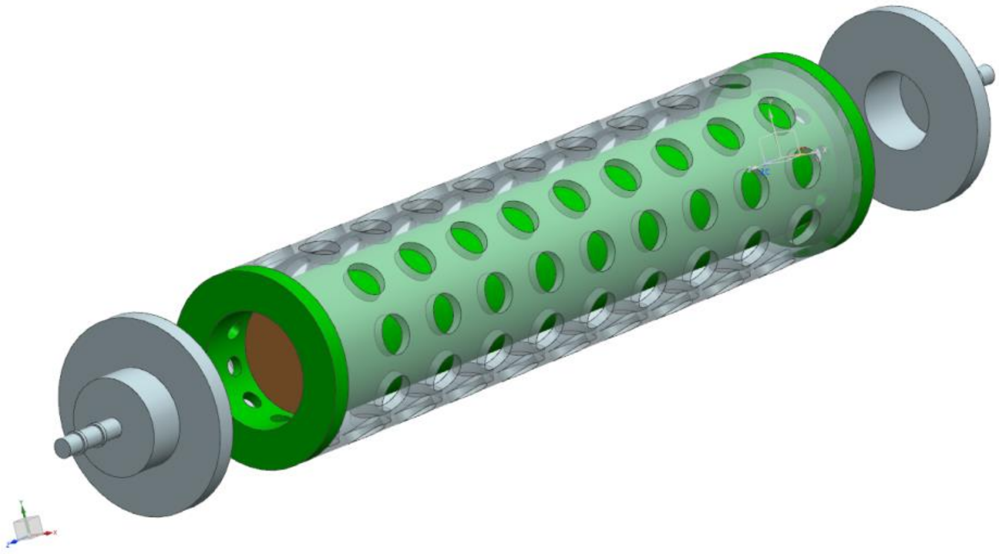

Figure 3.3: Conceptual design of cyclindrical fuel cell

They were theorized to possess significant advantages over the traditional flat plate designs including:

- Greater exposure to air
- Smaller form factor and improved aesthetics

- Lesser number of components to assemble. (Nut and bolt assembly significantly reduced)
- Ease of manufacture
- Lesser number and area of sections to seal

An example of such a design is shown in Figure 3.4.

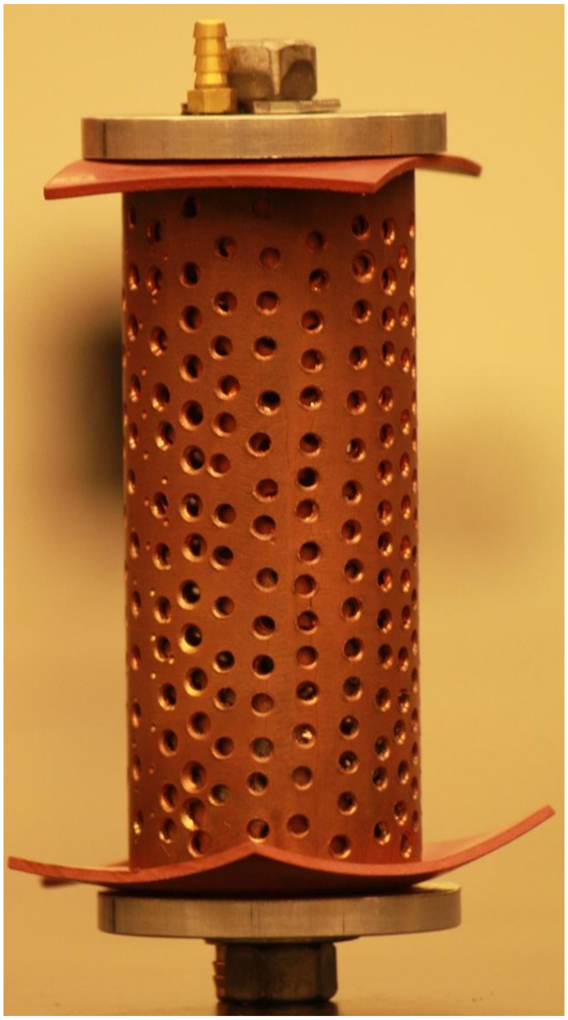

Figure 3.4: Cylindrical prototype with an active area of 120 square centimeters

The trend of this design is much removed from the traditional PEM design methodology. The design shown in Figure 3.4 includes reduced number of components, 13 to be exact. The traditional flat plate design had 46 major components in comparison. This made this new design much easier to manufacture and assemble. Also, even with a smaller form factor the active area of the cell is 120 square centimeters. For a traditional design to have a 120 square centimeter active area, the form factor would have been huge. The number of bolts required to clamp down a larger plate would be significantly higher and therefore the number of components and weight would also be larger. The next stage of this design process was making a working prototype with tighter tolerances and better materials. To make the design smaller and leak proof, the next prototype was constructed with a soldered internal cylindrical structure made from a single piece of drilled copper. The design is shown in Figure 3.5.

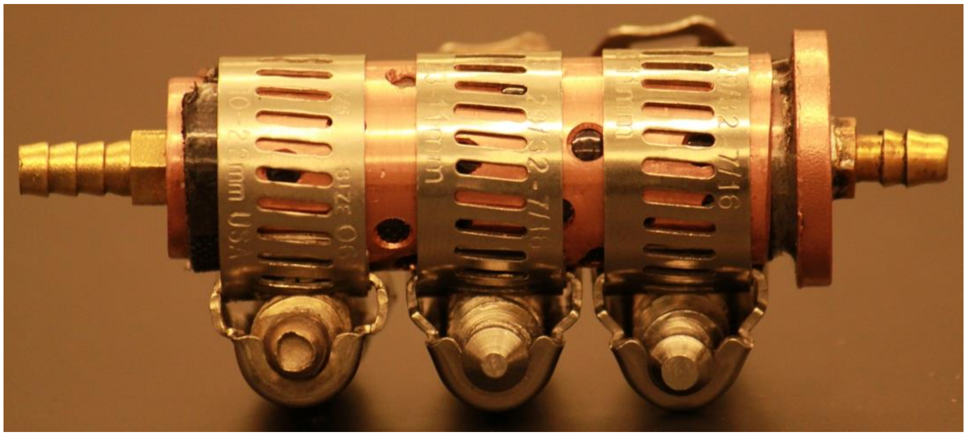

Figure 3.5: Cylindrical prototype with an active area of 25 square centimeters

The active area is 25 square centimeters and its form factor resembles the size of a small AA battery. The number of components in this design is 6. Therefore the manufacture and assembly issues are much less prevalent. All of these designs are proposed taking cost and manufacturing constraints into consideration. These designs were theorized to possess improved power densities without penalizing cost or increasing the manufacturing difficulty.

3.2.CHOICE OF MATERIALS

While the initial prototypes were made using metals, a major portion of the final prototypes were made using plastics. While improving power densities, the plastics also enabled the use of solvent welding and additive manufacturing. Additive manufacturing significantly benefitted the cost and complexity involved, while the use of solvent welding produced leak proof sealing. Some data of the plastics investigated and their solubility in organic solvents is shown in Table 3.1. The final choice of materials came to be ABS and polycarbonate owing to their favorable mechanical properties and softening temperatures coupled with their ability to be additively manufactured. Polycarbonate also exhibits solubility with every organic solvent on the list making it exceedingly flexible to use.

Table 3.1: Plastics and their solubility on organic solvents

S. No	**Plastic / Solvent**	1,2 Dichloro ethane	Acetone	Cyclo hexanone	Dichloro methane	Methyl ethyl ketone	Methyl benzene	Tetra hydrofuran
1	Polymethyl methacrylate (**Acrylic**)	X	X	X	X	X	X	X
2	Acrylonitrile butadiene styrene (**ABS**)	X	X	X		X		
3	Polyacetal (**Delrin – POM**)					X	X	
4	Cellulose acetate butyrate (**Butyrate**)							
5	Cross-linked low density polyethylene (**PEX**)	X	X		X		X	X
6	Low density polyethylene (**LDPE**)	X	X	X	X	X		
7	High density polyethylene (**HDPE**)	X	X			X	X	
8	Ultra high molecular weight polyethylene (**UHMW**)				X		X	
9	Nylon							
10	Polycarbonate	X	X	X	X	X	X	X
11	Polyethylene terephthalate (**PET**)	X	X		X			X
12	Polyethylene terephthalate glycol (**PETG**)	X	X	X	X	X	X	X
13	Polypropylene	X	X		X		X	
14	Polystyrene	X	X	X	X	X	X	X
15	Polyvinyl chloride (**PVC**)	X	X	X	X	X	X	X
16	Teflon (**PTFE**)							

PAPER

I. NON-PRISMATIC AIR-BREATHING FUEL CELLS – CONCEPT, THEORY, DESIGN, AND MANUFACTURING

Sriram Praneeth Isanaka[1]
Department of Mechanical Engineering
Missouri University of Science and Technology
1870 Miner Circle
Rolla, MO, 65401 USA
Email: sihyd@mst.edu

Frank F. Liou
Department of Mechanical Engineering
Missouri University of Science and Technology
1870 Miner Circle
Rolla, MO, 65401 USA
liou@mst.edu
ASME Membership (if applicable)

Joseph W. Newkirk
Department of Materials Science
Missouri University of Science and Technology
1870 Miner Circle
Rolla, MO, 65401 USA
Email: jnewkirk@mst.edu

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[1] Corresponding author.

1.1. ABSTRACT

This paper details the research into Axis Symmetric Architecture (ASA) Proton Exchange Membrane fuel cells (PEMFC) (possessing non-prismatic cylindrical architecture). Advantages of the ASA include increased fuel flow, reduced sealing area and weight, and increased power densities. Numerical and finite element studies will show improvements to flow characteristics. The ASA design facilitates natural convective flow to promote improved reactant availability and the prototypes created also show the ease of manufacture and assembly. ASA's unlike traditional fuel cells, do not require clamping plates and fastening mechanisms and lead to prototypes with reduced size, weight and cost.

1.2. INTRODUCTION

Over the last few decades PEM fuel cells have come a long way from their humble single cell beginnings. This is primarily due to the volume of research conducted in the areas of bipolar plates (graphite and metallic), polymer electrolyte membranes (nafion and polybenzimidazole), catalysis materials (platinum, iridium oxide, etc.) and fluid flow mechanics. Traditionally, fuel cells have been designed with flat flow field plates that govern their construction to make them bulky fastener intensive designs. This leads to significant manufacturing and assembly complexity, while also increasing the fuel cell's size and weight. The ASA design will address these inherent disadvantages by fundamentally changing the architecture of the design thus reducing the manufacturing and assembly constraints in PEM fuel cells.

Proton Exchange Membrane fuel cells use hydrogen and oxygen to produce electricity. Current designs are almost exclusively based on the flat plate sections where a proton conducting membrane is sandwiched between conductive plates which collect the electrons produced in the cell. The edges of the plates are sealed to prevent hydrogen leaks while ensuring that the opposing sides of the membrane remain electrically isolated. Stacks of these plates are assembled and aligned. Significant clamping force is then applied to the stacks to minimize electrical contact resistance and simultaneously produce sealing. In addition to these requirements, others like managing moisture on the air side, and managing heat (both insufficient and overly abundant) must also be met. To meet these challenges intricate flow designs are added to the plate surfaces to manage fuel, air flow, and exhaust moisture. Owing to the intricacy in the designs and the nature of the materials employed, these plates, even when made of commonly used graphite, add significant weight and manufacturing cost.

1.3. LITERATURE REVIEW AND RESEARCH NEED

The theory of fuel cells has been in existence for over a century and from their humble beginnings, they have always been envisioned as an ideal energy source [1, 2]. Fuel cells can lead to substantial energy savings. They can also help reduce imported petroleum and carbon emissions by acting as energy storage mechanisms [3]. A number of studies have been focused on numerical modelling and analysis of fuel cells. These detailed studies have led to fluid flow [4-7], thermal management [8-10], water management [11-13], and membrane electro-chemistry [14-16] improvements. Significant experimental research has also been conducted to validate transport phenomena [17-23], waste management [24, 25], corrosion [26], stack designs [27], and membrane performance [28-33]. Additional research areas included manufacturing [34], economics [35-37], applicability [38, 39], and alternate membrane materials [40-42]. The volume of research accomplished and material published might indicate that research avenues in PEMFC are dwindling. This research however has only been performed on prismatic flat plate designs. Limited research has been accomplished outside the purview of flat graphite flow plates, metallic end plates, and membrane sections. An unconventional design approach towards the geometry and materials involved in existing fuel cell research will lead to reactant flow improvements, complexity reduction in manufacturing and assembly, and also open fuel cell applicability into the portable realm. Recently, researchers have attempted to diversify the conventional design approach of PEMFC. For example, Blakely et al. [43] targeted portability with spiral winding, Bullecks et al. [44] developed cylindrical fuel cells, and Meyers et al. [45] tried to miniaturize PEMFC. A targeted approach that could lead to the realization of a non-prismatic design is proposed here. This approach could re-envision conventional rationale in the area of PEMFC shape, materials and functions. The concept of Axis Symmetric Architecture (ASA), along with a comparative assessment over conventional designs, is outlined in this paper. The advantages of this concept over the existing design methodology are discussed as well.

1.4. THEORY

A novel cylindrical design was proposed to reduce sealing, air-breathing, and assembly issues and thus target these aforementioned problems. Computer Aided Design (CAD) illustrations of the Axis Symmetric Architecture (ASA), a non-prismatic design envisioned for performance improvements and manufacturing ease, are presented in Figure 1. An inner cylinder in the ASA serves as a mandrel for the membrane assembly. This cylindrical configuration allows any hydrogen leaks to move toward the membrane.

One electrode (SS316 wire) is wrapped around the mandrel, and the polymer electrolyte membrane is then wrapped around this electrode. Another electrode (SS 316 wire) is wrapped next over the membrane. The entire design is then enveloped with an enclosure that serves as a permeable air source allowing the fuel cell to breathe from all sides. This new design, coupled with a choice of materials and reduced fastening requirements, provides significant advantages to the ASA which will be discussed in detail in forthcoming sections. Non-prismatic designs as shown in Figure 1 enjoy several hypothetical advantages including the following:

- *Improved reactant flow characteristics:* The ASA has been tailored to provide multi-point fuel entry into the flow field entry on the anode side while keeping design complexity and thereby manufacturing costs to a minimum. Also, investigations performed on serpentine designs indicate that ASA exhibits significantly less energy losses as compared to conventional designs. The inherent shape of the ASA (on the cathode side) is capable of creating a naturally convective flow for the circulation and availability of oxygen rich air.
- *Reduced manufacturing and assembly complexity:* Reducing the number of fasteners ensures assembly ease. Reducing the number of plates (flow and end plates) reduces manufacturing complexity. The flow field and the manifold design on the anode side of the ASA pose fewer design and manufacturing complexities than do conventional flat plate designs.
- *Improved sealing:* The ASA's shape by nature ensures that fewer sections are present through which hydrogen can leak. If utilized with cylindrical membranes, an ASA

design reduces sections that need sealing 50% more than flat plate designs (for the same active area).

- *Economics:* The extensive use of plastics in the ASA reduces expensive tooling requirements that are mandatory for graphite plates. It also reduces time of manufacture and thereby ensures low cost. With these reduced assembly costs and high power densities the ASA design becomes economical, aesthetic and safe.
- *Portability:* The choice of stainless steel wire winding and polycarbonate is important. These materials can provide better conductivity and strength than graphite-based designs while ensuring the design remains light. The ASA does away with end plates and cathode side flow plate. This design also significantly reduces the number of fasteners, ensuring both a small form factor and a low weight.

1.5. MATERIAL & METHOD

Assumptions made during this research include”

- The target application is for charging portable mobile devices like cellphones, tablets, GPS navigators, digital watches etc.
- The primary target variables are design novelty, reactant flow characteristics, economics, form factor & portability, and power-density.
- The design is air-breathing to reduce the need for storage and delivery of oxygen, which would add bulk, weight, complexity, and cost to the fuel cell.
- The research team is targeting any losses in performance owing to the use of air, with reduction in the weight, cost of manufacturing and assembly, and improved reactant availability.

- Conventional prismatic designs used as a comparison in this paper are flat plate PEM fuel cell designs which use graphite in the flow plates, and stainless steel 304 in the end plates.
- Simulations were performed to replicate 3-dimensional fluid dynamics in both the cathode and anode flow sections. The variables of importance were the velocity, temperature and mass fractions. Mesh independence was achieved in each case.
- CAD models were created in Unigraphics, meshing was completed in Gambit, solution generated in FLUENT, and post-processing was performed in Tecplot.
- Manufacturing processes used in the production of graphite flow plates and metal end plates (for conventional designs) are assumed to be CNC enabled machining operations.
- Prototypes of both the conventional prismatic design and the non-prismatic ASA were manufactured in-house and used to test for performance. Membranes were sourced from an external manufacturer.
- The membrane used for performance testing is nafion based with 0.5 mg platinum loading and was used with both the conventional design and the non-prismatic ASA. Both prototypes employed active membrane areas of 50 square centimeters.

1.6. CALCULATION

Simulation models of the cathode, anode and flow-channel cross-sections have been used to assess the fluid dynamics in both the ASA and conventional designs. The results from preliminary theoretical studies are discussed in this section.

1.6.1. Analytical Assessment of Fluid Flow in Both Conventional and ASA Designs Using Serpentine Channel Sections

Theoretically, non-prismatic designs have the ability to provide improved reactant flow characteristics over their conventional counterparts. Figure 2 and Figure 3 show serpentine flow channel designs in the conventional flat plate and ASA respectively. In fuel cell convention a serpentine flow channel is defined as a single lengthy flow path (alternating in direction across the active area of the plate) that connects the inlet and outlet. While the concept behind the serpentine in both cases remains the same, the nature of the flat plate and ASA lead to the creation of diverse designs with dramatically different radius of curvatures as shown in Figure 2 and Figure 3. The effect that these variations produce is seen in the energy losses in both cases. In Figure 2, the conventional flat plate facilitates the creation of a serpentine design with a long travel path and multiple 90^{o} elbow bends with small radii of curvature. This leads to significant major energy losses. In Figure 3 the serpentine design incorporated on the ASA produces a helical section with multiple 90^{o} turns with large radii of curvature. This produces significant minor energy losses.

A combination of the major and minor energy losses can be employed to determine the efficiency of flow that can be achieved in each of the designs. The energy loss for a flat plate flow channel (illustrated in Figure 2) can be computed from

$$\frac{4f_t\, L v^2}{2gD_h} + \sum_1^n (f_t\, L_e v^2/(2gD_h)) \tag{1}$$

The energy loss for an ASA flow channel (illustrated in Figure 3) can be computed from

$$\left\{\left((n-1)\left[0.25\pi f_t\left(\frac{r}{D_h}\right)+\left(0.5 f_t\frac{L_e}{D_h}\right)\right]\right)+f_t\frac{L_e}{D_h}\right\}*\frac{v^2}{2g} \tag{2}$$

The numerical values of equation 1 and equation 2 are calculated to be 2180.918 N.m/N and 408.24 N.m/N respectively. For the same active area (50 cm^2) and comparable length of travel, non-prismatic ASA designs are noticed to lose five times less energy than conventional designs. This supports the proposed theory and ensures that the energy of the fuel in these channels is not expended in travel alone. The fuel needs to possess sufficient energy to diffuse into the porous gas-diffusion layer and interact with the membrane to produce chemical action and electrical current. The ASA design encourages this with its minimal energy losses.

1.6.2. Simulating Cathode Side Fluid Flow

The preliminary Finite Element Method (FEM) simulations that were performed with FLUENT flow modeling software support the hypothesis of natural convective flow, as illustrated in Figure 4 and Table 1.

Air-breathing fuel cells are typically plagued by poor reactant dynamics on the cathode side. The ASA by virtue of its shape promotes natural convection to systematically bring oxygen-rich air to the immediate environment of the membrane. The tendency of hot air to rise and create a draft (producing a chimney effect) is theorized as one of the advantages of ASA. Flow sections with cross-sectional thicknesses of 1mm were designed and fluid flow simulations performed to analytically assess the occurrence of this convective phenomenon. The draft velocity values generated from the flow simulations performed using FLUENT are listed in Table 1. The maximum fuel cell temperature is retained at 75^{o}C due to the fact that Nafion membranes dehydrate beyond this temperature. The ASA will be employed in wide ranging atmospheric conditions, with differing temperatures and humidities because it has been designed to be an air-breathing and portable fuel cell. Hence, the simulations performed will detail their use in both common and also demanding environments.

Draft is produced in nearly all environments while it is more predominant at lower ambient air temperatures. This finding is expected, validating the basic concept of natural convection, which can be engineered into the ASA.

1.6.3. Simulating Anode Side Fluid Flow

During the course of the research the team performed 3D finite element modelling to simulate the flow of hydrogen through the anode flow fields for both conventional flat plate design and non-prismatic ASA. Conventional flat plate designs possess a single-point fuel entry and a single-point fuel exit. Thus, they are identified as restrictive flow systems that possess poor flow characteristics. The existence of stagnant sections (low velocity and mass flow regions as illustrated in Figure 5) confirms this observation. An analysis of both a conventional flat plate pin and a flat plate straight design produced stagnant flow regions. One of the solutions for this problem is a multi-point fuel entry and exit system. Although multi-point fuel entry and exit can be included in conventional designs, their inclusion, however would complicate the manifold’s design and manufacture. Implementing the multi-point design on flat plates is still no guarantee of uniform velocity zones and stream-lined flow.

The ASA (as shown in Figure 6) is not restricted by these problems. The nature of the ASA’s shape does not add manufacturing complexity when designing a multi-point inlet and exit system. It does, however, provide uniform, stream-lined fluid dynamics for any flow field design incorporated in the ASA. As proof of the uniform flow, both a pin-type and a straight-type design were used to analytically assess the ASA. The velocity and mass fraction profiles (indicated in Figure 7 and Figure 8) respectively prove the hypothesis.

1.6.4. Cross Sectional Analysis of Flow Channels

The FEA models analyzed as part of the conventional flat plate and the non-prismatic ASA also indicate that the cross-sections of the flow channels affect the dynamics of the fuel in the PEMFC. It was theorized that this was due to the frictional losses being more pronounced in certain cross-sections as compared to others. The flow channel cross-sections were studied to minimize frictional losses in the system. The cross-sections analyzed are represented in Figure 9. The maximum velocity profile of hydrogen passing through a rectangular and a semi-circular cross-section is shown in Table 2.

The analysis revealed the following:

- The channel’s depth and cross-section each impact the reactant’s flow (see table 2).
- Large amounts of gas present in deep channels is not utilized for chemical reaction but instead exhausted prematurely.
- Semi-circular channels provide improved reactant flow while utilizing less fuel.

1.7. RESULTS AND DISCUSSION

Based on the results obtained from finite element methods, two working prototypes, one each of the conventional design and ASA, were manufactured. Instead of the traditional graphite flow plates and metal end plates, the ASA uses a polycarbonate mandrel over which stainless steel – 316 (SS-316) electrodes are wrapped. The manufacturing complexity reduction, and cost benefits realized in the manufacture of the ASA prototype were determined and are discussed in this section.

1.7.1. Manufacturing and Assembly Complexity Reduction

To better understand the manufacturing and assembly complexity that is involved, Figure 10 and Figure 11 show assembly drawings of flat plate and ASA designs respectively. It is to be noted that since the flat plate design uses graphite and stainless steel extensively there will be requirements for a large number of high cost tooling such as (carbide) end mills and drill bits. It can also be seen in Figure 10 that owing to the large number of components there will be a significant number of alignment issues and hence the assembly and labor to make this design will be considerable. In comparison, in the ASA design the frame and end caps of the cylindrical fuel cell are made of polycarbonate, which being a softer material has less cutting requirements. Also, by wrapping the electrodes around the mandrel, which by nature is compressive the need for the nut and bolt assembly based fastening requirements is eliminated.

The stainless steel wire winding employed is a compressive assembly mechanism simultaneously achieving compression (by imparting force around the circumference of the ASA) and sealing, thereby minimizing contact resistance. Polycarbonate was chosen as the material for the ASA’s mandrel as it has a high softening temperature while retaining strength characteristics across the entire working temperature range of nafion membranes (highs of 75 C). SS–316 was chosen as the electrode material for its high corrosion resistance and excellent current conduction characteristics.

1.7.2. Component and Weight Reduction

A major factor in any design is the number and type of fasteners used. These fasteners not only increase the complexity but also significantly increase the number of components that go into the flat plate design as illustrated in Figure 10. Table 3 shows the number of components in the assembly of a flat plate fuel cell design, 47 to be exact. The large numbers of fasteners in this design are mandatory to ensure proper surface contact and also to reduce the contact electrical resistance inherent in this design. The insulating washers and sleeves are necessary to ensure that the cathode and anode plates are electrically isolated from one another and will never come in contact to produce a short (direct contact between the anode and the cathode for electron transfer). In comparison (Figure 11), the ASA design has a vastly reduced component list of just 10. This will produce a drastic reduction in the assembly time and labor requirements and will reduce costs. The number of fasteners in this design is significantly lesser than the flat plate design because the SS-316 electrode wrapping by nature is a compressive design and will reduce contact resistance. Two sets of these windings will ensure sufficient surface contact without the need for excessive fasteners and their insulating elements.

In the flat plate, design metal and graphite are used to ensure solid construction and a design that has good contact and conductivity without the tendency to bow. The choice of material also has to be SS-316 which has a much higher corrosion resistance while having good electrical properties as compared to other materials like aluminum and copper. The weight of the flat plate design made in house was measured to be close to 2875 grams. This makes the design extremely bulky and to overcome this issue the frame of the cylindrical design is made out of polycarbonate. The use of stainless steel is restricted to the wire winding which makes the total weight of cylindrical design approximately 180 grams. The extensive use of polycarbonate ensures that this design is much lighter, making it extremely portable and ideal for mobile applications.

1.7.3. Comparison of Economics Between the Designs

The choice of materials and its small form factor enables the ASA to save significantly on the raw material and machining costs. The ASA also does not require the high cost carbide tooling that conventional flat plate designs require to machine metal and graphite. Owing to use of significantly less fasteners and reduced assembly times, the labor cost of the ASA is also lower. Currently the ASA requires assembly fixturing which adds an extra component to its total cost, but as this design matures and more prototypes are made this cost can be negated. Since the membrane in both fuel cells is to be the same its cost is not included in this analysis. Table 4 shows the comparison of manufacturing costs between conventional and ASA designs.

Greater economics can be realized by eliminating the use of machining to manufacture the ASA. The central component of the ASA, the mandrel is made of polycarbonate. By choosing processes like injection molding and additive manufacturing the ASA can be more economically manufactured as compared to the data in Table 4, which is derived from CNC enabled machining. Conventional designs though cannot claim this advantage as long as they utilize metal and graphite in their construction. Their manufacture will always be restricted by high-cost tooling, and CNC enabled machining.

1.7.4. Assessment of the Sealing and Performance Characteristics

The credibility of any fuel cell system relies on its efficiency and safety. If the design is incapable of retaining the seal between the hydrogen flow section and the membrane it will exhibit systematic drops in performance, and will be incapable of reaching steady state. Any leakage of hydrogen is also potentially dangerous to the user with hydrogen's flammability factors ranging from 5%-75%. Therefore both the prototypes manufactured were tested for hydrogen leaks over extended periods of continuous operation. They did not exhibit leaks or drops in voltage and power during the course of multiple tests. The results of tests are discussed in Table 5.

While the ASA at its current power output lags behind traditional fuel cell designs in a direct comparison of power outputs, due to the significant savings in weight and mass, the ASA achieves 4 times the power density of conventional fuel cells. The research team's aim is to improve power output with further research and reduce weight and size by improving manufacturing practices.

1.8. CONCLUSIONS

Mass transport finite element analysis has been employed in both the designs to assess preliminary feasibility of concept. A variety of flow field configurations have been assessed during the course of this research including pin-type, straight/parallel channels, and serpentine channels. It is to be noted that the design alone is not a guarantee for the successful operation of the fuel cell. Manufacturing and proper assembly is of equal importance which will ensure sealing between the electrode and the MEA while eliminating shorts. If the cell is prone to reactant leakage it will exhibit performance drops and will be unable to reach a steady state thereby reducing its efficiency and also leading to a hazardous environment for the user. Manufacturability and economic assessments were made on conventional flat plate designs and the modifications that were proposed to the design, materials and assembly, lead to the development of non-prismatic ASA design. Non-prismatic designs that were conceptualized and built show that lighter, smaller fuel cells can be made and have the potential to become the ideal portable power choice. Working single cell prototypes weighing 180 grams have been developed. They have been shown to work, have a low form factor and high power densities, and very favorable economics. The authors are currently working to improve the performance of the existing design and also investigating avenues for scaling up to multi cell designs that will be suitable for other applications.

1.9. ACKNOWLEDGMENT

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1.10. FUNDING

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Intelligent Systems Center (ISC), Missouri University of Science and Technology

1.11. NOMENCLATURE

f_t	friction factor (computed from the kinematic viscosity of hydrogen and pipe roughness of polycarbonate)
L	length of the pipe section without bends, m
v	velocity of flow, m/s
g	acceleration due to gravity, m/s^2
D_h	hydraulic diameter, m
n	number of 90^o elbow bends through the pipe section
L_e	length of each elbow bend, m
r	the radius of curvature of the bend sections, m

1.12. REFERENCES

[1] Farooque, M., and Maru, H. C., 2001, "Fuel Cells - The Clean and Efficient Power Generators," Proceedings of the IEEE, 89(12), pp. 1819-1829.

[2] Prater, K. B., 1994, "Polymer electrolyte fuel cells: a review of recent developments," Journal of Power Sources, 51(1-2), pp. 129-144.

[3] Smith, W., 2000, "Role of fuel cells in energy storage," J Power Sources, 86(1), pp. 74-83.

[4] He, W., Yi, J. S., and Van Nguyen, T., 2000, "Two-phase flow model of the cathode of PEM fuel cells using interdigitated flow fields," AIChE Journal, 46(10), pp. 2053-2064.

[5] Jeon, D. H., Greenway, S., Shimpalee, S., and Van Zee, J. W., 2008, "The effect of serpentine flow-field designs on PEM fuel cell performance," International Journal of Hydrogen Energy, 33(3), pp. 1052-1066.

[6] Nguyen, P. T., Berning, T., and Djilali, N., 2004, "Computational model of a PEM fuel cell with serpentine gas flow channels," Journal of Power Sources, 130(1-2), pp. 149-157.

[7] Wang, Z. H., Wang, C. Y., and Chen, K. S., 2001, "Two-phase flow and transport in the air cathode of proton exchange membrane fuel cells," Journal of Power Sources, 94(1), pp. 40-50.

[8] Rowe, A., and Li, X., 2001, "Mathematical modeling of proton exchange membrane fuel cells," Journal of Power Sources, 102(1-2), pp. 82-96.

[9] Shan, Y., and Choe, S. Y., 2005, "A high dynamic PEM fuel cell model with temperature effects," Journal of Power Sources, 145(1), pp. 30-39.

[10] Sivertsen, B. R., and Djilali, N., 2005, "CFD-based modelling of proton exchange membrane fuel cells," Journal of Power Sources, 141(1), pp. 65-78.

[11] Baschuk, J. J., and Li, X., 2000, "Modelling of polymer electrolyte membrane fuel cells with variable degrees of water flooding," J Power Sources, 86(1), pp. 181-196.

[12] Li, X., Sabir, I., and Park, J., 2007, "A flow channel design procedure for PEM fuel cells with effective water removal," Journal of Power Sources, 163(2), pp. 933-942.

[13] You, L., and Liu, H., 2002, "A two-phase flow and transport model for the cathode of PEM fuel cells," International Journal of Heat and Mass Transfer, 45(11), pp. 2277-2287.

[14] Mann, R. F., Amphlett, J. C., Hooper, M. A. I., Jensen, H. M., Peppley, B. A., and Roberge, P. R., 2000, "Development and application of a generalized steady-state electrochemical model for a PEM fuel cell," J Power Sources, 86(1), pp. 173-180.

[15] Um, S., and Wang, C. Y., 2004, "Three-dimensional analysis of transport and electrochemical reactions in polymer electrolyte fuel cells," Journal of Power Sources, 125(1), pp. 40-51.

[16] Wang, C., Nehrir, M. H., and Shaw, S. R., 2005, "Dynamic models and model validation for PEM fuel cells using electrical circuits," IEEE Transactions on Energy Conversion, 20(2), pp. 442-451.

[17] Bazylak, A., Sinton, D., Liu, Z. S., and Djilali, N., 2007, "Effect of compression on liquid water transport and microstructure of PEMFC gas diffusion layers," Journal of Power Sources, 163(2), pp. 784-792.

[18] Pharoah, J. G., 2005, "On the permeability of gas diffusion media used in PEM fuel cells," Journal of Power Sources, 144(1), pp. 77-82.

[19] Shimpalee, S., Greenway, S., and Van Zee, J. W., 2006, "The impact of channel path length on PEMFC flow-field design," Journal of Power Sources, 160(1), pp. 398-406.

[20] Shimpalee, S., and Van Zee, J. W., 2007, "Numerical studies on rib & channel dimension of flow-field on PEMFC performance," International Journal of Hydrogen Energy, 32(7), pp. 842-856.

[21] Spernjak, D., Prasad, A. K., and Advani, S. G., 2007, "Experimental investigation of liquid water formation and transport in a transparent single-serpentine PEM fuel cell," Journal of Power Sources, 170(2), pp. 334-344.

[22] Wang, L., Husar, A., Zhou, T., and Liu, H., 2003, "A parametric study of PEM fuel cell performances," International Journal of Hydrogen Energy, 28(11), pp. 1263-1272.

[23] Wang, L., and Liu, H., 2004, "Performance studies of PEM fuel cells with interdigitated flow fields," Journal of Power Sources, 134(2), pp. 185-196.

[24] Kandlikar, S. G., and Lu, Z., 2009, "Thermal management issues in a PEMFC stack - A brief review of current status," Applied Thermal Engineering, 29(7), pp. 1276-1280.

[25] Satija, R., Jacobson, D. L., Arif, M., and Werner, S. A., 2004, "In situ neutron imaging technique for evaluation of water management systems in operating PEM fuel cells," Journal of Power Sources, 129(2), pp. 238-245.

[26] Tang, H., Qi, Z., Ramani, M., and Elter, J. F., 2006, "PEM fuel cell cathode carbon corrosion due to the formation of air/fuel boundary at the anode," Journal of Power Sources, 158(2 SPEC. ISS.), pp. 1306-1312.

[27] Hamelin, J., Agbossou, K., Laperrière, A., Laurencelle, F., and Bose, T. K., 2001, "Dynamic behavior of a PEM fuel cell stack for stationary applications," International Journal of Hydrogen Energy, 26(6), pp. 625-629.

[28] Borup, R. L., Davey, J. R., Garzon, F. H., Wood, D. L., and Inbody, M. A., 2006, "PEM fuel cell electrocatalyst durability measurements," Journal of Power Sources, 163(1 SPEC. ISS.), pp. 76-81.

[29] Cai, M., Ruthkosky, M. S., Merzougui, B., Swathirajan, S., Balogh, M. P., and Oh, S. H., 2006, "Investigation of thermal and electrochemical degradation of fuel cell catalysts," Journal of Power Sources, 160(2 SPEC. ISS.), pp. 977-986.

[30] Collier, A., Wang, H., Zi Yuan, X., Zhang, J., and Wilkinson, D. P., 2006, "Degradation of polymer electrolyte membranes," International Journal of Hydrogen Energy, 31(13), pp. 1838-1854.

[31] Colón-Mercado, H. R., and Popov, B. N., 2006, "Stability of platinum based alloy cathode catalysts in PEM fuel cells," Journal of Power Sources, 155(2), pp. 253-263.

[32] Curtin, D. E., Lousenberg, R. D., Henry, T. J., Tangeman, P. C., and Tisack, M. E., 2004, "Advanced materials for improved PEMFC performance and life," J Power Sources, 131(1-2), pp. 41-48.

[33] Qi, Z., He, C., and Kaufman, A., 2002, "Effect of CO in the anode fuel on the performance of PEM fuel cell cathode," Journal of Power Sources, 111(2), pp. 239-247.

[34] Kim, H., Subramanian, N. P., and Popov, B. N., 2004, "Preparation of PEM fuel cell electrodes using pulse electrodeposition," Journal of Power Sources, 138(1-2), pp. 14-24.

[35] Barbir, F., and Gómez, T., 1997, "Efficiency and economics of proton exchange membrane (PEM) fuel cells," International Journal of Hydrogen Energy, 22(10-11), pp. 1027-1037.

[36] Bar-On, I., Kirchain, R., and Roth, R., 2002, "Technical cost analysis for PEM fuel cells," Journal of Power Sources, 109(1), pp. 71-75.

[37] Lipman, T. E., Edwards, J. L., and Kammen, D. M., 2004, "Fuel cell system economics: Comparing the costs of generating power with stationary and motor vehicle PEM fuel cell systems," Energy Policy, 32(1), pp. 101-125.

[38] Chalk, S. G., Miller, J. F., and Wagner, F. W., 2000, "Challenges for fuel cells in transport applications," J Power Sources, 86(1), pp. 40-51.

[39] Cleghorn, S. J. C., Ren, X., Springer, T. E., Wilson, M. S., Zawodzinski, C., Zawodzinski, T. A., and Gottesfeld, S., 1997, "PEM fuel cells for transportation and stationary power generation applications," International Journal of Hydrogen Energy, 22(12), pp. 1137-1144.

[40] Nallathambi, V., Lee, J. W., Kumaraguru, S. P., Wu, G., and Popov, B. N., 2008, "Development of high performance carbon composite catalyst for oxygen reduction reaction in PEM Proton Exchange Membrane fuel cells," Journal of Power Sources, 183(1), pp. 34-42.

[41] Wang, B., 2005, "Recent development of non-platinum catalysts for oxygen reduction reaction," Journal of Power Sources, 152(1-2), pp. 1-15.

[42] Wood, T. E., Tan, Z., Schmoeckel, A. K., O'Neill, D., and Atanasoski, R., 2008, "Non-precious metal oxygen reduction catalyst for PEM fuel cells based on nitroaniline precursor," Journal of Power Sources, 178(2), pp. 510-516.

[43] Blakley, T. J., Jayne, K. D., and Kimble, M. C., "Spiral-wound PEM fuel cells for portable applications," Proc. Proton Exchange Membrane Fuel Cells 6 - 210th Electrochemical Society Meeting, pp. 1187-1195.

[44] Bullecks, B., Rengaswamy, R., Bhattacharyya, D., and Campbell, G., 2011, "Development of a cylindrical PEM fuel cell," International Journal of Hydrogen Energy, 36(1), pp. 713-719.

[45] Meyers, J. P., and Maynard, H. L., 2002, "Design considerations for miniaturized PEM fuel cells," Journal of Power Sources, 109(1), pp. 76-88.

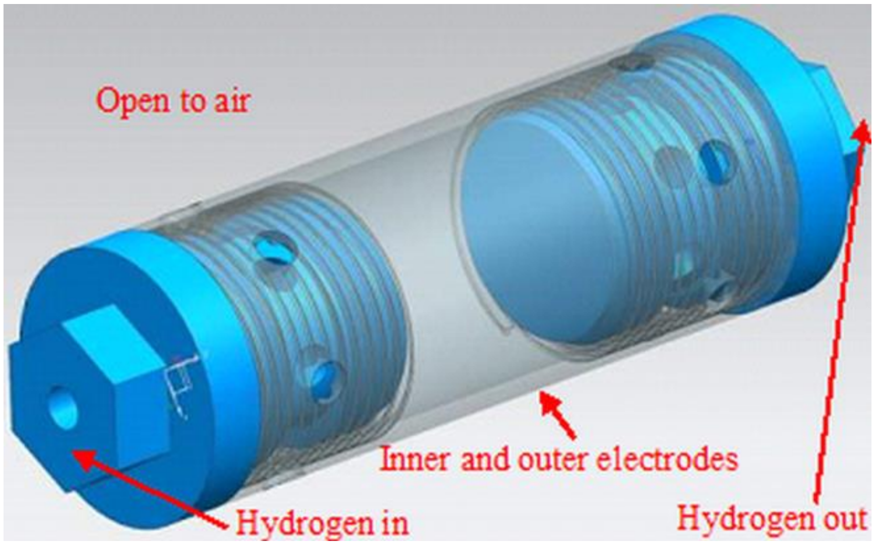

Figure 1: CAD model section of the ASA

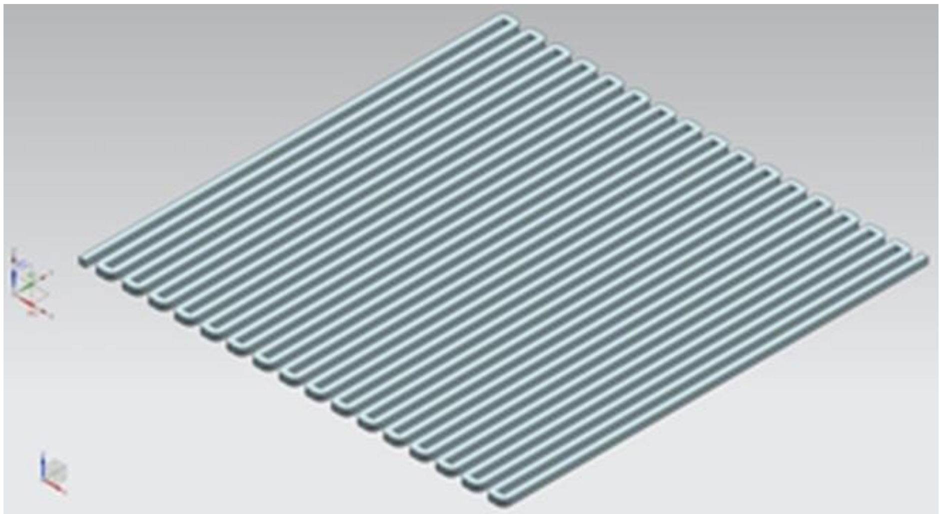

Figure 2: Serpentine flow sections with multiple 90º elbow bends

Figure 3: Helical flow sections with multiple 90º elbow bends

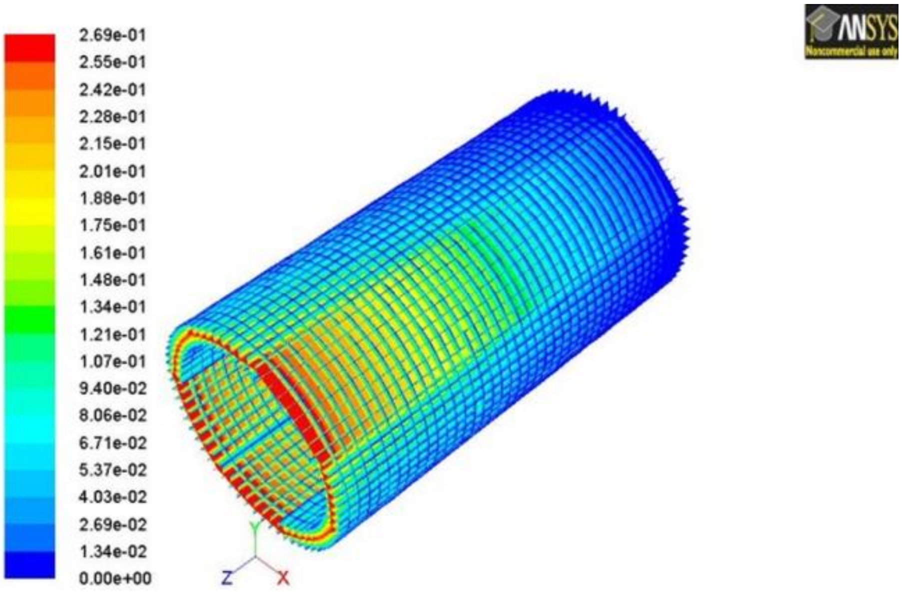

Figure 4: Velocity diagram indicating the occurrence of the natural convective flow

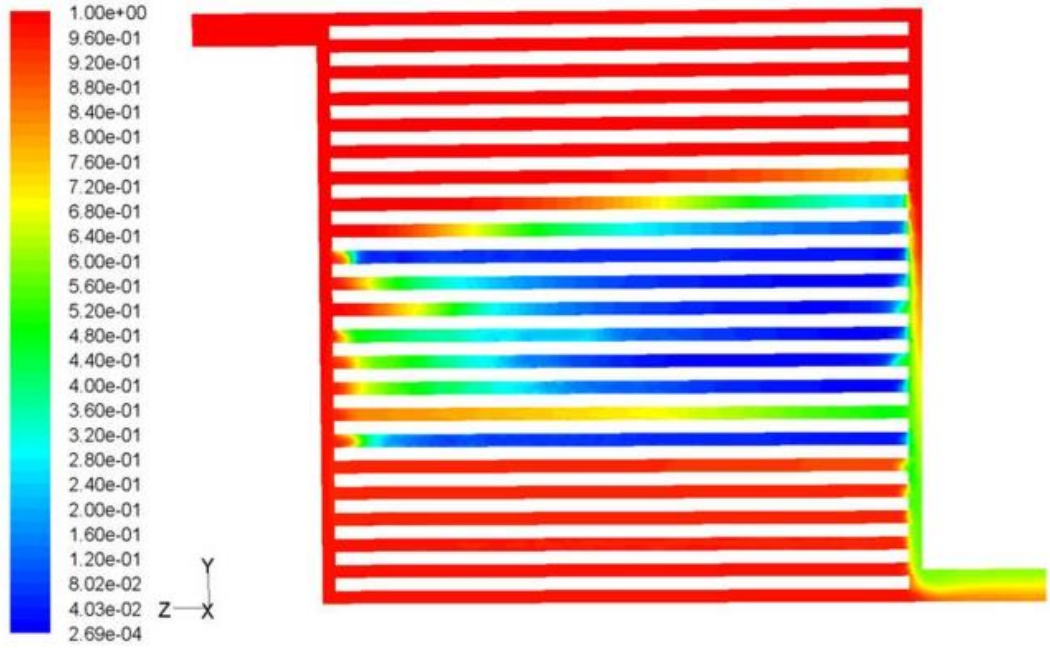

Figure 5: Mass fraction in straight channel flow field on conventional flat plate design (Single point fuel entry and exit, indicating stagnant zones as seen by all zones other than red)

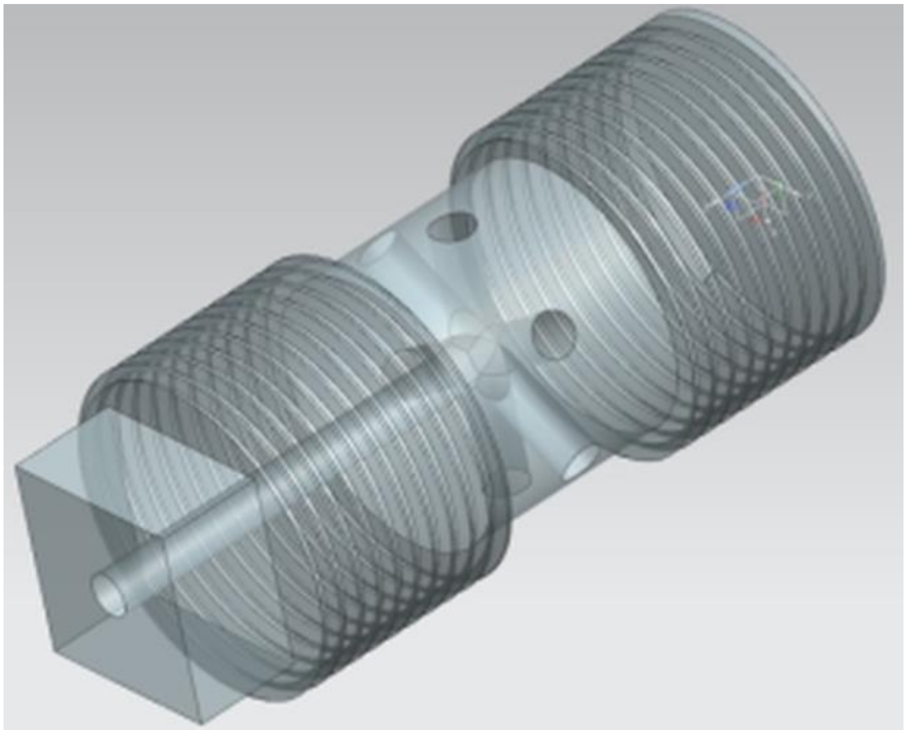

Figure 6: Internal view of manifold design in ASA (Multi point entry and exit of fuel with limited manufacturing complexity)

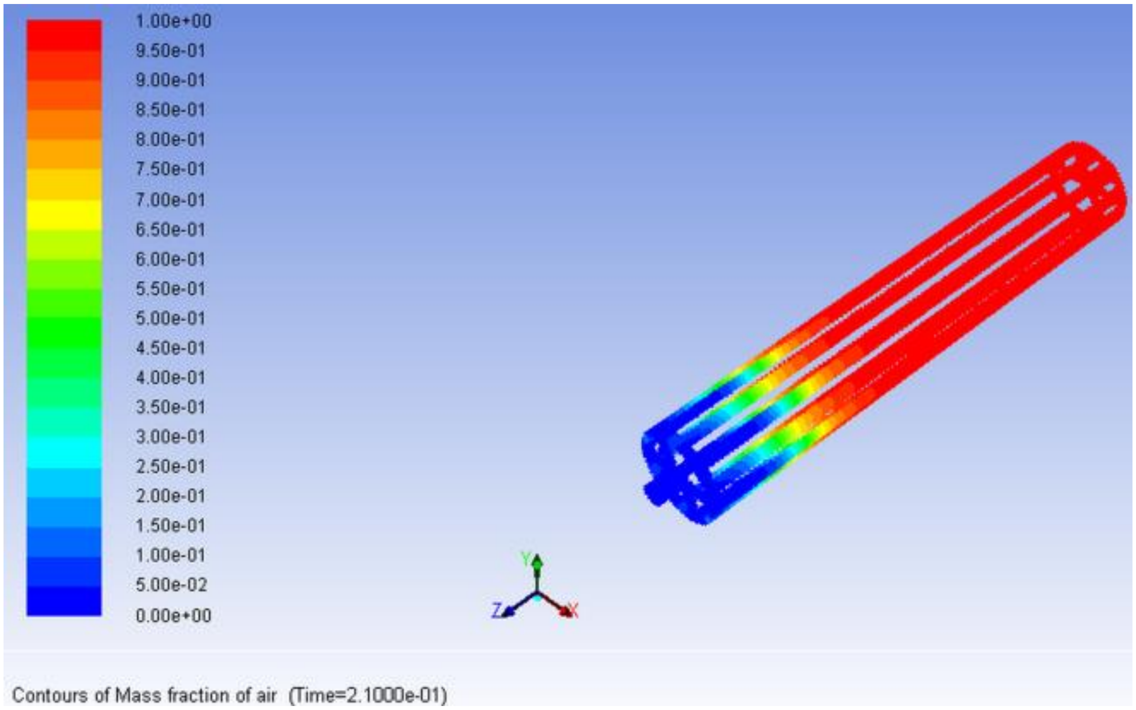

Figure 7: Straight channel design in ASA indicating mass fractions of hydrogen and air

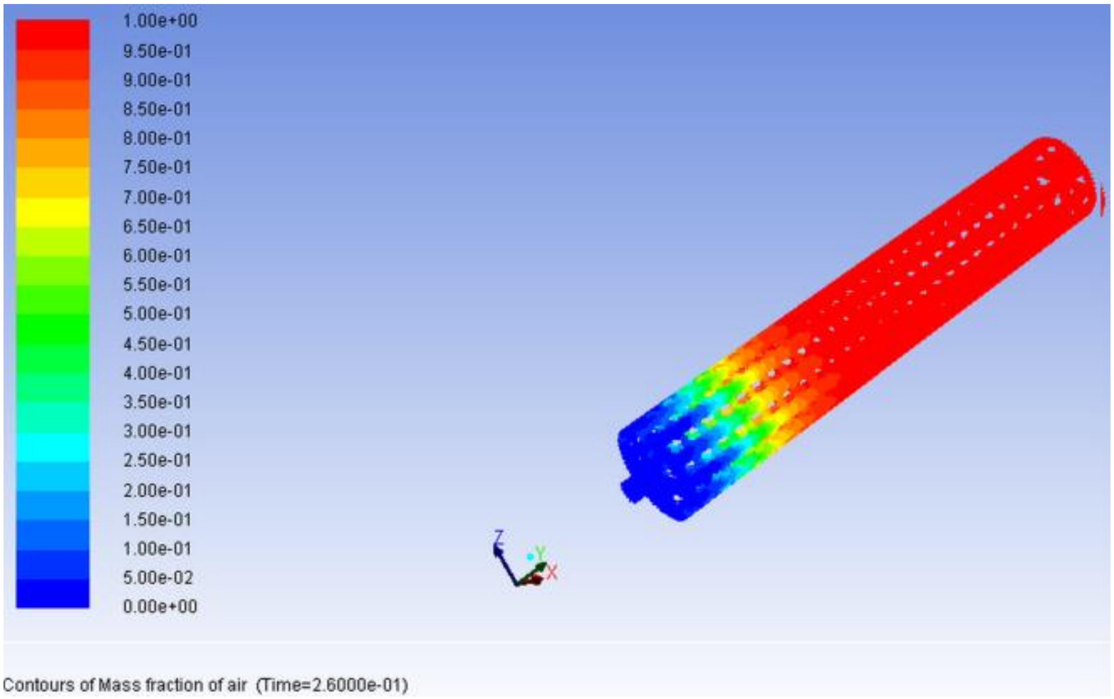

Figure 8: Pin channel design in ASA indicating mass fractions of hydrogen and air

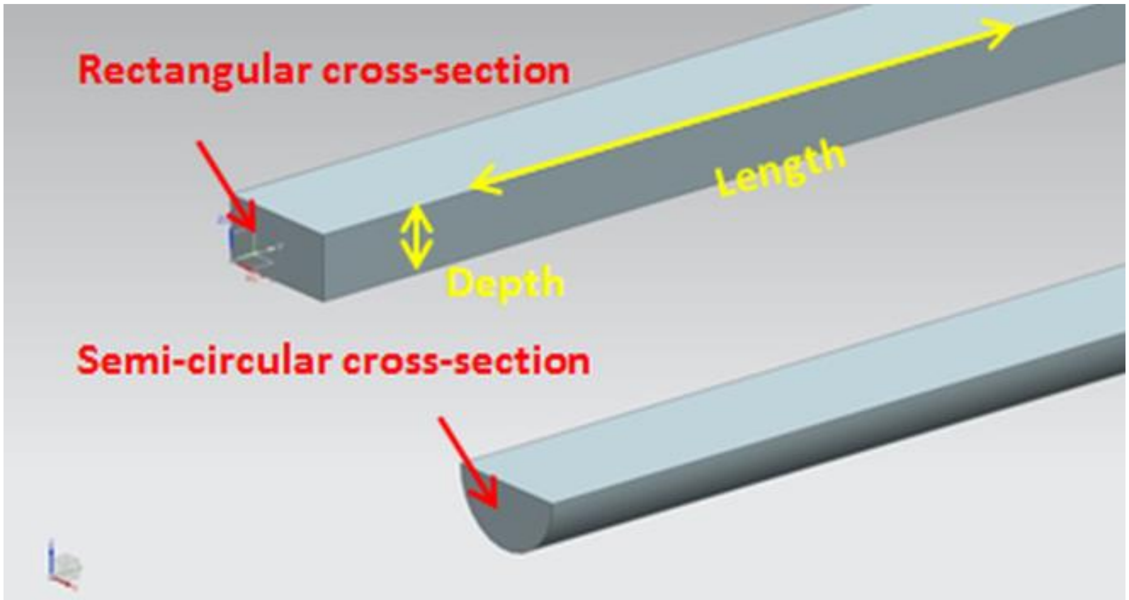

Figure 9: CAD representation of cross-sections in straight channel designs

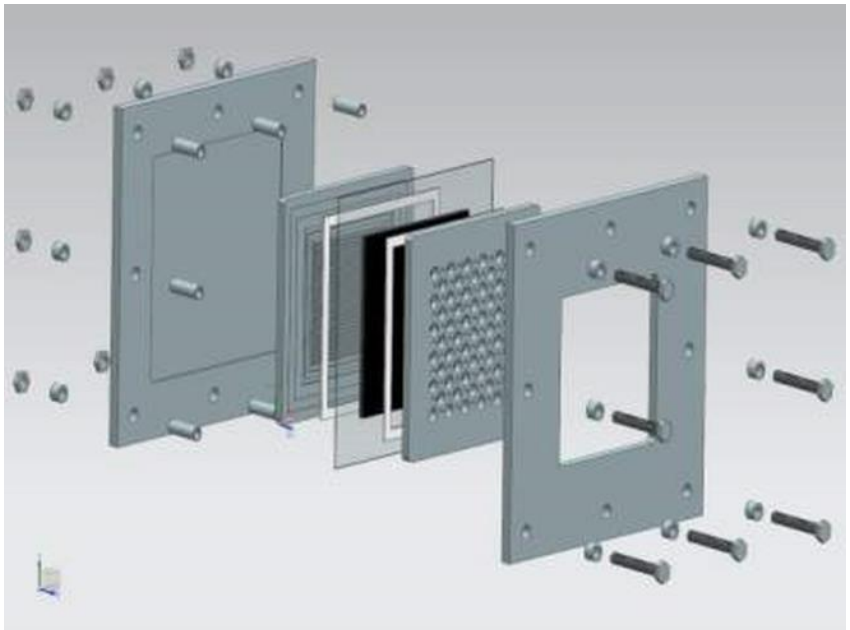

Figure 10: Assembly drawing of flat plate design

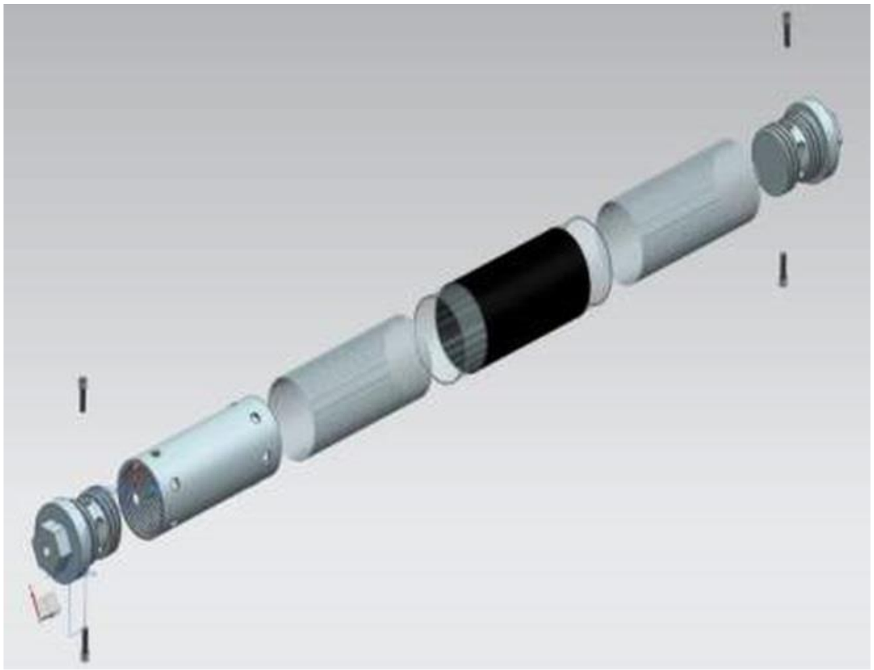

Figure 11: Assembly drawing of ASA

Table 1: **Convective air velocity produced at various ambient temperatures generated using FLUENT**

S. No	Fuel cell temperature (C)	Ambient air temperature (C)	Maximum draft velocity produced (mm/s)
1	75	-50	270
2	75	-25	190
3	75	0	160
4	75	25	110
5	75	50	50

Table 2: Flow of hydrogen in a fuel cell design

Channel Design	Cross section	Velocity (m/s)	Time taken (seconds)
Straight channel	Semi-circular	8.92	1.7
Straight channel	Rectangular	8.92	2.3

Table 3: Comparison of component and weight reduction between conventional flat plate and ASA designs

Type of design	**Material of construction**	**No. of components**	**Weight (gms)**
Conventional	SS–316/ graphite	47	2875
ASA	Polycarbonate/ SS-316	10	181
Percentage reduction in number of components			**78.7 %**
Percentage reduction in weight achieved			**93.8 %**

Table 4: Comparison of manufacturing cost estimates between conventional and ASA designs

S. No	**Cost**	**Conventional**	**ASA**
1	Raw material	124	20
2	Machining ($100 /hr)	260 mins	28 mins
3	Labor ($60 /hr)	131 mins	52 mins
4	Miscellaneous	-------	21
Total cost per fuel cell($)		**515**	**120**
Percentage reduction in cost achieved			**77%**

Table 5: Comparison of performance and power densities between conventional and ASA designs

S. No	Performance	Conventional	ASA
1	Continuous operation time (minutes)	30	30
2	Hydrogen leakage	No	No
3	Maximum power output (W)	.45	0.114
4	Weight (Kilograms)	2.875	0.181
Power density(Power/weight) W/kg		**0.157**	**0.63**

II. DESIGN STRATEGY FOR REDUCING MANUFACTURING AND ASSEMBLY COMPLEXITY OF AIR-BREATHING PROTON EXCHANGE MEMBRANE FUEL CELLS (PEMFC)

Sriram P. Isanaka[1*], Todd E. Sparks[1], Frank F. Liou[1], Joseph W. Newkirk[2]

1 – Department of Mechanical Engineering, Missouri University of Science and Technology, 1870 Miner Circle, Rolla, Missouri – 65401, USA.

2 – Department of Materials Science, Missouri University of Science and Technology, 1870 Miner Circle, Rolla, Missouri – 65401, USA.

*- Corresponding author

1.1.KEYWORDS

Proton exchange membrane fuel cells; novel design strategy; reduced manufacturing complexity; assembly ease; solvent welding; improved power density; fuel cell economics.

1.2. ABSTRACT

Conventional flat plate Proton Exchange Membrane Fuel Cell (PEMFC) designs have been under investigation for the last five decades with the majority of the research being conducted in fluid dynamics of the reactants, membrane chemistry, thermal characteristics, stacking and electrical properties. By rigidly adhering to design characteristics and material choices (graphite flow plates & metal end plates), conventional fuel cell designs have become bulky, fastener intense designs that have a high degree of manufacturing and assembly complexity. The department of energy has recognized the need for economical and efficient manufacturing practices to further the market penetration and end user adoption of fuel cells. Therefore this paper analyzes air-breathing PEMFC's from the perspective of reducing manufacturing complexity,

assembly complexity, and costs. Areas of complexity like the flow plates, end plates, and sealing methods, have been reassessed and this paper proposes alternatives to component functions, and the commonly employed materials along with an alternate assembly strategy. Prototypes built using the new design strategy achieved about 90% reduction in weight and number of components while enjoying an 80% reduction in costs. The new prototypes also possess a superior form factor, along with a 10-fold increase in power density as compared to conventional designs.

1.3. INTRODUCTION

The fuel cell is an electrochemical device that enables direct and efficient conversion of chemical energy stored in the fuel along with oxidant into electrical energy. There are many types of fuel cells currently under research including the polymer electrolyte membrane fuel cell, direct methanol fuel cell, solid oxide fuel cell, molten carbonate fuel cell, phosphoric acid fuel cell, and the alkaline fuel cell. This paper investigates the conventional design strategy involved in the manufacture and assembly of portable air-breathing fuel cells and proposes alternatives. PEMFC design is comprised of a proton-conducting polymer membrane (the electrolyte being a teflon skeleton infused with sulphonic acid), that separates the anode and cathode sides. On the anode side, hydrogen diffuses to the anode catalyst where it dissociates into protons and electrons. The protons are conducted through the membrane to the cathode, while the electrons are forced to travel in an external circuit (supplying power) as the membrane is electrically insulating. On the cathode side, oxygen molecules react with the electrons (which have traveled through the external circuit) and protons (from the membrane) to form water which in this type of fuel cell, is the only waste product.

The main components of a PEM fuel cell are the flow plates, membrane electrode assembly, and the end plates. The flow plate sections are typically made of graphite and metal which are difficult materials to work with (as related to manufacturing). The high cost of the materials employed and their difficult manufacturing characteristics are still a hindering factor in the widespread economical acceptance of fuel cell technology. Fuel cells have long been considered viable options for long-term clean energy sustainability and independence from fossil fuel sources [1-3]. Over the last decade significant research has been conducted in both the theory and the practical development of PEM fuel cells. Comprehensive numerical and analytical models have been developed to address fuel distribution flow-fields [4-7], thermal management [8-10], water management [11-13] and catalytic action [14-16]. Developmental research has also led to the validation of theory in the areas of transport phenomena [17-23], by-product management [24, 25], corrosion effects [26], stacking [27] and MEA performance characterization [28-33]. While work has also been conducted in fuel cell manufacture [34], most of the research follows traditional design strategy, material choices, and component functions. There is limited literature on addressing the manufacturing and assembly complexity involved in these conventional designs. The functional and material cues that are followed in this conventional design strategy have existed for decades with little to no change proposed. While some authors have investigated alternate catalyst materials [35-37] to minimize costs, they still do not address the manufacturability and the possibility of mass-market production. Lin et al. [38] estimate the clamping force needed during the assembly of fuel cell stacks while Laskowski et al. [39] acknowledge the difficulty involved in the assembly of PEMFC and try to address it using robotic manipulation.

Manufacturing and assembly considerations are vital to ensure that fuel cells become viable mass market options for portable energy. The Department Of Energy (DOE) has tried to address this and has targeted mass-manufacturing practices that would reduce the cost of a fuel cell stack to $21/KW by 2020 [40]. This research believes that novel, efficient manufacturing and assembly practices alone are insufficient to reach the DOE's target. The need of the hour is a novel design strategy that re-envisions the functions and materials employed in existing fuel cells. For example, for a given MEA, the power density (power/weight ratio) of a fuel cell stack can be significantly increased by altering functions and materials of the flow and end plates (which are typically made of graphite and metal). Also, by employing a novel fastening mechanism, the need for excessive fasteners is mitigated leading to a more assembly friendly design. A key prerequisite for many power applications is the production of compact and lightweight PEMFC stacks which can be achieved with the appropriate design changes and selection of materials that this strategy proposes. If the power density and economics of the existing designs are improved, PEMFC's could become a significant power source for transportation and portable electronics.

1.4.THEORY: ELIMINATING THE NEED FOR CERTAIN COMPONENTS AND MODIFYING THE FUNCTION OF OTHERS

To meet the DOE's performance targets for portable energy solutions, a change in the design, material choices and component functions is warranted. Traditional flat plate fuel cell construction has been hampered by design and functional restrictions selected decades ago. While various research avenues have led to the improved performance and reliability of fuel cells, they are yet to meet the economics and functionality standards that would make them attractive for the open market. This is due to the fact that fuel cells as they stand today are bulky and fastener intensive designs that cannot match the power-to-weight ratios of other forms of energy generation. The materials employed and the fastening mechanisms used, make traditional fuel cells heavy and manufacturing and assembly intense. An analysis of the current fuel cell design (illustrated in Figure 1) and proposed changes is shown in Table 1. This research aims to address manufacturing and assembly considerations along with the economics involved in PEMFC. In order to better define these problems, a preliminary investigation into literature was employed to design and build a PEMFC prototype using the conventional design strategies and materials (as shown in Figure 1 and Table 1).

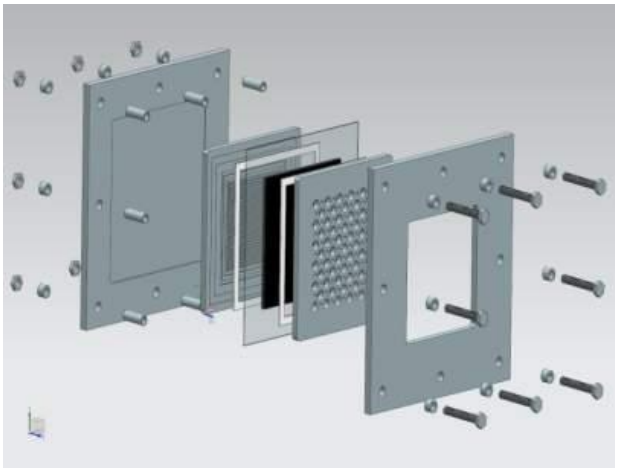

Figure 1: Assembly model of a conventional air-breathing PEMFC design

Testing this prototype led to the quantification of variables including power output, weight, the number of components, manufacturing cost, insulation, and clamping force. Important components of a PEMFC like the end plates, flow plates, gas diffusion layer and the fastening mechanism were identified and their design and functionality was re-assessed. From this preliminary study it was hypothesized that the elimination of the end plates and the fastening mechanisms would not adversely affect the PEMFC performance. It was also theorized that choosing new materials for the flow plates would significantly reduce weight and manufacturing cost. Based on this rationale a novel design strategy was proposed to eliminate certain components and modify the functionality of others. It was theorized that the new design strategy would produce increased power densities, while reducing the manufacturing complexity and cost. Important changes proposed (detailed in Table 1) by the design strategy were to the:

- *End plates:* By eliminating the end plates the research aimed at reducing the metal weight, tooling, and assembly time of PEMFC's. Functionally, the end plates provide support to the fuel cell, and also provide clamping surfaces to impart force to reduce contact resistance between the anode, cathode and, membrane surfaces of the cell. This research theorizes that the functions of the end plates can be performed by the flow plates, thereby negating the need for them.
- *Flow plates:* Traditionally, flow plates perform multiple functions of fuel distribution, membrane support and electrical conductivity. They are made using graphite to facilitate conductivity but that has the downside of increasing the weight and manufacturing complexity. This research proposes the use of polycarbonate instead of graphite which will provide sufficient strength and support while minimizing the tooling costs involved.

Table 1: Bill of materials of traditional flat plate fuel cell design and a hypothetical design strategy for improvement

Part name	**Material of construction**	**Quantity**	**Design changes**	**Functional changes**
Hydrogen side end plate	Stainless steel 316	1	**Eliminate**	
Air side end plate	Stainless steel 316	1	**Eliminate**	
Hydrogen flow plate	Graphite	1		**Modify**
Air flow plate	Graphite	1		**Modify**
Proton Exchange Membrane	Teflon skeleton infused with Sulphonic acid	1		
Flow plate gasket	Silicone	2		
Bolt	Stainless steel 304	8	**Eliminate**	
Nut	Stainless steel 304	8	**Eliminate**	
Insulating washer	Nylon	16	**Eliminate**	
Insulating sleeve	Silicone	8	**Eliminate**	
Total number of components		**47**		

- *Gas diffusion layer:* To compensate for the loss of conductivity in the flow plates, porous stainless steel sheets will be employed for current collection and transfer. Stainless steel has increased electrical conductivity when compared to graphite and the design will greatly reduce through-plane contact resistance. Although made of metal, these layers do not add significant cost or weight to the PEMFC owing to the low volume of use.

- *Fastening mechanism:* Conventional PEMFC designs employ metal fasteners and insulating sleeves and washers for imparting the requisite force to the end plates while still electrically isolating the electrodes. This research proposes the use of solvent welding in place of the nut-and-bolt based fastening mechanisms. The use of polycarbonate as flow plate material enables the use of solvent welding as the fastening mechanism thereby reducing weight, improving sealing and promoting ease of assembly.

1.5. MATERIAL AND METHOD

1.5.1. Assumptions and statements:

The research team has made certain assumptions to perform the research and analysis discussed in this paper which include:

- The target application is for charging portable mobile devices like cellphones, GPS navigators etc.
- The primary target variables are manufacturing and assembly ease, economics, reduced form factor and portability, and high power-densities.
- The design is air-breathing to reduce the need for storage and delivery of oxygen, which will add bulk, weight, complexity and cost to the fuel cell.
- The research team is targeting the compensation of any losses in performance owing to the use of air, with reduction in weight, cost of manufacturing, assembly ease, and better reactant availability.

- Conventional designs used as a comparison in this paper are flat plate PEM fuel cell designs which use graphite extensively in the flow plates, and stainless steel as end plates.
- Manufacturing processes used in the production of graphite flow plates and metal end plates (for conventional designs) are assumed to be Computer Numerical Control (CNC) enabled machining.
- Prototypes of both the conventional design and the modified designs from the new strategy were manufactured in house and used to test for performance. Nafion membranes were sourced externally.
- The membrane used for performance testing is Nafion based with 0.5 mg platinum loading and was used with both the conventional design and the modified design. Both prototypes had active membrane areas of 50 square centimeters.
- Simulations were performed to replicate 3-dimensional fluid dynamics in both the cathode and anode flow sections. The variables of importance were the velocity, temperature and mass fractions. Mesh independence was achieved in each case.
- CAD models were created in Unigraphics NX, meshing was completed in Gambit, solution generated in FLUENT and post-processing was performed in Tecplot.
- Assumptions used during the finite element analysis for both the GDL and MEA: the viscous permeability of $0.44 * 10^{-12}$ (m^2) and inertial permeability of $34 * 10^{-8}$ (m). The simulated mass fraction studies are employed in the detailed design of the flow field channels of both the conventional and new design strategy prototypes. These prototypes are manufactured in house and used to experimentally quantify the

manufacturing economics, assembly ease, ergonomics and performance between the conventional design prototypes and the new design strategy prototypes.

Table 2: Weight of components in conventional flat plate fuel cells

Part name	**Material of construction**	**Quantity**	**Weight / comp (grams)**	**Total Weight (grams)**
Hydrogen side end plate	Stainless steel 316	1	1134.16	1134.16
Air side end plate	Stainless steel 316	1	864.298	864.298
Hydrogen flow plate	Graphite	1	96.4	96.4
Air flow plate	Graphite	1	71.5	71.5
Proton Exchange Membrane (With carbon cloth on either side)	Teflon skeleton infused with Sulphonic acid	1	8.083	8.083
Flow plate gasket	Silicone	2	2.554	5.108
Bolt	Stainless steel 304	8	14.184	113.472
Nut	Stainless steel 304	8	1.358	10.584
Insulating washer	Nylon	16	0.735	11.76
Insulating sleeve	Silicone	8	1.141	9.128
Total Weight				**2324.805**

1.5.2. Specifications of the conventional flat plate prototype

A major factor in any design is the number and type of fasteners used. These fasteners increase the assembly complexity by significantly increasing the number of components that go into the conventional flat plate design. In the flat plate design, metal and graphite are used extensively to ensure solid construction and a design that has good contact and conductivity. This makes the design extremely heavy as shown in Table 2. The weight of the prototype flat plate design was measured to be close to 2325 grams. It is perceived that this size, manufacturing and assembly complexity, and weight is detrimental for use in portable applications.

1.6. PRELIMINARY FLOW FIELD SIMULATIONS

One of the pre-requisites to minimize the weight, cost and manufacturing complexity involved in the construction of conventional PEMFC, is the efficient usage of the active membrane area. To ensure this efficient usage it is vital to determine the optimum flow channels and maintain the distribution of fuel on the both the cathode and anode sections. To address the same, finite element analysis of various flow channels and the cross-sections was conducted. Figure 2 shows the flow of hydrogen into plates in a straight/parallel flow field design and a pin-type design along with forced transmission into the gas diffusion layer (GDL) and subsequently the membrane electrode assembly (MEA). The aim of these analyses was to find the effect of the width and depth of the channel on the type of flow. The images show the mass fraction of the reactant (i.e. in this case hydrogen) which is displacing the air in the system. From the analyses, it was observed that in wider channels, the reactant gas is exhibiting turbulence which in turn would affect the rate of diffusion of the gas into the GDL and MEA. Turbulence is an unacceptable phenomenon in the flow channels of a PEMFC. The energy loss impedes reactant diffusion into the GDL at the land areas (i.e. the straight/parallel obstructions or the pins in the corresponding designs as seen in Figure 2). The depth of the channels is observed to have an effect on the flow of the reactants. In deep channels a large amount of reactant is not being utilized for the chemical reaction and prematurely exhausted. To increase reactant utilization, it was concluded that channels with depth close to 1mm would be more suitable for portable applications. The above conclusions are similar to the conclusions reached by the University of Alabama research team [41] as shown in Figure 3. Figure 4 illustrates that parts of the MEA are inactive when the land area is large (> 5mm) leading to decrease in performance of the fuel cell. The images in Figure 4 suggest a reduction of the cross-sectional area that comprises the land sections. But this would have to be a balancing act as having too thin or a small land area would apply excessive pressure on the MEA thereby damaging it and producing electrical shorts.

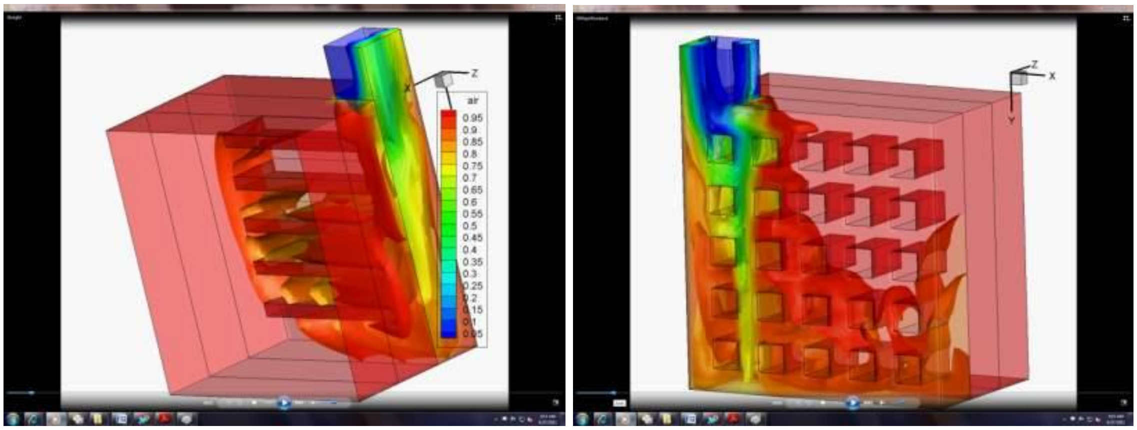

Figure 2: Reactant flow (mass fraction of hydrogen) in straight (left image) and pin type (right image) flow field design.

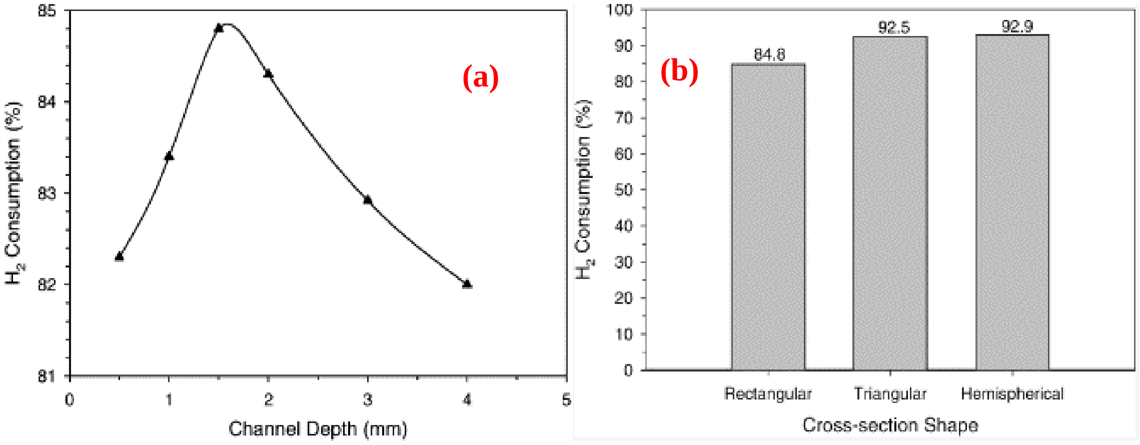

Figure 3: Effect of different design parameters on H2 absorption and pressure drop [41]. (a) Hydrogen consumption due to channel depth, (b) Hydrogen consumption due to channel cross-section.

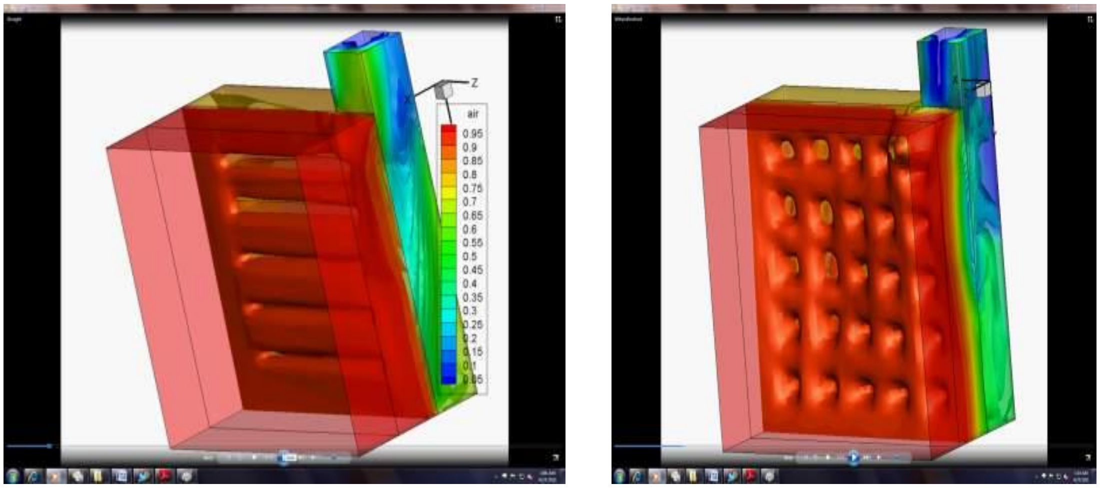

Figure 4: Reactant flow into the MEA from the bipolar plate using straight type (left image) and pin type (right image) channels indicating the presence of inactive areas.

1.7. REDESIGN OF FLAT PLATE DESIGN

A design weighing nearly 2.3kgs for a 50 cms^2 active area has an unacceptable power density for employment in portable applications. To ensure that the design is lighter and has a smaller form factor the flat plate design was re-designed using polycarbonate and stainless steel (Table 3). To improve the sealing and promote ease of assembly, solvent welding was employed which is a phenomenon by which plastics dissolve in organic solvents and recrystallize to form a homogenous material bond. As part of the new design strategy the choice of materials needs sufficient mechanical strength to replace metals but also be light and exhibit dissolution properties when exposed to organic solvents. Nylon and Teflon are excellent with regards to strength and high softening temperatures but show poor solvent welding properties. Acrylics and PETG exhibit good solvent welding properties but they show poor strength and soften easily.

Table 3 : Bill of materials of fuel cell prototype constructed using new design strategy

Part name	**Material of construction**	**Quantity**
Hydrogen flow plate	Polycarbonate	1
Air flow plate	Polycarbonate	1
Current collectors	Stainless Steel 316	2
Hydrogen side gasket	Silicone	1
Proton exchange membrane	Teflon/sulfonic acid	1
Total number of components		**6**

Therefore polycarbonate was chosen as the material for the flow plates owing to its high softening temperature and strength characteristics across the entire working temperature range of Nafion membranes (75^{o} C). Stainless Steel – 316 (SS-316) was chosen as the electrode material for its high corrosion resistance and electrical conductivity. Di-chloro methane was chosen as the welding media. Hydrogen side and air side plates were then manufactured using polycarbonate (using dimensions generated from FEA simulations) and are illustrated in Figure 5 and Figure 6 respectively.

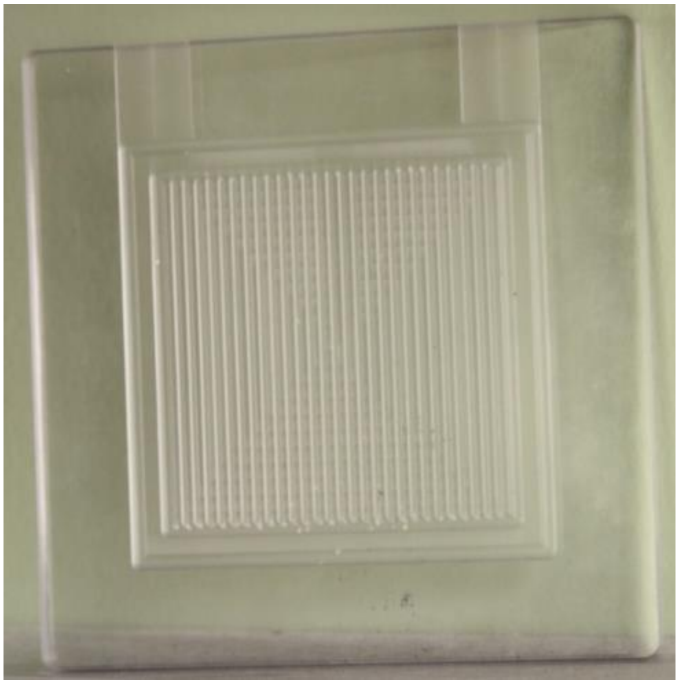

Figure 5: Hydrogen side flow plate manufactured in polycarbonate

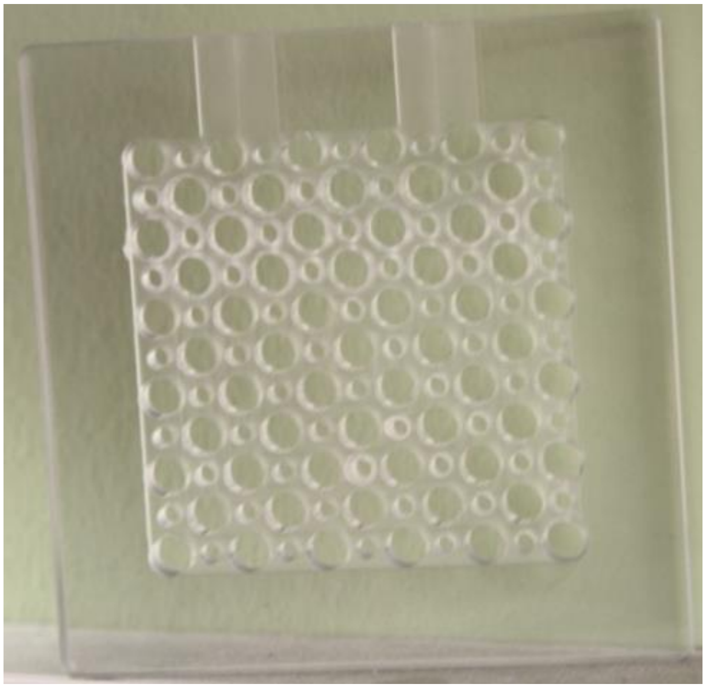

Figure 6: Air side flow plate manufactured in polycarbonate

1.8. PROTOTYPE OF FLAT PLATE DESIGN MADE USING NEW DESIGN STRATEGY

The polycarbonate plates are assembled with porous stainless steel sheets which now act as the combined current collectors and gas diffusion layers. These leads are directly drawn out of the fuel cell thereby reducing electrical contact losses between components occurring due to in-plane and through-plane resistance. In the conventional flat plate design the electrons produced at the membrane are transferred to the carbon cloth and then to the bipolar plate and finally to the end plate before being drawn into external circuits. These triple layer contact losses will be eliminated in the new design since leads are directly drawn from the stainless steel GDL.

Figure 7: PEMFC prototype manufactured using the new design strategy

The prototype manufactured using the new design is shown in Figure 7. The latest prototype while being a fraction of the weight of the conventional flat plate fuel cell design produces comparable power output of 0.25 W with a platinum loading of 0.5 mg/cm^2. The use of solvent welding and polycarbonate completely negates the use of nut and bolt assemblies thereby significantly reducing manufacturing and assembly cost. The solvent welding bonds the plates together completely forming a single piece and imparts significant force to the membrane to reduce contact resistance. This makes the end plates irrelevant.

1.9.RESULTS AND DISCUSSION

Two working prototypes, one each of conventional and modified flat plate designs, were manufactured. The manufacturing complexity reduction, and cost benefits realized in the manufacture of the modified prototype were determined and are discussed in the forth-coming sections.

1.9.1. Manufacturing and assembly complexity reduction

It is to be noted that since the conventional flat plate design uses graphite and stainless steel extensively there will be requirements for a large number of high cost tooling such as end mills and drill bits. Owing to the large number of components there will be a significant number of alignment issues and hence the assembly and labor requirements to make this design will be considerable. In comparison, the flow plates of the modified design are made of polycarbonate, which being a much softer material as compared to graphite or stainless steel has significantly lower cutting requirements. The end plates have also been eliminated in favor of the use of polycarbonate flow and stainless steel current collectors. The use of solvent welding led to the elimination of the nut and bolt assembly based fastening requirements.

1.9.2. Component and weight reduction

The large numbers of fasteners in the conventional design are mandatory to ensure proper surface contact and also to reduce the contact electrical resistance inherent in this type of design. Also insulating washers and sleeves are necessary to ensure that the cathode and anode plates are isolated from one another and will never come in contact to produce a short. In comparison, the modified flat plate has vastly reduced component list of just 6 as shown in Table 4. This will produce a drastic reduction in the assembly time and labor requirements and will reduce costs.

Table 4: Comparison of assembly ease and portability between conventional and re-designed flat plate fuel cells

Type of design	**Material of construction**	**Number of components**	**Weight (grams)**
Conventional	SS – 316/Graphite	47	2325
Modified	Polycarbonate/SS - 316	6	142
Percentage reduction in number of components			**87.2 %**
Percentage reduction in weight			**93.9%**

The elimination of the end plate and use of polycarbonate flow plates drastically reduces the weight as shown in Table 4. The latest prototype while being a fraction of the weight of the traditional flat plate fuel cell design produces comparable power output of 0.25 W. The savings achieved by this redesign are significant as can be seen in Table 4. With the use of polycarbonate machining costs, tooling costs are significantly reduced and with the reduced number of components assembly costs are also reduced. This final prototype with a weight of 142 grams (for a 50 square centimeter active area) is now more suitable for portable power applications.

1.9.3. Economics

Table 5 shows the comparison of manufacturing costs between conventional and modified flat plate designs.

Table 5: Manufacturing cost estimates between conventional and re-designed flat plate fuel cells.

S. No	Cost	Conventional	Modified
1	Raw material	124	22
2	Machining (100 $/hr)	260 mins	16 mins
3	Labor (60 $/hr)	131 mins	29 mins
4	Fixture	-------	21
Total cost per fuel cell($)		**515**	**98**
Percentage reduction in cost			**81**

When compared to conventional design, in the modified design the flow plates are made of polycarbonate, which being a much softer material as compared to graphite or stainless steel has lesser cutting requirements. Also the lack of end plates reduces cutting and material requirements. Owing to choice of materials and reduction in components the modified flat plate design saves significantly on the raw material and machining costs. It also does not require the high cost carbide tooling that conventional flat plate design requires to machine metal and graphite. Owing to the lack of fasteners the labor cost of the ASA is also significantly lower. Currently the modified flat plate design requires assembly fixturing which adds an extra component to its total cost, but as this design matures and more prototypes are made this cost can be negated. Since the membrane in both fuel cells is to be the same its cost is not included in this analysis.

1.9.4. Sealing and performance

The credibility of any fuel cell system relies on its efficiency and safety. If the design is incapable of retaining the seal between the hydrogen flow section and the membrane it will exhibit systematic drops in performance, and will be incapable of reaching steady state. Any leakage of hydrogen is also potentially dangerous to the user with flammability factors ranging from 5%-75%, leaving the user in danger. Therefore both the prototypes manufactured were tested for hydrogen leaks over significant periods of time of continuous operation. They did not exhibit leaks or drops in voltage and power during the course of multiple tests. The results of tests are discussed in Table 6. While the modified flat plate at its current power output lacks behind traditional fuel cell designs, owing to the significant savings in weight and mass, the modified flat plate achieves 10 times the power density of conventional design. It is to be noted that the design alone is not a guarantee for the successful operation of the fuel cell. Manufacturing and proper assembly is of equal importance which will ensure sealing between the electrode and the MEA. If the cell is prone to reactant leakage it will exhibit performance drops and will be unable to reach a steady state thereby reducing its efficiency and also leading to a hazardous environment for the user.

Table 6: Comparison between the performance characteristics of conventional and redesigned flat plate fuel cells.

S. No	Performance	Conventional	Modified
1	Continuous operation time (mins)	30	30
2	Hydrogen leakage	No	No
3	Maximum power output (W)	.40	0.25
4	Weight (Kilograms)	2.325	0.142
Power density(Power/weight) W/kg		**0.172**	**1.761**

1.10. CONCLUSIONS

The research conducted by the team has shown the importance of manufacturing and assembly considerations in the development of fuel cells. If the DOE's performance targets for portability are to be met, the application of the new design strategy is vital. Manufacturability and economic assessments made on conventional flat plate designs led to the changes to the materials, component functionality and assembly. The modified flat plate design built elucidates that:

- Lighter, smaller fuel cells are viable for portable power requirements.
- Working single cell prototypes weighing 142 grams have been developed.
- They possess power-densities 10 times higher than conventional designs.

- They possess small form factors while still remaining 80% more economical to manufacture as compared to conventional designs.

The extensive use of plastics also opens up the flow plates in the new designs to be manufactured by economical processes for mass production like injection molding. The new design strategy brings about this possibility thereby enabling the DOE's manufacturing and cost targets.

1.11. ACKNOWLEDGEMENTS

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1.12. REFERENCES

[1] Farooque, M., and Maru, H. C., 2001, "Fuel Cells - The Clean and Efficient Power Generators," Proceedings of the IEEE, 89(12), pp. 1819-1829.

[2] Prater, K. B., 1994, "Polymer electrolyte fuel cells: a review of recent developments," Journal of Power Sources, 51(1-2), pp. 129-144.

[3] Smith, W., 2000, "Role of fuel cells in energy storage," J Power Sources, 86(1), pp. 74-83.

[4] He, W., Yi, J. S., and Van Nguyen, T., 2000, "Two-phase flow model of the cathode of PEM fuel cells using interdigitated flow fields," AIChE Journal, 46(10), pp. 2053-2064.

[5] Jeon, D. H., Greenway, S., Shimpalee, S., and Van Zee, J. W., 2008, "The effect of serpentine flow-field designs on PEM fuel cell performance," International Journal of Hydrogen Energy, 33(3), pp. 1052-1066.

[6] Nguyen, P. T., Berning, T., and Djilali, N., 2004, "Computational model of a PEM fuel cell with serpentine gas flow channels," Journal of Power Sources, 130(1-2), pp. 149-157.

[7] Wang, Z. H., Wang, C. Y., and Chen, K. S., 2001, "Two-phase flow and transport in the air cathode of proton exchange membrane fuel cells," Journal of Power Sources, 94(1), pp. 40-50.

[8] Rowe, A., and Li, X., 2001, "Mathematical modeling of proton exchange membrane fuel cells," Journal of Power Sources, 102(1-2), pp. 82-96.

[9] Shan, Y., and Choe, S. Y., 2005, "A high dynamic PEM fuel cell model with temperature effects," Journal of Power Sources, 145(1), pp. 30-39.

[10] Sivertsen, B. R., and Djilali, N., 2005, "CFD-based modelling of proton exchange membrane fuel cells," Journal of Power Sources, 141(1), pp. 65-78.

[11] Baschuk, J. J., and Li, X., 2000, "Modelling of polymer electrolyte membrane fuel cells with variable degrees of water flooding," J Power Sources, 86(1), pp. 181-196.

[12] Li, X., Sabir, I., and Park, J., 2007, "A flow channel design procedure for PEM fuel cells with effective water removal," Journal of Power Sources, 163(2), pp. 933-942.

[13] You, L., and Liu, H., 2002, "A two-phase flow and transport model for the cathode of PEM fuel cells," International Journal of Heat and Mass Transfer, 45(11), pp. 2277-2287.

[14] Mann, R. F., Amphlett, J. C., Hooper, M. A. I., Jensen, H. M., Peppley, B. A., and Roberge, P. R., 2000, "Development and application of a generalized steady-state electrochemical model for a PEM fuel cell," J Power Sources, 86(1), pp. 173-180.

[15] Um, S., and Wang, C. Y., 2004, "Three-dimensional analysis of transport and electrochemical reactions in polymer electrolyte fuel cells," Journal of Power Sources, 125(1), pp. 40-51.

[16] Wang, C., Nehrir, M. H., and Shaw, S. R., 2005, "Dynamic models and model validation for PEM fuel cells using electrical circuits," IEEE Transactions on Energy Conversion, 20(2), pp. 442-451.

[17] Bazylak, A., Sinton, D., Liu, Z. S., and Djilali, N., 2007, "Effect of compression on liquid water transport and microstructure of PEMFC gas diffusion layers," Journal of Power Sources, 163(2), pp. 784-792.

[18] Pharoah, J. G., 2005, "On the permeability of gas diffusion media used in PEM fuel cells," Journal of Power Sources, 144(1), pp. 77-82.

[19] Shimpalee, S., and Van Zee, J. W., 2007, "Numerical studies on rib & channel dimension of flow-field on PEMFC performance," International Journal of Hydrogen Energy, 32(7), pp. 842-856.

[20] Shimpalee, S., Greenway, S., and Van Zee, J. W., 2006, "The impact of channel path length on PEMFC flow-field design," Journal of Power Sources, 160(1), pp. 398-406.

[21] Spernjak, D., Prasad, A. K., and Advani, S. G., 2007, "Experimental investigation of liquid water formation and transport in a transparent single-serpentine PEM fuel cell," Journal of Power Sources, 170(2), pp. 334-344.

[22] Wang, L., Husar, A., Zhou, T., and Liu, H., 2003, "A parametric study of PEM fuel cell performances," International Journal of Hydrogen Energy, 28(11), pp. 1263-1272.

[23] Wang, L., and Liu, H., 2004, "Performance studies of PEM fuel cells with interdigitated flow fields," Journal of Power Sources, 134(2), pp. 185-196.

[24] Kandlikar, S. G., and Lu, Z., 2009, "Thermal management issues in a PEMFC stack - A brief review of current status," Applied Thermal Engineering, 29(7), pp. 1276-1280.

[25] Satija, R., Jacobson, D. L., Arif, M., and Werner, S. A., 2004, "In situ neutron imaging technique for evaluation of water management systems in operating PEM fuel cells," Journal of Power Sources, 129(2), pp. 238-245.

[26] Tang, H., Qi, Z., Ramani, M., and Elter, J. F., 2006, "PEM fuel cell cathode carbon corrosion due to the formation of air/fuel boundary at the anode," Journal of Power Sources, 158(2 SPEC. ISS.), pp. 1306-1312.

[27] Hamelin, J., Agbossou, K., Laperrière, A., Laurencelle, F., and Bose, T. K., 2001, "Dynamic behavior of a PEM fuel cell stack for stationary applications," International Journal of Hydrogen Energy, 26(6), pp. 625-629.

[28] Borup, R. L., Davey, J. R., Garzon, F. H., Wood, D. L., and Inbody, M. A., 2006, "PEM fuel cell electrocatalyst durability measurements," Journal of Power Sources, 163(1 SPEC. ISS.), pp. 76-81.

[29] Cai, M., Ruthkosky, M. S., Merzougui, B., Swathirajan, S., Balogh, M. P., and Oh, S. H., 2006, "Investigation of thermal and electrochemical degradation of fuel cell catalysts," Journal of Power Sources, 160(2 SPEC. ISS.), pp. 977-986.

[30] Collier, A., Wang, H., Zi Yuan, X., Zhang, J., and Wilkinson, D. P., 2006, "Degradation of polymer electrolyte membranes," International Journal of Hydrogen Energy, 31(13), pp. 1838-1854.

[31] Colón-Mercado, H. R., and Popov, B. N., 2006, "Stability of platinum based alloy cathode catalysts in PEM fuel cells," Journal of Power Sources, 155(2), pp. 253-263.

[32] Curtin, D. E., Lousenberg, R. D., Henry, T. J., Tangeman, P. C., and Tisack, M. E., 2004, "Advanced materials for improved PEMFC performance and life," J Power Sources, 131(1-2), pp. 41-48.

[33] Qi, Z., He, C., and Kaufman, A., 2002, "Effect of CO in the anode fuel on the performance of PEM fuel cell cathode," Journal of Power Sources, 111(2), pp. 239-247.

[34] Kim, H., Subramanian, N. P., and Popov, B. N., 2004, "Preparation of PEM fuel cell electrodes using pulse electrodeposition," Journal of Power Sources, 138(1-2), pp. 14-24.

[35] Nallathambi, V., Lee, J. W., Kumaraguru, S. P., Wu, G., and Popov, B. N., 2008, "Development of high performance carbon composite catalyst for oxygen reduction reaction in PEM Proton Exchange Membrane fuel cells," Journal of Power Sources, 183(1), pp. 34-42.

[36] Wang, B., 2005, "Recent development of non-platinum catalysts for oxygen reduction reaction," Journal of Power Sources, 152(1-2), pp. 1-15.

[37] Wood, T. E., Tan, Z., Schmoeckel, A. K., O'Neill, D., and Atanasoski, R., 2008, "Non-precious metal oxygen reduction catalyst for PEM fuel cells based on nitroaniline precursor," Journal of Power Sources, 178(2), pp. 510-516.

[38] Lin, P., Zhou, P., and Wu, C. W., 2009, "A high efficient assembly technique for large PEMFC stacks. Part I. Theory," Journal of Power Sources, 194(1), pp. 381-390.

[39] Laskowski, C., Gallagher, R., Winn, A., and Derby, S., "Automated fuel cell stack assembly: Lessons in design-for-manufacture," Proc. ASME 2010 8th International Conference on Fuel Cell Science, Engineering and Technology, FUELCELL 2010, June 14, 2010 - June 16, 2010, American Society of Mechanical Engineers, pp. 497-503.

[40] DOE, http://energy.gov/sites/prod/files/2014/11/f19/fcto_myrdd_manufacturing.pdf**.** - last referred on 02/17/2016.

[41] Kumar, A., Reddy, R. G., , 2003, "Effect of channel dimensions and shape in the flow-field distributor on the performance of polymer electrolyte membrane fuel cells," Journal of Power Sources, 113, pp. 11-18.

III. PROMOTING NATURAL CONVECTION IN AIR-BREATHING PROTON EXCHANGE MEMBRANE (PEM) FUEL CELLS USING NOVEL DESIGN STRATEGIES AND ADDITIVE MANUFACTURING

Sriram Praneeth Isanaka[1*], Amar Bala Sridhar[2], Joseph Newkirk[3], Frank Liou[1]

1 – Department of Mechanical Engineering, Missouri University of Science and Technology, 400 West 13th Street, Rolla, MO 65409.

2 – Department of Manufacturing Engineering, Missouri University of Science and Technology, 400 West 13th Street, Rolla, MO 65409.

3 – Department of Materials Science, Missouri University of Science and Technology, 1400 N. Bishop, Rolla, MO 65409.

*- Corresponding author

1.1.KEYWORDS

Air-breathing, PEM fuel cells, natural convection, eliminate external fans, chimney attachments, additive manufacturing, chimney-shaping, cylindrical designs.

1.2.ABSTRACT

Air-breathing PEM fuel cells of today employ peripheral components like fans to improve thermal characteristics, air-flow and ultimately their performance. The scope of this research is to investigate the means to eliminate these fans and their supplementary power electronics and batteries to reduce cost, manufacturing time, and assembly complexity. In this regard, the research details the investigations conducted to promote natural convection in air-breathing PEM fuel cells using novel cylindrical designs and chimney attachments. This research benefited from employing Additive Manufacturing (AM) to make these novel cylindrical designs and chimney attachments owing to its design flexibility and economical small-lot manufacturing. Results indicated that the employment of chimney attachments creates an air draft that systematically brings

oxygen rich air to an air-breathing PEM fuel cell and increases its performance. The chimney attachments produced over 20 percent increase in voltages and power densities. Using this premise, the research theorized a novel cylindrical fuel cell design that by its very shape mimics a chimney, as opposed to using attachments which still increases the cost and complexity. Numerical models were employed to study the feasibility of such a design and their results are detailed. The designs, models, and analyses were then employed in the successful development of working prototypes of the chimney-shaped designs.

1.3.INTRODUCTION TO PEM FUEL CELLS

The research presented in this paper is the successful adoption of a novel design strategy and the principles of additive manufacturing towards air-breathing PEM fuel cells. PEM fuel cells are electrochemical devices that convert chemical interaction into electrical energy. Fuel cells are currently being investigated as efficient energy mechanisms [1] towards long-term energy sustainability [2] and also as energy storage methods [3]. There are many types of fuel cells in existence including direct methanol, solid oxide, proton exchange membrane, molten carbonate, phosphoric acid, and alkaline fuel cells. This research investigated small-scale air-breathing PEM fuel cells as viable portable energy solutions. In air-breathing PEM fuels the reactants employed are hydrogen and air. Hydrogen is ionized and conducted through the proton exchange membrane and finally reacts with oxygen to form water (a by-product). The electrons produced with the hydrogen ions are directed through an external circuit to power electronic devices. Over the last few decades important components of the fuel cells like the membrane, flow plates, and gas diffusion layers have been investigated extensively.

Researchers have developed numerical models for the reactant flow characteristics [4-6] to promote favorable chemical reactions in PEM fuel cells [7-10]. Models that simulate the catalytic action [11-13] and waste management (water [14-16], heat [17-20]) have also been developed. Many researchers have also extended the theoretical studies with experimental data of the transport phenomena [21-25] and their by-products [26, 27]. Other prominent research includes the characterization of the membrane’s performance [28-33], alternate membrane materials [34-36], the effects of corrosion [37], and finally the consequences of stacking [38]. While some authors have identified the need for improved manufacturing practices [39], research work has been restricted to prismatic flat plate designs [40-42] and conventional manufacturing processes.

1.4.RESEARCH NEED

Fans and forced convection mechanisms have been typically employed as peripheral systems to air-breathing PEM fuel cells to promote thermal management [43] and performance improvements [44-46]. Air-breathing fuel cells target portability by eliminating the need for oxygen-side canisters, transport mechanisms and reactant filtration thereby promoting manufacturing and assembly ease and minimizing costs. Although some of these targets have been met, the use of fans in air-breathing fuel cells and coupling them with power electronics also leads to an increase in components and complexity. This defeats the purpose of choosing air-breathability. In an effort to propose an alternate solution, this research has successfully developed novel design strategies like non-prismatic cylindrical designs and chimney attachments to promote natural convection without the need for any peripheral systems. While Al-Baghdadi et al. [47] have investigated certain designs in this regard, the research presented here couples the novel designs with additive manufacturing to minimize manufacturing and assembly complexity and cost. The research unites novel design strategies and manufacturing practices to improve power densities of portable air-breathing PEM fuel cell. The successful implementation of this research will impact the sectors of portable power and hand held electronics.

1.5.THEORY: THE NEED FOR NATURAL CONVECTION

Chimneys have been in use in homes for centuries owing to their favorable gas dynamics in expelling smoke. The principle of hot air rising has also been successfully employed in industry for heat and power generation [48] and to expel waste products and flue gases [49, 50]. Their designs have been extensively investigated and employed for large scale applications [51]. Many researchers have developed numerical models [52-54] to predict this natural convective effect of chimneys thereby enabling their adoption for multiple markets. One novel application is the cooling of electronic components [55-57]. Some researchers have also extended this into the realm of hybrid energy [58, 59] and solid oxide fuel cells [60]. This research will extend the benefit of chimneys into small-size power generation systems.

The research theorizes that the effect of chimneys will benefit portable air-breathing PEM fuel cells. By creating a naturally convective draft, this research hopes to provide cyclical oxygen-rich air to the fuel cell along with evaporative cooling. The results to justify this hypothesis will be shown as experimental data of performance improvements and numerical data of fluid flow improvements. The data will be presented in the form of two case studies:

- The first detailing the attachments of chimneys to conventional fuel cells (illustrated in Figure 1)
- The second being the redesign and manufacture of PEM fuel cells to mimic chimney geometry (illustrated in Figure 2)

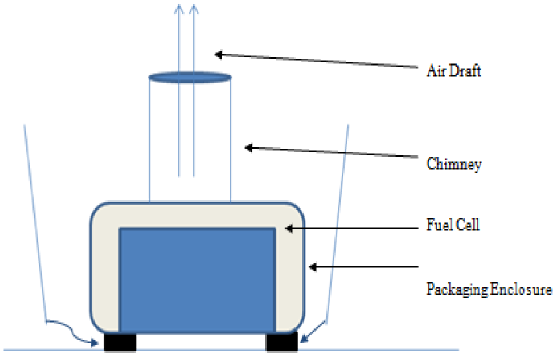


Figure 1: Schematic diagram of a fuel cell inside enclosure with a chimney attachment

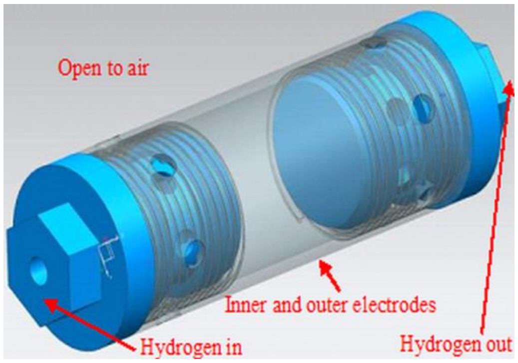


Figure 2: A redesigned air-breathing PEM fuel cell to mimic chimney geometry.

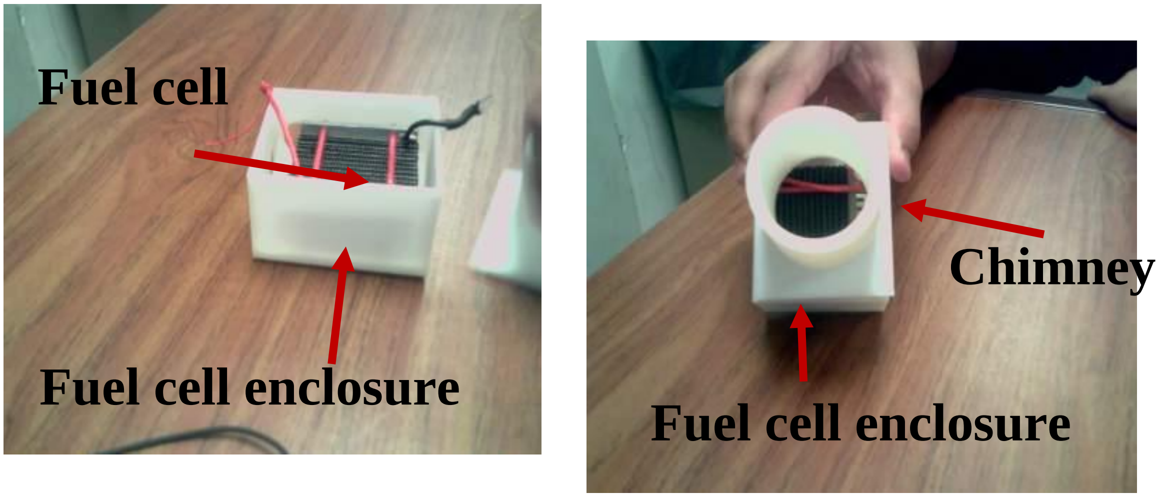
1.6.RESEARCH APPROACH

The designs for the packaging enclosure, chimney attachments and redesigned geometries were modelled using Solid works, and Unigraphics NX software. These models were then exported to a Ultimaker Fused Deposition Modelling (FDM) machine that additively manufactured the designs using Acrylonitrile Butadiene Styrene (ABS). This AM machine has a layer resolution of 20 microns and benefitted this research with its extreme design flexibility [61] and manufacturing ease [62]. While literature review was used as a start, numerical models were developed in-house using ANSYS software and employed as the proof of concept. Some analytical models were also employed to study air flow. The initial experimental investigations using chimney attachments were performed on a Horizon H-20 fuel cell stack. Important parameters including the reactant flow (pressure and velocities), voltage, current density and power were continuously monitored using a Greenlight Innovation fuel cell test station. The observations and conclusions from these studies were employed in the design and manufacture of working prototypes of the novel chimney shaped PEM fuel cell that was built entirely in-house for the purposes of this research.

1.7.RESULTS AND DISCUSSION

1.7.1. Case study 1: Promoting natural convection using chimney-shaped attachments

With the high energy density of the fuel cells coupled with the formation of water on the cathode side, constantly cycling air inside the fuel cell is beneficial. This will aid in cooling, evaporation and replenishing oxygen levels in the PEM fuel cell. Although large scale fuel cell systems can afford to use fans and other peripheral systems to aid these occurrences, portable PEM fuel cells can lose considerable amounts of power while feeding these peripheral components. The added manufacturing and assembly complexity, along with the cost and weight penalties make this solution even less desirable for portable power solutions. There is a need for a naturally convective air cycling mechanism that can be employed in portable designs to overcome these issues. A packaging enclosure with a pipe-shaped device (that mimics a chimney) mounted on top can create a chimney effect. To prove this theory, tests were conducted on an off-the-shelf PEM fuel cell by incorporating chimney attachments onto it as shown in Figure 3. The Horizon fuel cell with the chimney attachment and enclosure as shown in Figure 3 was tested to measure performance improvements. Tests were carried out at the recommended anode pressure of 7psi with the room temperature at 23°C. The data was recorded after ten minutes of operation and the voltage and power charts obtained are shown in Figure 4 and Figure 5. Measured data on the voltage and power both indicated an increase of over 20 percent.



(a) PEM fuel cell mounted inside an enclosure

(b) Chimney attachment made using AM

Figure 3: The construction of fuel cell enclosures and chimney attachments using AM to test the theory of performance improvements using natural convection

The fuel cell with the chimney comfortably outperformed the same fuel cell with no chimney, thereby proving theory. With the fuel cell enclosure being additively manufactured using ABS (a light weight plastic) the power/weight ratios of the fuel cell with the chimney also bettered the conventional fuel cell. These investigations led to the conclusion that the performance of air-breathing PEM fuel cells can be improved using AM made chimney enclosures. The next logical step was the investigation and improvement of the chimney design to determine the best possible dimensional values of the chimney's to be used in portable PEM fuel cells. The research progressed to assessing the slope, height and inclination angle of chimneys as a measure of their performance.

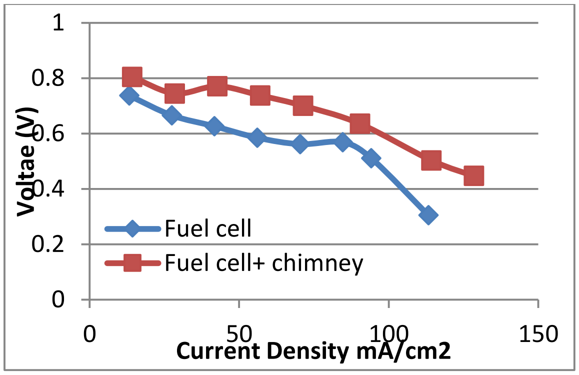


Figure 4: Polarization curves of air breathing fuel cell with and without chimney indicating peak increase of 21% in voltage of fuel cell with chimney.

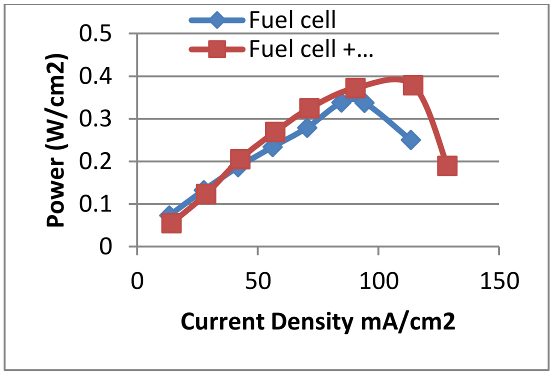


Figure 5: Comparison of power densities of air breathing fuel cell with and without chimney indicating peak increase of 24% in power density of fuel cell with chimney.

1.7.1.1.Effect of chimney dimensions (slope and height) on the air draft

The draft in a chimney is caused by the tendency of hot air to rise. As long as a temperature gradient is maintained between the air inside and outside the chimney this phenomenon will cyclically reoccur. Tests indicate that PEM fuel cells produce heat as a by-product which will instigate the phenomenon of natural convection. As for the chimney's height, an increase in height will also increase air velocity. This logic though cannot define portable PEM fuel cells as long chimney attachments will make the design unwieldly and difficult to manufacture. Establishing the requisite height is important not just to maximize the fuel cell performance but also to minimize manufacturing and portability difficulties. Kitamura et all [55, 56] proved that increasing the angle of inclination enhances the effects of natural convection and represents an increase in the airflow rate. Their data indicated that a higher angle of inclination yields higher volume flow of air and lower temperatures as illustrated in Figure 6 and Figure 7.

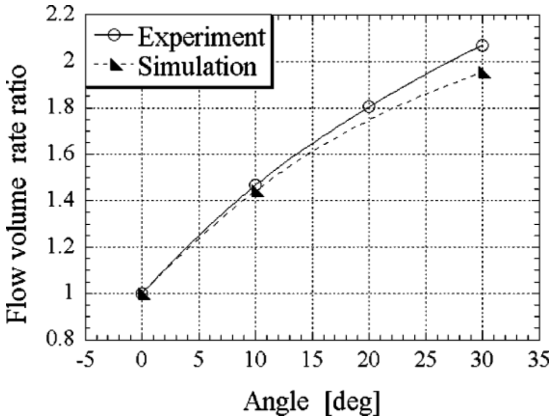


Figure 6: Effect of inclination on volume flow ratio [55]

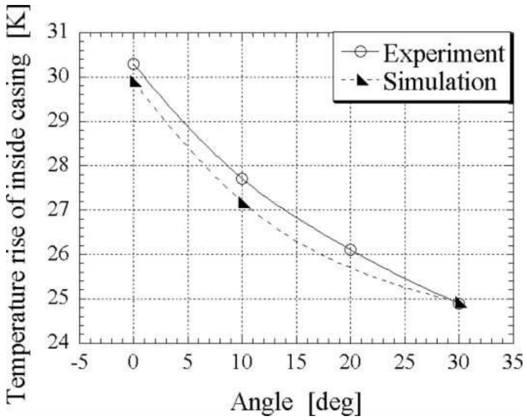


Figure 7: Effect of inclination on temperature inside casing [55]

As an extension of their work, this research numerically investigated the ideal dimensions of the chimney. Using Equation 1, the air draft [Q] in the chimney at different temperatures was calculated (Table 1).

$$Q = C_d * A * \sqrt{[2gh(T_i - T_0)/T_i]} \qquad \text{Equation 1}$$

Where Q is the volume of air draft (m^3/s), C_d is a discharge coefficient, A is the free area of inlet opening (m^2), g is the acceleration due to gravity, h is the vertical distance between inlet and outlet midpoints (m), T_i is the average of the temperature inside the chimney (K), and T_e is the external air temperature (K). Data from Table indicated that when chimney heights were less than 12 centimeters there was a significant increase in the volume of the air draft produced. Above this threshold the increase in air flow volume was less pronounced. The temperature T_i employed in the calculation, mimics the steady-state operating temperature of a nafion membrane. While a draft was produced in every situation the increase in air flow volume was less pronounced at larger heights as seen in Figure 8.

Table 1: Calculations of air draft present in a chimney of uniform diameter and varying heights.

Height(cm)	**C**	**A**	**2g**	**T_i**	**T_e**	**$T=(T_i-T_e)/T_e$**	**2ghT**	**SQRT**	**Q(10^{-4} m^3/s)**
2	0.65	0.00141	19.6	322.35	297.15	0.078176	0.030645	0.175057	1.6044
4	0.65	0.00141	19.6	322.98	297.15	0.079974	0.0627	0.250399	2.2949
6	0.65	0.00141	19.6	324.18	297.15	0.08338	0.098054	0.313136	2.8699
8	0.65	0.00141	19.6	325.99	297.15	0.088469	0.138719	0.37245	3.4135
10	0.65	0.00141	19.6	328.55	297.15	0.095571	0.18732	0.432805	3.9667
12	0.65	0.00141	19.6	329.05	297.15	0.096946	0.228016	0.477511	4.3764
14	0.65	0.00141	19.6	324.15	297.15	0.083295	0.228561	0.47808	4.3816
16	0.65	0.00141	19.6	322.25	297.15	0.07789	0.244263	0.494229	4.5296

The increase in height was producing a cooling effect (shown in Figure 9) which was detrimentally affecting the air draft. Therefore recommended values of chimney height for this research are estimated to be 12 cm and below. This determination also works favorably towards the ease of manufacture and portability.

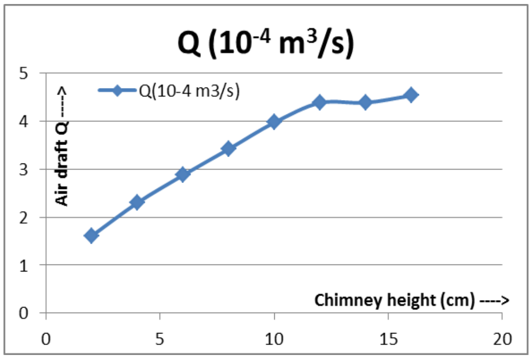


Figure 8: Diminishing returns in the air draft with an increase in chimney height

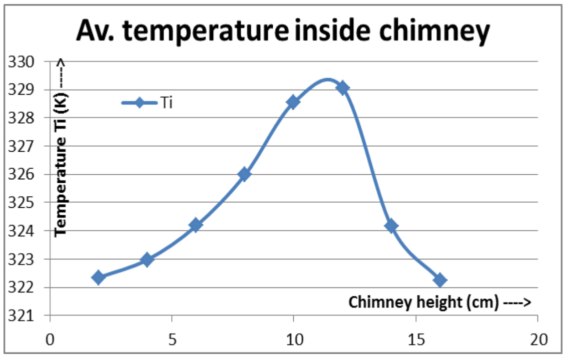


Figure 9: Average temperature inside the chimney indicating a cooling effect with increase in chimney height

Kitamura et al.’s research [56] also indicates that the angle of inclination plays an important role in reducing temperature of the heat producing surface and the casing of the electronic equipment. An interesting side to the research presented in this paper is the investigation of the inclination angle as shown in Figure 10. Straight and sloped chimneys of height 16cm were investigated by varying load on the fuel cell between 0.8-1 amperes. While data from Table 1 indicated a favorable height of 12cm, that assessment was for a predefined cylindrical shape. The same could not be applied across the other shapes and cross-sections involved in this analysis and hence a value of 16 cm was chosen. Of the chimney designs investigated, one was without any inclination whereas the other had a slant of 30 degrees as shown in the Figure 10. It was noticed that an increase in the angle of inclination produced an increase in the air flow.

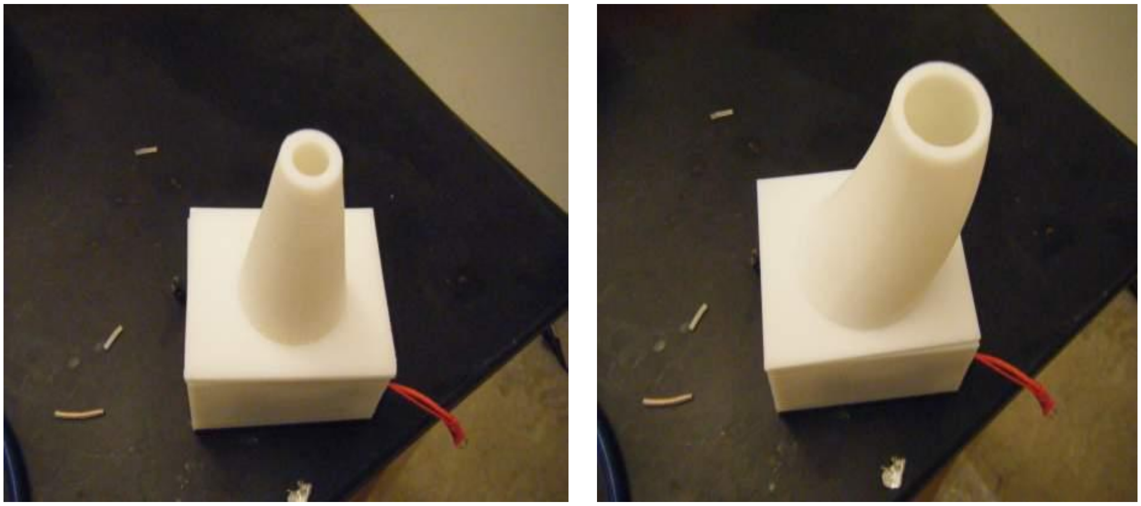


Figure 10: Chimney design modeled with the FDM indicating chimney's with and without inclination on the left and right respectively.

This result was in agreement with research conducted by Bassiouny et al during their investigation of solar chimney's for energy efficient buildings [63]. Again FDM proved beneficial to fabricating these diverse chimney shapes whose manufacture would be prohibitively complex and expensive using conventional machining processes.

1.7.2. Case study 2: Chimney-shaped fuel cell design – An overview

The results of case study one have shown that chimney shaped attachments can significantly improve air flow and fuel cell performance. While a twenty four percent performance improvement is significant the attachments are bulky and could be impractical in many situations. Next, the research team wanted to achieve these benefits of natural convective air flow in fuel cells without the added attachments. The research thereby theorized a novel PEM fuel cell design that mimics the shape of a chimney and is shaped like a cylinder. While conventional fuel cell strategy has always been based on flat, plate-like structures, by creating a novel chimney shaped design the research hopes to incorporate the tangible advantages of chimneys into portable air-breathing PEM fuel cells.

1.7.2.1.Numerical models of natural convection

Preliminary Finite Element Method (FEM) simulations performed using FLUENT flow modeling software, support the hypothesis as shown in Figure 11 and Table 2. Table 2 shows values of draft velocity generated using flow simulations in FLUENT. The fuel cell temperature is retained at 75^{o}C, owing to the fact that Nafion membrane will dehydrate beyond this temperature. The simulations were performed at a wide range of ambient temperatures. As it can be seen from Table 2, a draft is produced in all the situations while it is more predominant at lower ambient air temperatures. This was expected and validates the basic concept of the chimney. This leads to the conclusion that if the packaging around the new fuel cell is designed and built without hindrance to flow it is theoretically possible to create forced convection without any peripheral attachments.

Table 2: Convective air velocity produced at various ambient temperatures generated using FLUENT.

S. No	Fuel cell temperature (C)	Ambient air temperature (C)	Maximum draft velocity produced (mm/s)
1	75	-50	270
2	75	-25	190
3	75	0	160
4	75	25	110
5	75	50	50

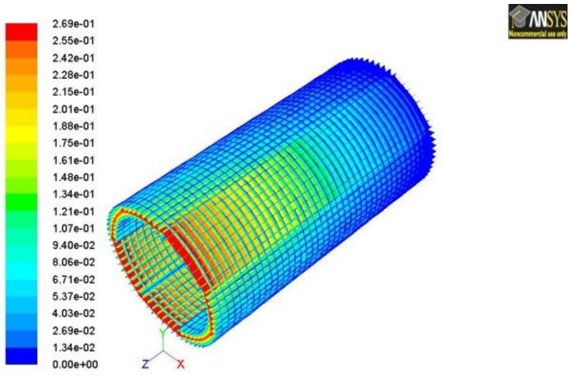


Figure 11: Velocity diagram indicating the occurrence of the chimney effect

1.7.2.2. Novel cylinder shaped fuel cell with improved fluid flow on the hydrogen side as well

The new portable air-breathing PEM fuel cell was then designed taking into consideration common problems associated with PEM cells like sealing and clamping force. The mandrel (Figure 13) was designed to include the inlet and exit caps (Figure 12) and was assembled into a cylindrical tube that acted as a frame. The mandrel houses the fuel flow channels employed to evenly distribute the reactant fluid (hydrogen) across the entire surface area. The inlet and exit caps have been designed to include manifold sections (shown in blue lines in Figure 14) without compromising the structural integrity or the seal-ability of this design. To help with weight savings, this section was made of polycarbonate. Stainless steel wire of 0.5 mm thickness and 8 m length was used for both the hydrogen side electrode and the air side electrode. The wire size was chosen to maximize the number of contact sections and thereby contact points with the membrane. There are 160 wire sections each on either side of the membrane in this design. Theoretical calculations into the chosen stainless steel wires current carrying capacity have indicated that the wire can carry 4.15 Amps of current. The threads, in conjunction with solvent welding were used to completely eliminate hydrogen leaks. While the design decision to create a chimney shaped design was made to assimilate the advantages of natural convection on the air side of the PEM fuel cell, it had the added benefit of improving the fluid flow of the hydrogen side as well. The benefit is the possibility of multiple inlets and exits for fuel to flow through. Figure 15 and Figure 16 are mass fractions of hydrogen and air in the conventional and new designs respectively. Conventional design’s flow channels always employed a single inlet and exit point. As Newtonian fluids flow across sections of least energy loss there is a possibility of the formation of low velocity stagnant zones as seen in Figure 15 (indicated by the blue, green and yellow zones). This is common problem in conventional design’s flow channels especially with an increase in the channel’s length.

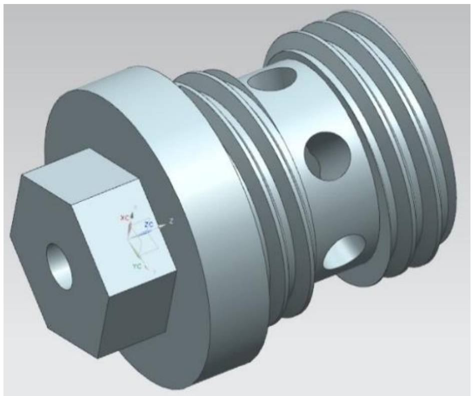


Figure 12: Inlet and exit caps designs with threads to help sealing

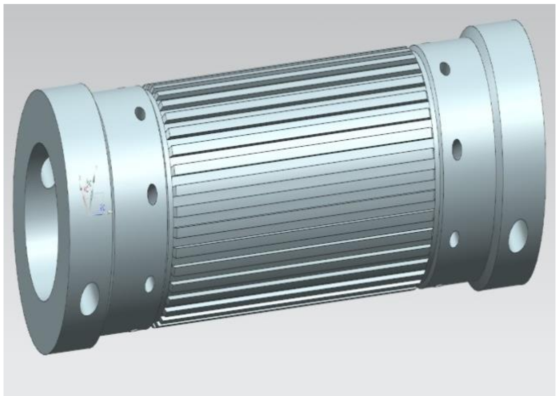


Figure 13: Mandrel sections housing fuel flow channels

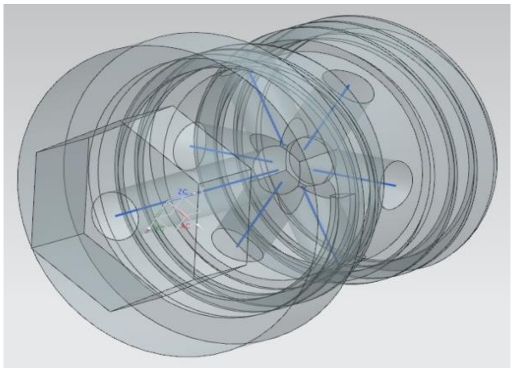


Figure 14: Inlet/exit cap with manifold sections for fuel flow indicated in blue

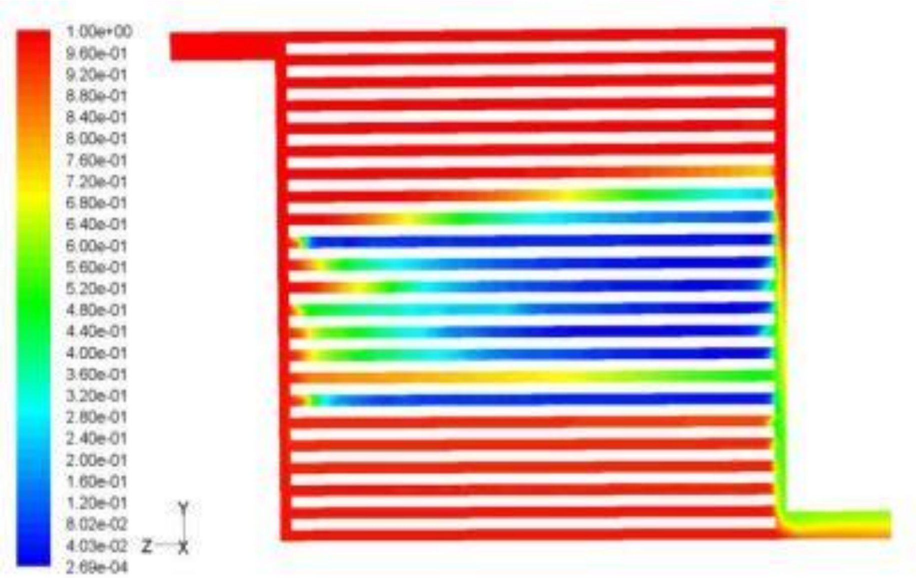


Figure 15: Mass fractions of flow channels in conventional fuel cell design with stagnant zones with low velocities. Blue and colored zones retain air in varying percentages which reduces PEM fuel cell efficiency

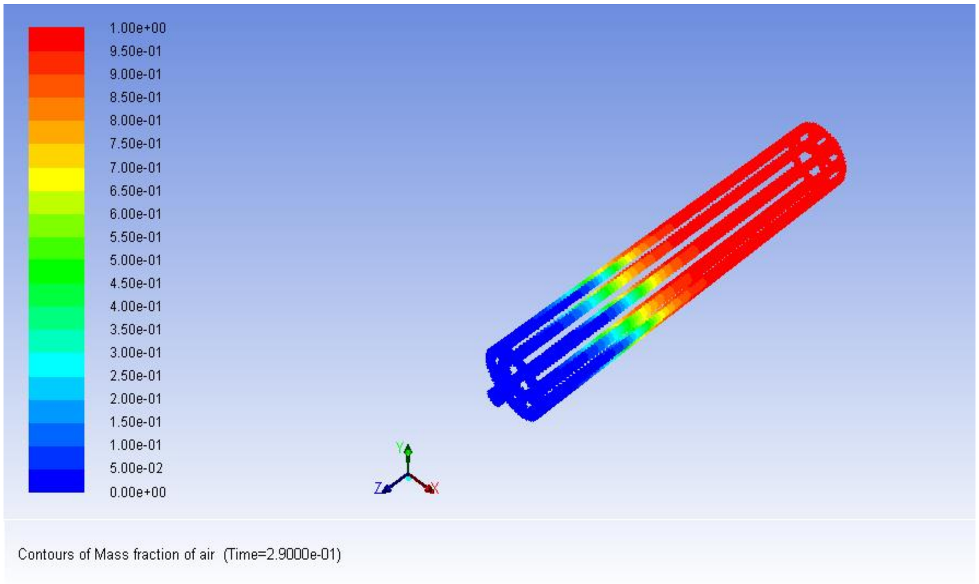


Figure 16: Mass fractions of same flow channels in new chimney shaped design without any stagnant zones. With multiple inlets/exits flow is more streamlined with hydrogen perfectly displacing air

While this can be remedied by increasing inlet pressure or the numbers of inlets/exits, both solutions are expensive, increase manufacturing complexity and weight, and thereby would be unsuitable for portable applications. In the new cylindrical design though, the ability to create multiple inlets and exits for the fuel flow is straightforward as shown in the end caps (Figure 14). In this case the fuel exhibits streamlined flow with the hydrogen fuel perfectly displacing air. The modelling and analysis results indicate that this design is more suitable for portable applications, as is the research need.

1.7.3. Development of working prototypes

Using the results of the two case studies, working prototypes of the new PEM fuel cell design were manufactured. Multiple prototypes of the new design were manufactured in-house as proof of concept. The mandrel and end caps were manufactured using plastics while Stainless Steel-316 (SS-316) wire was used for the electrodes. The plastics employed during prototyping evolved from Teflon to polycarbonate and ABS owing to their favorable temperature regimes and ability to be fabricated using FDM. Unlike conventional PEM fuel cells the mandrel (Figure 17) acts as the base around which the entire cell is built. Comparable to the flow plates of the conventional PEM fuel cell it is one of the most important components in the assembly. An electrode (stainless steel wire) is wrapped around the mandrel which is followed by the polymer electrolyte membrane being wrapped around the electrode.

Figure 17: Chimney shaped mandrel manufactured using FDM

Figure 18: Prototype of chimney shaped air-breathing PEM fuel cell

Another electrode is wrapped next around the membrane, finished with an enclosure which serves as a permeable air source. The two stainless steel wire wrapping on either side of the membrane act as the cathode and the anode. A working prototype manufactured in-house is shown in Figure 18. While theoretical data shows that the new chimney shaped design enjoys superior reactant flow characteristics, this design has also helped negate common problems associated with conventional PEM fuel cells. This design has reduced weight and improved portability owing to the fact that stainless steel wire winding is naturally compressive and more conductive when compared to conventional graphite flat plate designs. This eliminates the need for graphite flow plates and metal end plates and thereby ensures the design remains light. The extensive use of plastics reduces expensive tooling requirements necessary for graphite and metal plates and reduces time of manufacture thereby ensuring low cost. The use of plastics also enables the use of solvent welding to ensure leak proof sealing against hydrogen. Working prototypes of the new design with a power output of 0.18W have been manufactured. While this value might be low, the new prototype still has four-fold increased power density over conventional designs. The research is currently focused on further improving the power output.

This research also quantified the advantages that FDM based additive manufacturing has brought to this new chimney shaped design. Table 3 details a comparative study of the mandrel (Figure 17) manufactured using both conventional lathe operations and FDM. The cost and time estimates are based on a 6-axis twin spindle lathe as the indexing needed to machine the grooves on the mandrel pose significant challenges in conventional lathe machines. FDM though does not have these design limitations. While employing FDM does increase the manufacturing time as compared to conventional lathe operations, FDM more than makes up for the shortcoming with the reduced material used and cost. FDM uses only half the material and is also nearly forty percent cost effective as compared to conventional lathe operations. There is also a significant setup time involved with the lathe operations which is not the case in FDM. The adoption of the new design and manufacturing practices has led to an improved economy of manufacture and working prototypes of the chimney shaped designs.

Table 3: Comparison of the manufacture-ability of the new mandrel using conventional lathe operations and FDM

	Conventional multi-axes lathe operation ($125/hr)	**Fused Deposition Modelling ($47/hr)**	**Percentage Change**
Manufacturing time (mins)	9	22	**-144**
Setup and post processing time (mins)	5	1	**80**
Material volume (mm^3)	50671	26851	**47**
Total Cost ($)	30.6	18.8	**39**

1.8.CONCLUSIONS

From the results established through this research, it was concluded that

- Chimney attachments improve the performance of air-breathing PEM fuel cells.
- Chimney attachments increase voltage by 21% and power by 24% over conventional cells.
- Numerical studies and analytical models support the occurrence of natural convection in portable PEM fuel cells.

- Theoretical studies can be used to ascertain dimensional values of the chimney attachments and the height and inclination angle values determined are supported by literature.
- Analytical models also indicate improved fluid dynamics on the hydrogen side owing to the shape of the new design which facilitates multi-point fuel inlet and exit.
- It is possible to create chimney shaped air-breathing PEM fuel cells.
- As proof, working prototypes of this new design have been successfully manufactured.
- The new design and manufacturing practices also lead to significant material and cost savings.

1.9.ACKNOWLEDGEMENT

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1.10. REFERENCES

[1] Farooque, M., and Maru, H. C., 2001, "Fuel Cells - The Clean and Efficient Power Generators," Proceedings of the IEEE, 89(12), pp. 1819-1829.

[2] Prater, K. B., 1994, "Polymer electrolyte fuel cells: a review of recent developments," Journal of Power Sources, 51(1-2), pp. 129-144.

[3] Smith, W., 2000, "Role of fuel cells in energy storage," J Power Sources, 86(1), pp. 74-83.

[4] Shimpalee, S., and Van Zee, J. W., 2007, "Numerical studies on rib & channel dimension of flow-field on PEMFC performance," International Journal of Hydrogen Energy, 32(7), pp. 842-856.

[5] Shimpalee, S., Greenway, S., and Van Zee, J. W., 2006, "The impact of channel path length on PEMFC flow-field design," Journal of Power Sources, 160(1), pp. 398-406.

[6] Kumar, A., Reddy, R. G., , 2003, "Effect of channel dimensions and shape in the flow-field distributor on the performance of polymer electrolyte membrane fuel cells," Journal of Power Sources, 113, pp. 11-18.

[7] He, W., Yi, J. S., and Van Nguyen, T., 2000, "Two-phase flow model of the cathode of PEM fuel cells using interdigitated flow fields," AIChE Journal, 46(10), pp. 2053-2064.

[8] Jeon, D. H., Greenway, S., Shimpalee, S., and Van Zee, J. W., 2008, "The effect of serpentine flow-field designs on PEM fuel cell performance," International Journal of Hydrogen Energy, 33(3), pp. 1052-1066.

[9] Nguyen, P. T., Berning, T., and Djilali, N., 2004, "Computational model of a PEM fuel cell with serpentine gas flow channels," Journal of Power Sources, 130(1-2), pp. 149-157.

[10] Wang, Z. H., Wang, C. Y., and Chen, K. S., 2001, "Two-phase flow and transport in the air cathode of proton exchange membrane fuel cells," Journal of Power Sources, 94(1), pp. 40-50.

[11] Mann, R. F., Amphlett, J. C., Hooper, M. A. I., Jensen, H. M., Peppley, B. A., and Roberge, P. R., 2000, "Development and application of a generalized steady-state electrochemical model for a PEM fuel cell," J Power Sources, 86(1), pp. 173-180.

[12] Um, S., and Wang, C. Y., 2004, "Three-dimensional analysis of transport and electrochemical reactions in polymer electrolyte fuel cells," Journal of Power Sources, 125(1), pp. 40-51.

[13] Wang, C., Nehrir, M. H., and Shaw, S. R., 2005, "Dynamic models and model validation for PEM fuel cells using electrical circuits," IEEE Transactions on Energy Conversion, 20(2), pp. 442-451.

[14] Baschuk, J. J., and Li, X., 2000, "Modelling of polymer electrolyte membrane fuel cells with variable degrees of water flooding," J Power Sources, 86(1), pp. 181-196.

[15] Li, X., Sabir, I., and Park, J., 2007, "A flow channel design procedure for PEM fuel cells with effective water removal," Journal of Power Sources, 163(2), pp. 933-942.

[16] You, L., and Liu, H., 2002, "A two-phase flow and transport model for the cathode of PEM fuel cells," International Journal of Heat and Mass Transfer, 45(11), pp. 2277-2287.

[17] Rowe, A., and Li, X., 2001, "Mathematical modeling of proton exchange membrane fuel cells," Journal of Power Sources, 102(1-2), pp. 82-96.

[18] Shan, Y., and Choe, S. Y., 2005, "A high dynamic PEM fuel cell model with temperature effects," Journal of Power Sources, 145(1), pp. 30-39.

[19] Sivertsen, B. R., and Djilali, N., 2005, "CFD-based modelling of proton exchange membrane fuel cells," Journal of Power Sources, 141(1), pp. 65-78.

[20] Ahn, J.-W., and Choe, S.-Y., 2008, "Coolant controls of a PEM fuel cell system," Journal of Power Sources, 179(1), pp. 252-264.

[21] Bazylak, A., Sinton, D., Liu, Z. S., and Djilali, N., 2007, "Effect of compression on liquid water transport and microstructure of PEMFC gas diffusion layers," Journal of Power Sources, 163(2), pp. 784-792.

[22] Pharoah, J. G., 2005, "On the permeability of gas diffusion media used in PEM fuel cells," Journal of Power Sources, 144(1), pp. 77-82.

[23] Spernjak, D., Prasad, A. K., and Advani, S. G., 2007, "Experimental investigation of liquid water formation and transport in a transparent single-serpentine PEM fuel cell," Journal of Power Sources, 170(2), pp. 334-344.

[24] Wang, L., Husar, A., Zhou, T., and Liu, H., 2003, "A parametric study of PEM fuel cell performances," International Journal of Hydrogen Energy, 28(11), pp. 1263-1272.

[25] Wang, L., and Liu, H., 2004, "Performance studies of PEM fuel cells with interdigitated flow fields," Journal of Power Sources, 134(2), pp. 185-196.

[26] Kandlikar, S. G., and Lu, Z., 2009, "Thermal management issues in a PEMFC stack - A brief review of current status," Applied Thermal Engineering, 29(7), pp. 1276-1280.

[27] Satija, R., Jacobson, D. L., Arif, M., and Werner, S. A., 2004, "In situ neutron imaging technique for evaluation of water management systems in operating PEM fuel cells," Journal of Power Sources, 129(2), pp. 238-245.

[28] Borup, R. L., Davey, J. R., Garzon, F. H., Wood, D. L., and Inbody, M. A., 2006, "PEM fuel cell electrocatalyst durability measurements," Journal of Power Sources, 163(1 SPEC. ISS.), pp. 76-81.

[29] Cai, M., Ruthkosky, M. S., Merzougui, B., Swathirajan, S., Balogh, M. P., and Oh, S. H., 2006, "Investigation of thermal and electrochemical degradation of fuel cell catalysts," Journal of Power Sources, 160(2 SPEC. ISS.), pp. 977-986.

[30] Collier, A., Wang, H., Zi Yuan, X., Zhang, J., and Wilkinson, D. P., 2006, "Degradation of polymer electrolyte membranes," International Journal of Hydrogen Energy, 31(13), pp. 1838-1854.

[31] Colón-Mercado, H. R., and Popov, B. N., 2006, "Stability of platinum based alloy cathode catalysts in PEM fuel cells," Journal of Power Sources, 155(2), pp. 253-263.

[32] Curtin, D. E., Lousenberg, R. D., Henry, T. J., Tangeman, P. C., and Tisack, M. E., 2004, "Advanced materials for improved PEMFC performance and life," J Power Sources, 131(1-2), pp. 41-48.

[33] Qi, Z., He, C., and Kaufman, A., 2002, "Effect of CO in the anode fuel on the performance of PEM fuel cell cathode," Journal of Power Sources, 111(2), pp. 239-247.

[34] Nallathambi, V., Lee, J. W., Kumaraguru, S. P., Wu, G., and Popov, B. N., 2008, "Development of high performance carbon composite catalyst for oxygen reduction reaction in PEM Proton Exchange Membrane fuel cells," Journal of Power Sources, 183(1), pp. 34-42.

[35] Wood, T. E., Tan, Z., Schmoeckel, A. K., O'Neill, D., and Atanasoski, R., 2008, "Non-precious metal oxygen reduction catalyst for PEM fuel cells based on nitroaniline precursor," Journal of Power Sources, 178(2), pp. 510-516.

[36] Wang, B., 2005, "Recent development of non-platinum catalysts for oxygen reduction reaction," Journal of Power Sources, 152(1-2), pp. 1-15.

[37] Tang, H., Qi, Z., Ramani, M., and Elter, J. F., 2006, "PEM fuel cell cathode carbon corrosion due to the formation of air/fuel boundary at the anode," Journal of Power Sources, 158(2 SPEC. ISS.), pp. 1306-1312.

[38] Hamelin, J., Agbossou, K., Laperrière, A., Laurencelle, F., and Bose, T. K., 2001, "Dynamic behavior of a PEM fuel cell stack for stationary applications," International Journal of Hydrogen Energy, 26(6), pp. 625-629.

[39] Lin, P., Zhou, P., and Wu, C. W., 2009, "A high efficient assembly technique for large PEMFC stacks. Part I. Theory," Journal of Power Sources, 194(1), pp. 381-390.

[40] Kim, H., Subramanian, N. P., and Popov, B. N., 2004, "Preparation of PEM fuel cell electrodes using pulse electrodeposition," Journal of Power Sources, 138(1-2), pp. 14-24.

[41] Laskowski, C., Gallagher, R., Winn, A., and Derby, S., "Automated fuel cell stack assembly: Lessons in design-for-manufacture," Proc. ASME 2010 8th International Conference on Fuel Cell Science, Engineering and Technology, FUELCELL 2010, June 14, 2010 - June 16, 2010, American Society of Mechanical Engineers, pp. 497-503.

[42] Isanaka, S. P., Sparks, T. E., Liou, F. F., and Newkirk, J. W., "Design strategy for reducing manufacturing and assembly complexity of air-breathing Proton Exchange Membrane Fuel Cells (PEMFC)," Journal of Manufacturing Systems.

[43] Fly, A., and Thring, R. H., "System thermal and water balance in an evaporatively cooled PEM fuel cell vehicle," Proc. Vehicle Thermal Management Systems Conference, VTMS 2011, May 15, 2013 - May 16, 2013, Woodhead Publishing Limited, pp. 267-277.

[44] Benziger, J., Chia, J. E., Kimball, E., and Kevrekidis, I. G., 2007, "Reaction dynamics in a parallel flow channel PEM fuel cell," Journal of the Electrochemical Society, 154(8), pp. B835-B844.

[45] Chiang, H.-L., Feng, T.-L., Su, A., and Huang, Z.-M., "Performance analysis of an open-cathode PEM fuel cell stack," Proc. 16th International Conference on Advanced Materials and Processing Technologies, AMPT 2013, September 22, 2013 - September 26, 2013, Trans Tech Publications, pp. 630-634.

[46] Modroukas, D., Frechette, L. G., and Modi, V., "An experimental and numerical study of two-phase flow and transport in miniature open-air proton exchange membrane fuel cells," Proc. 1st European Fuel Cell Technology and Applications Conference 2005, EFC2005, December 14, 2005 - December 16, 2005, American Society of Mechanical Engineers, p. 128.

[47] Al-Baghdadi, M. A. R. S., 2008, "Three-dimensional computational fluid dynamics model of a tubular-shaped ambient air-breathing proton exchange membrane fuel cell," Proceedings of the Institution of Mechanical Engineers, Part A: Journal of Power and Energy, 222(6), pp. 569-585.

[48] Zhou, Z., Ming, T., Pan, Y., Liu, W., and Huang, S., 2011, "Analysis on the thermodynamic performance of the solar chimney power generation systems," Taiyangneng Xuebao/Acta Energiae Solaris Sinica, 32(1), pp. 72-76.

[49] Booth, W. H., 1904, "Chimney action," Electrical Review, London.

[50] Third, A. D., 1967, "Aim of chimney design," Engineering and Boiler house Review, 82(5), pp. 124-128.

[51] Pritchard, B. N., 1996, "Industrial chimneys: a review of the current state of the art," Proceedings of the Institution of Civil Engineers: Structures and Buildings, 116(1), pp. 69-81.

[52] Andreozzi, A., Buonomo, B., and Manca, O., 2010, "Thermal and fluid dynamic behaviors in symmetrical heated channel-chimney systems," International Journal of Numerical Methods for Heat and Fluid Flow, 20(7), pp. 811-833.

[53] Han, Z., and Agonafer, D., "Numerical studies on chimney-enhanced natural convection," Proc. Advances in Electronic Packaging, July 8, 2001 - July 13, 2001, American Society of Mechanical Engineers, pp. 1769-1774.

[54] Lau, G. E., Timchenko, V., Reizes, J., Fossa, M., and Yeoh, G. H., "Natural convection in an asymmetrically-heated open-ended channel: A three-dimensional computational study," Proc. ASME 2013 Heat Transfer Summer Conference, HT 2013 Collocated with the ASME 2013 7th International Conference on Energy Sustainability and the ASME 2013 11th International Conference on Fuel Cell Science, Engineering and Technology, July 14, 2013 - July 19, 2013, American Society of Mechanical Engineers, p. Heat Transfer Division.

[55] Kitamura, Y., and Ishizuka, M., 2004, "Study on chimney effect in natural air cooled electronic equipment casings under inclination (the proposal of a thermal design correlation with inclination)," Nippon Kikai Gakkai Ronbunshu, B Hen/Transactions of the Japan Society of Mechanical Engineers, Part B, 70(696), pp. 2097-2104.

[56] Kitamura, Y., Ishizuka, M., and Nakagawa, S., 2006, "Study on the chimney effect in natural air-cooled electronic equipment casings under inclination: Proposal of a thermal design correlation that includes the porosity coefficient of an outlet opening," Heat Transfer - Asian Research, 35(2), pp. 122-136.

[57] Mey, G. D., Wojcik, M., Pilarski, J., Lasota, M., Banaszczyk, J., Vermeersch, B., Napieralski, A., and Paepe, M. D., 2009, "Chimney effect on natural convection cooling of a transistor mounted on a cooling fin," Journal of Electronic Packaging, Transactions of the ASME, 131(1), pp. 0145011-0145013.

[58] Joneydi Shariatzadeh, O., Refahi, A. H., Abolhassani, S. S., and Rahmani, M., 2015, "Modeling and optimization of a novel solar chimney cogeneration power plant combined with solid oxide electrolysis/fuel cell," Energy Conversion and Management, 105, pp. 423-432.

[59] Ming, T. Z., Zheng, Y., Liu, C., Liu, W., and Pan, Y., 2010, "Simple analysis on thermal performance of solar chimney power generation systems," Journal of the Energy Institute, 83(1), pp. 6-11.

[60] Boersma, R. J., Sammes, N. M., and Fee, C., 2000, "Integrated fuel cell system with tubular solid oxide fuel cells," Journal of Power Sources, 86(1), pp. 369-375.

[61] Shi, Z., Peng, Y., and Wei, W., 2014, "Recent advance on fused deposition modeling," Recent Patents on Mechanical Engineering, 7(2), pp. 122-130.

[62] Choi, J.-W., Medina, F., Kim, C., Espalin, D., Rodriguez, D., Stucker, B., and Wicker, R., 2011, "Development of a mobile fused deposition modeling system with enhanced manufacturing flexibility," Journal of Materials Processing Technology, 211(3), pp. 424-432.

[63] Bassiouny, R., and Korah, N. S. A., 2009, "Effect of solar chimney inclination angle on space flow pattern and ventilation rate," Energy and Buildings, 41(2), pp. 190-196.

SECTION

4. CONCLUSION

This research set out to investigate alternate design and manufacturing strategies towards air-breathing portable PEM fuel cells. The research theorized significant benefits to fluid flow, power densities and cost, using these novel design and manufacturing strategies. The three papers presented in this dissertation document the research and success achieved in this regard. Some of the highlights include

- The successful development of non-primatic designs and the manufacture of working prototypes
- Research into alternate materials for the flow plates and current collectors
- Numerical and experimental proof of improvements in fluid flow
- Reduction in the manufacturing and assembly complexity and cost
- Development of alternate fastening mechanism and designs for improved sealing

APPENDIX

UNPUBLISHED ANALYTICAL DATA ON STACKING

As a progression to any fuel cell system the effects of stacking on the fluid flow were assessed using FLUENT simulation software. Figure 1 and Figure 2 detail the pressure and velocities of a stacked fuel cell system containing 4 individual cells.

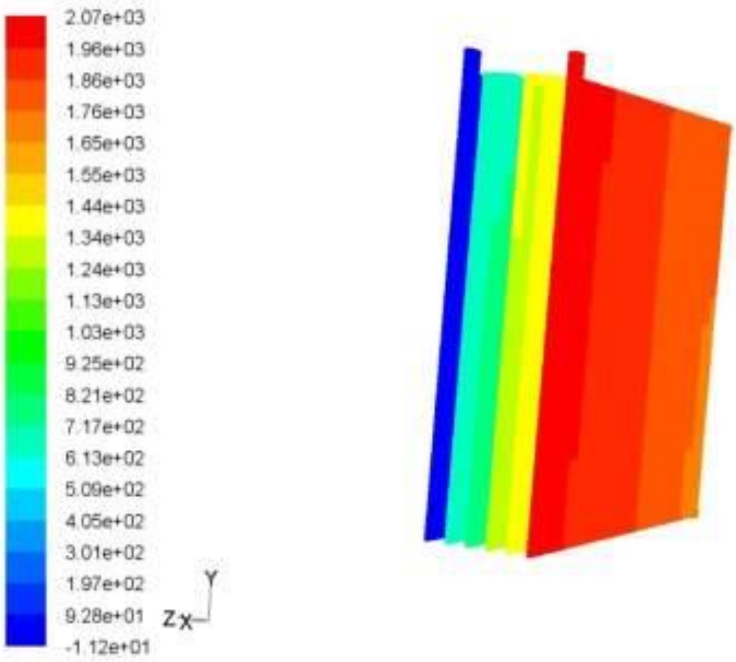

Figure 1: Simulated data on the effects of stacking.

During the course of the research it was noticed that some of the hydrogen in the flow fields was being expelled through the exit without utilization. In an effort to increase the hydrogen fuel utilization the research theorized the linking of one cell's exit to the entry of the next. The simulated data indicated that this idea was unsuitable owing to the excessive pressure drops and energy losses it produced across the system.

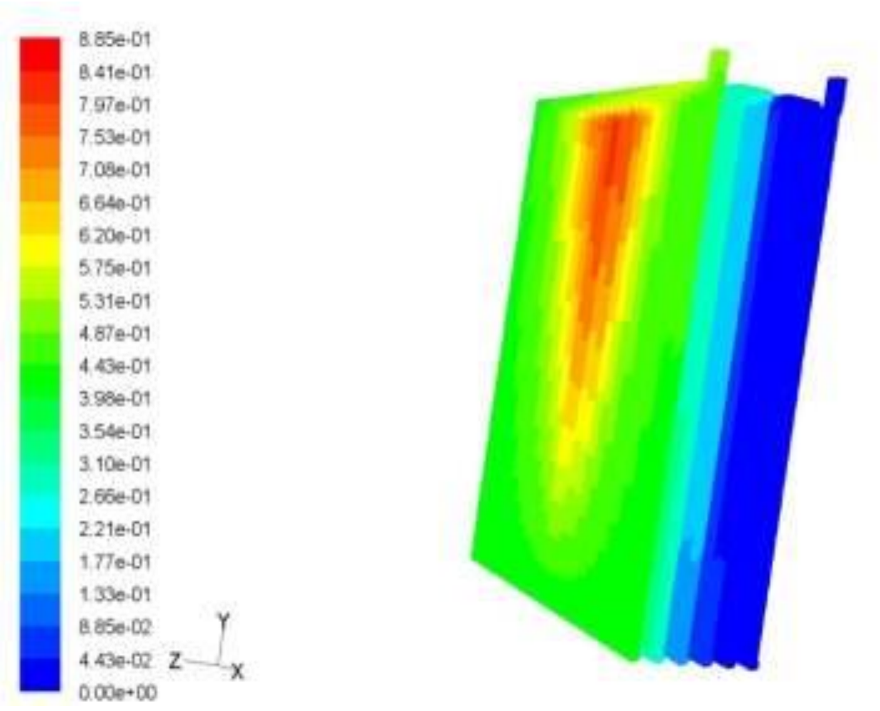

Figure 2: Simulated data of a fuel cell stack where the outlet of one cell is connected to the inlet of the next.

This linkage mimicked a long serpentine channel design, only magnifying its detrimental effects many-fold.

VITA

Sriram Praneeth Isanaka was born in southern India, in the city of Chennai. He studied in schools in and around his hometown and completed his bachelor's degree in mechanical engineering with distinction. Upon receiving his bachelor's degree from Anna University in India, he decided to pursue higher studies in the United States of America. He completed his master's in mechanical engineering in 2009 from the University of Missouri – Rolla. During his masters he conducted research in the area of Rapid Freeze Prototyping and wrote a thesis on the same. After a short break he began to work on his doctoral program. During the course of his doctoral program he conducted research in areas of fuel cells, conventional and unconventional manufacturing, and metal deposition. He has published research material in numerous journal articles and conference proceedings. He actively seeks out knowledge in the areas of additive manufacturing, alternate energy, design and manufacturing strategies, and materials research and characterization. He received his Ph.D. in Mechanical Engineering from the Missouri University of Science and Technology in July 2016.