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Innovative air breathing design and output control for portable proton exchange membrane fuel cell

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INNOVATIVE AIR BREATHING DESIGN AND OUTPUT CONTROL FOR PORTABLE PROTON EXCHANGE MEMBRANE FUEL CELL

by

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ABSTRACT

Proton Exchange Membrane (PEM) Fuel Cell Technology is an energy source that can provide several times more energy per unit volume than current lithium ion batteries that are available in the market today. The barriers that exist that prevent the fuel cell from entering the world of portable applications are mainly system architecture integration. The idea is to have a fully functioning fuel cell with optimum power output using an innovative chimney design.Tests were conducted to quantify the advantage of using a chimney with the fuel cell. Further research was done to shed light on how different chimney designs may perform with cross air across the chimney. This innovative design is approached with taking minimum set up into consideration for the ease of manufacturability. A control circuit for an air breathing design is discussed and a cost model is presented for the same.

ACKNOWLEDGMENTS

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Last but not the least; I would like to thank my family. Their constant inspiration and guidance kept me focused. I can't express my gratitude in words to my parents, Abitha and Sridharan Bala whose unconditional love and support have been my greatest strength. Also, want to sincerely thank my sister for her help and motivation.

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1. INTRODUCTION

1.1. WHAT IS A FUEL CELL

Fuel cells, which have an anode side and cathode side, are electrochemical devices similar to batteries which convert energy from chemical state to electricity. Fuel enters the cell from the anode side and oxidant flows into it from the cathode side. The reactants react inside the cell and the reaction products or the waste products flow out of the fuel cell. The basic difference between batteries and a fuel cell is that fuel cell is only an energy conversion device and not energy storage device. Fuel cells consume reactant (fuel) from an external source which must be replenished. Hence, fuel cells represent a thermodynamically open system. However, batteries are both energy storage and conversion devices and hence they represent a thermodynamically closed system. The advantage of separating the storage and conversion functions is that power and energy capacity can be sized independently of each other.

Presently, most fuel cell research is being done in the area of stationery power and stacks capable of delivering 1-200kW. To create a miniature fuel cell for portable devices in the range of 1-20W, an optimum design cannot be achieved by scaling down a larger system [1]. Rather, a system redesign is required.

The basic cathode-electrolyte-anode construction of a fuel cell is as shown in Figure 1.1. It can be observed that the electrons are flowing from anode to cathode. The cathode is thus electrically positive terminal, since electrons flow from negative to positive terminal. At anode, the hydrogen reacts, releasing energy. The rate at which energy proceeds has the 'classic form' shown in Figure 1. 2.

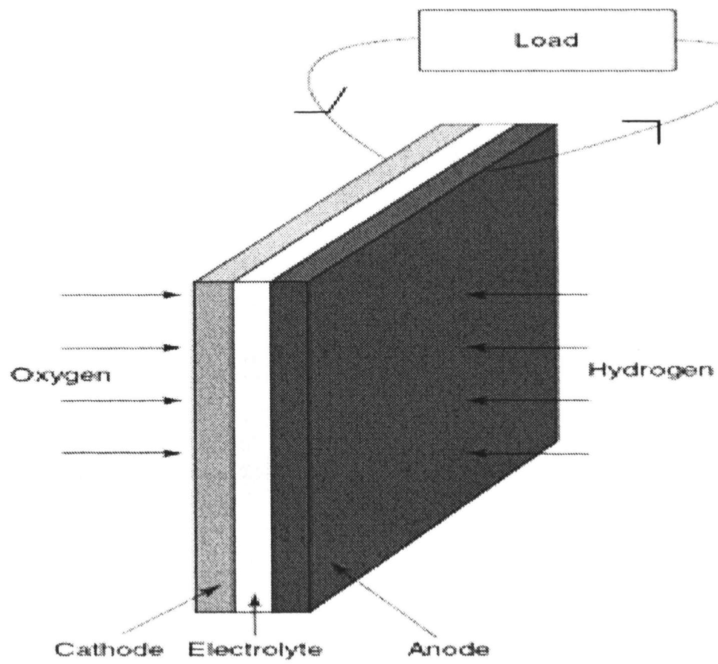


Figure 1.1: Basic cathode-electrode-anode construction of a fuel cell [Larminie p3]

Although energy is released, the 'activation energy' must be supplied to get over the energy hill. If the probability of a molecule having enough energy is low, the reaction proceeds slowly [3]. Slow reactions can be dealt by raising the temperature, using a catalyst or increasing the electrode area.

Increasing the surface area is especially important to fuel cells. It is in the surface of the electrode that the electron is removed and the reaction between water and hydroxyl ion takes place. This reaction involving fuel with the electrolyte and the electrode is called the three phase contact. This is a very important issue in fuel cell design.

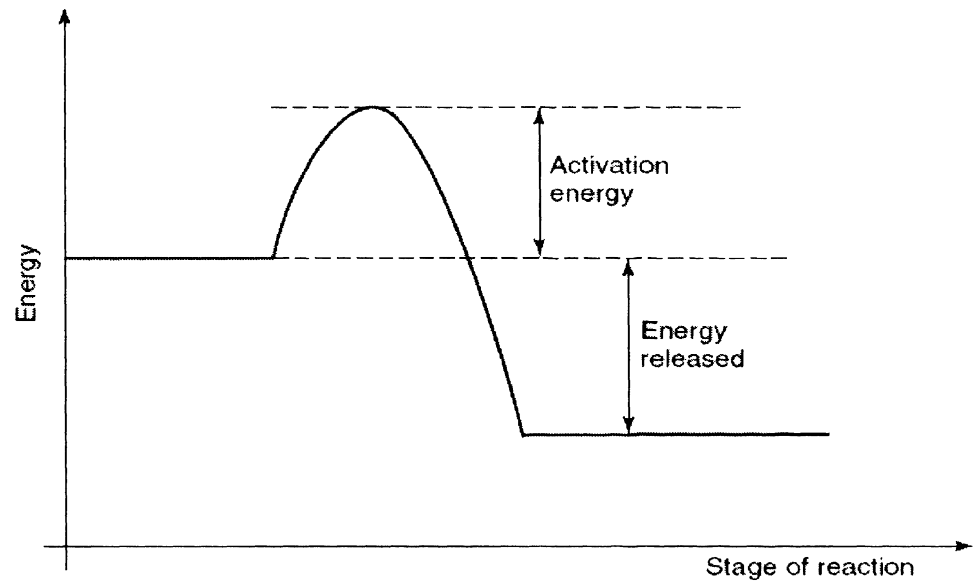


Figure 1.2: Classical energy diagram for a simple exothermic reaction [Larminie, p5]

The key aspects to fuel cell portability are water management, MEA assembly and number of components. Bare minimum numbers of components were used to ensure robust design. The essentials to run a fuel cell are MEA's, current collectors and fuel source. The other components commonly used are gas diffusion layers (GDL), gaskets and purge valves. The usage of these components is design specific.

To be truly portable, it is better not to have power "leeches" in the system. This means experimenting with different set ups on the cathode. Figure 1.3 depicts the design selected for the portable PEM fuel cell.

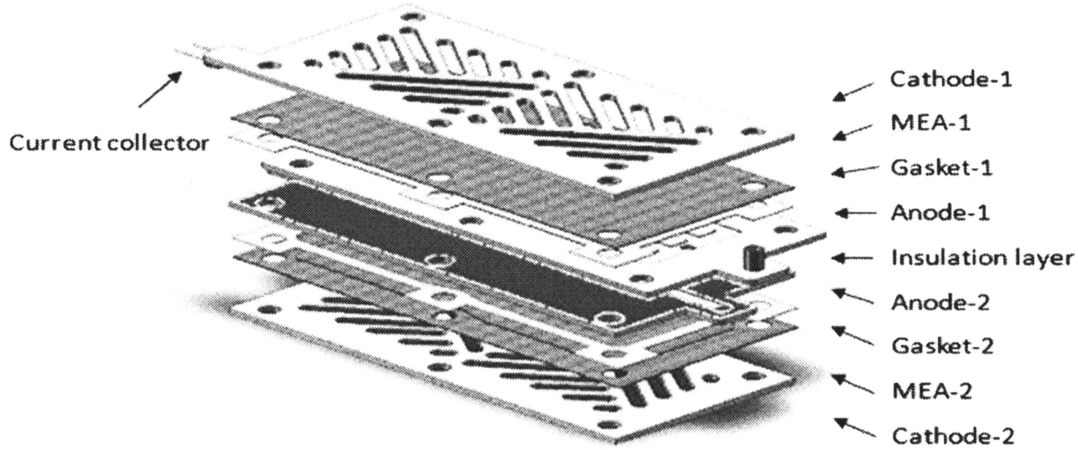


Figure 1.3: Fuel cell assembly [Bussayajarn, p2]

1.2. FUEL CELL TECHNOLOGY

Although the concept of a fuel cell has existed for more than 150 years, it is only in the last 3 decades that research has been done in its application. The initial application of fuel cells was seen only in specialty applications such as military and space industry.

Many fuel cells technologies are being researched for various applications. Solid oxide fuel cells [SOFC's] are larger stationary, high temperature fuel cells. They have the potential to be widely used in large scale power generation system.

Direct methanol fuel cells [DMFC] are used in portable electronics. Most DMFCs use methanol as the main source of fuel. The advantages of using DMFC with methanol are that the energy density of methanol is very high and is also easy to refill. The disadvantage is that the fuel anode reactions proceed more slowly than with hydrogen. Another issue is that of fuel crossover. Methanol mixes with water and reaches the cathode and reduces the open circuit voltage.

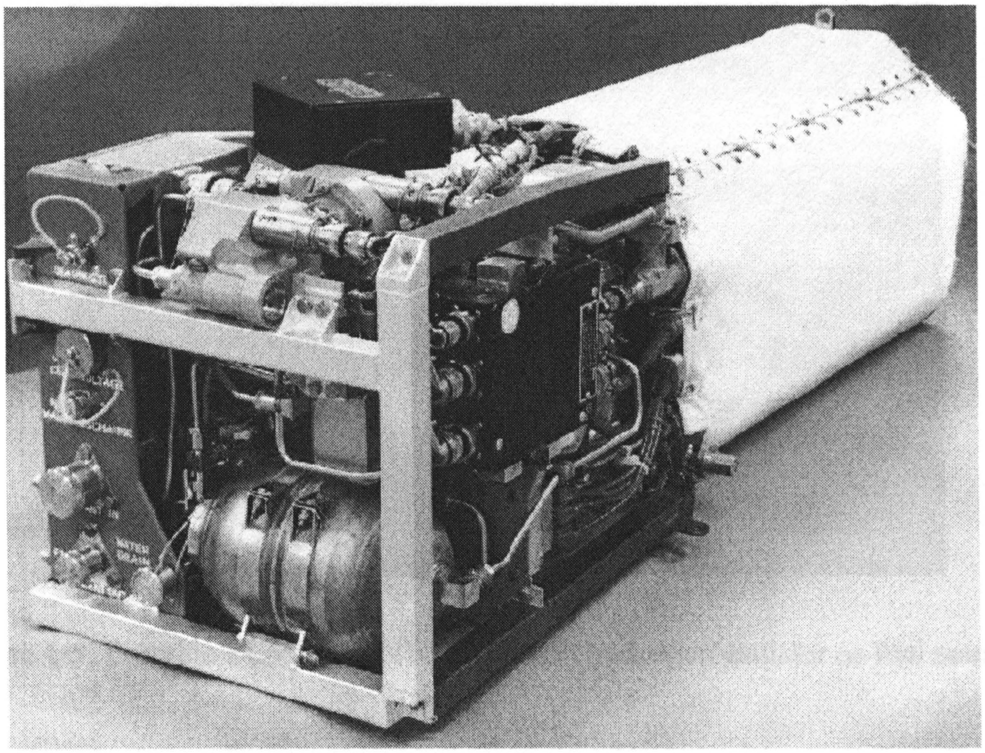


Figure 1.4: A 12 KW fuel cell used in the space shuttle orbiter [Larminie, p124]

PEM fuel cells are very versatile and its range of applications can vary from portable fuel cells to large scale applications. PEM fuel cells have higher density than that of direct methanol fuel cells. This is due to the usage of hydrogen as fuel source as compared to methanol. Some of the challenges of using PEM are storage and refilling of hydrogen gas and safety issues concerned with that. To overcome these issues, a portable metal hydride canister can be used. Metal hydride canisters have relatively high energy density and are safer than using direct hydrogen. Figure 1.5 shows a prototype design of a portable PEM Fuel cell with metal hydride canister as its fuel source. This design was made in Solidworks and rendered in PhotoView360.

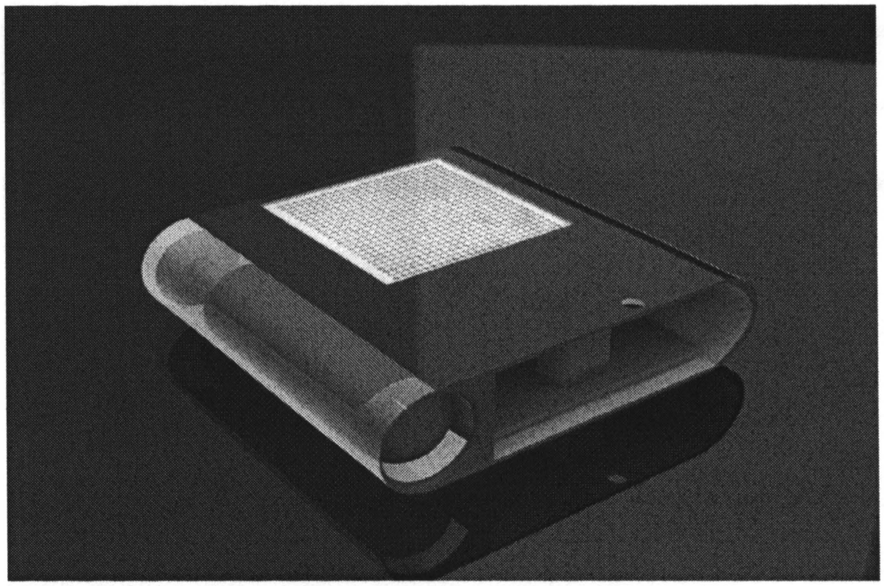


Figure 1.5: Portable PEM fuel cell design with hydrogen canister as fuel source

1. 3. COSTS ASSOCIATED WITH FUEL CELLS

For manufacturing portable PEM fuel cells, it is very important to look from a cost model point of view. The cost breakdown of important parts of fuel cell is as follows

Table 1.1 Contribution of the components to the entire cost of the fuel cells [DOE 2005]

Cell Stack	Membrane	35~40 %
	Catalyst	15~20 %
	Bipolar plates	10~15 %
	MEA's	30~35 %

From Table 1.1 it is seen that the bipolar plates only constitute 10-15% of the cost. Irrespective of that, it is very important to have a good design in a portable fuel cell because oxidation reaction takes place at the cathode and the fuel cell reaction rate is determined by the amount of hydrogen present in the system at any given point in time. To understand the working on the innards of the fuel cell, it is very important to understand the electrochemistry that is going on.

2. BACKGROUND TO PEM FUEL CELLS

2.1. PEM FUEL CELL THEORY

In the PEM fuel cell, hydrogen is the fuel which enters the fuel cell through the anode end and oxygen through the cathode end. The following reactions take place at the cathode and the anode

Anode:	H_2 (g)			→	$2H^+$ (aq) + $2e^-$
Cathode:	1/2 O_2 (g)	+ $2H^+$ (aq)	+ $2e^-$	→	H_2O (l)
Overall Reaction:	H_2 (g)	+ 1/2 O_2 (g)		→	H_2O (l)

The reactions occur in the MEA which consists of active catalysts on both sides of a proton exchange membrane. The catalysts are usually noble metals such as platinum or iridium. The catalyst on the cathode side breaks down H_2 into a proton and electron. The proton is allowed to pass through the proton exchange membrane (PEM) to react with the oxygen at the cathode side.

Apart from the electrochemical reaction occurring, some of the other parameters are commonly used to evaluate fuel cell performance are open circuit voltage (OCV) and standard voltage vs. current (polarization curves) results. The OCV is used to gauge the kinetic efficiency of the fuel cell and the polarization curve gives details about the cell(s) performance.

2.2. POLARIZATION CURVES

A polarization curve is used to quantify the performance of a fuel cell. This is done by plotting the points of range from open circuit voltage to near zero and recording current at all the voltages. Thus the power output of the fuel cell is a simple function of the voltage multiplied by the current. Current density [A/cm^2] and power density [W/cm^2] are the normal conventions used. An example polarization of a 20W PEM fuel cell for back pressure at 50kpa and hydrogen flow rate to anode at 0.7nlpm is as shown in Figure 2.1. The maximum current and power densities obtained were 258.5 mA/cm^2 and 0.31W/cm^2.

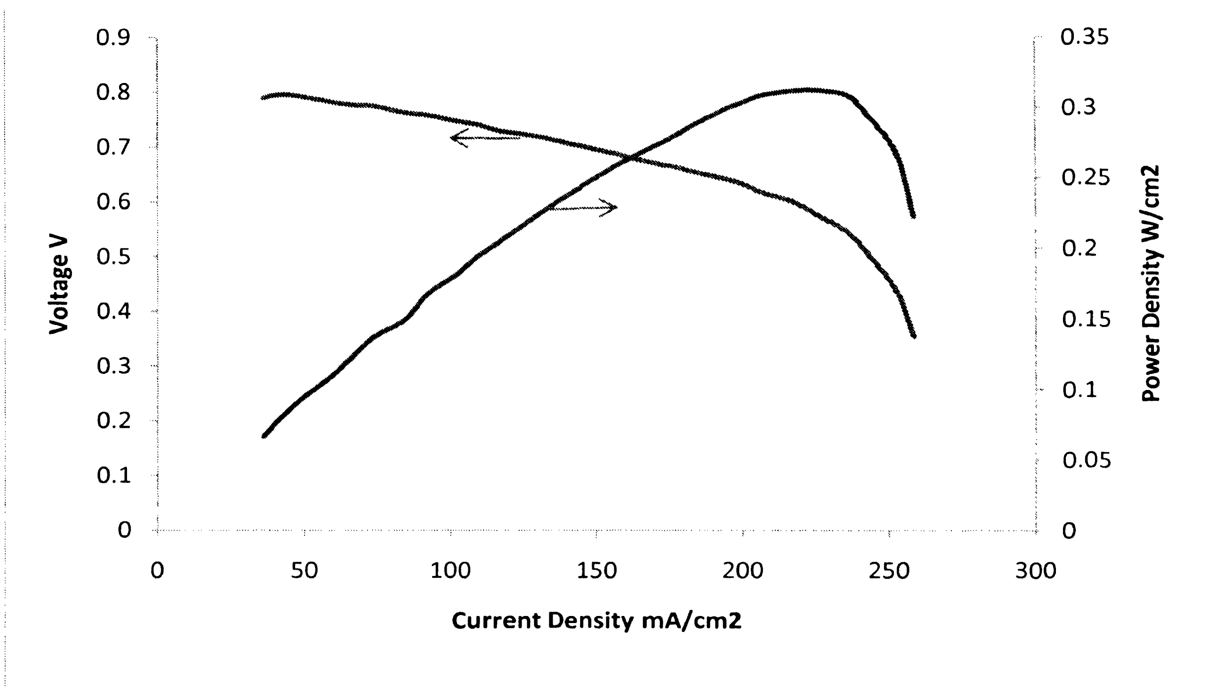


Figure 2.1: Polarization curve of a fuel cell operated under forced air condition

2.3. OPEN CIRCUIT VOLTAGE (OCV)

The theoretical value of OCV is shown in Equation 1 [Larminie, P45]

$$E = \frac{-\Delta g_f}{2F} \tag{1}$$

E = Voltage of the fuel cell

F = Faraday's constant

Δg_f = Gibbs free energy released

It is important to remember that even the open circuit voltage is less than the predicted theoretical value.

2.4. THE MEMBRANE ELECTRODE ASSEMBLY (MEA)

MEA is the assembly of the membrane and two electrodes on either side of the membrane. An electrode is a carbon cloth which is fabricated in a particular pattern depending on the mesh size required. The type of MEA is usually specific to the fuel cell in application. The MEA is one of the most expensive parts in the fuel cell. It is often considered to be the heart of the fuel cell. From a manufacturing stand point, it is very important to address this issue.

To achieve the target of production cost of $30/kW by 2015 as set by the US DOE [DOE 2005], there is a need to achieve low cost fabrication of fuel cells and use alternate cheaper materials in the manufacturing processes.

2.5. GASKETS

Gaskets are used as sealants in fuel cell systems to keep the reactant gases within their respective regions. It is a very important factor in the reliability of the system. They are usually deformable material and are clamped down with high pressure.

Some of the materials used as gaskets are

- EPDM rubber
- Silicone rubber
- Fluorocarbon rubber

The selection of a gasket for PEM Cell involves factors such as cost of raw materials, installation and fabrication. Gaskets are important because if gases start leaking, they might mix which will eventually result in degradation of the output.

2.6. WATER AND THERMAL MANAGEMENT

While it is possible to operate a fuel cell passively without any active control of water flow in and out of the device, performance enhancements can be achieved if one is able to move the water within the device from where it is produced in excess to where it is often depleted. [8]

In a PEM Fuel cell, water is required by the membrane to have suitable ion conductivity. Excessive water must be removed from the cathode side and fed into anode to improve ion conductivity while making sure flooding does not occur. These forms of external and active monitoring methods are disadvantageous for portable applications as they lead to increase in weight, size and complexity. Moreover, for small current consumption, there will be relatively less water produced.

The main issue with thermal management is poor kinetics of the oxygen reduction reaction at the anode. A fuel cell operating at maximum power density will only be 50% efficient. So a 20W Fuel cell releases close to 20W worth of heat.

2.7. BI-POLAR PLATES

There are three types of materials identified for the manufacture of fuel cell bipolar plates which are: pure graphite, metallic materials, and carbon-polymer composites.

Pure graphite, with peak conductivity of 1.44×10^3 S/cm is suitable for bipolar plates due to adequate conductivity. Graphite is very difficult to machine when it comes to the machining of the flow field channels because of its flaky microstructure and irregular geometry. This also reduces its mechanical strength [Chen 2006].

Metals such as stainless steel, titanium, gold, aluminum, have good machining characteristics as compared to graphite. However, gold and titanium are very costly. Aluminum can be used with a gold coating. However, there is large difference in co-efficient of thermal expansion which leads to micro-cracks in the coating. Stainless steel has corrosion issues [Maeda 2004, Chen 2006].

Composite materials suitable for the application of bipolar plates are a combination of porous graphite along with polycarbonate plastic. Graphite is an allotrope of carbon and a semimetal. The carbon based materials suitable are resins such as polyethylene, phenolic, Vinyl ester etc. with filler materials like carbon black and carbon/graphite powders. These composite systems provide electrical conductivity of 80 S/cm as well as corrosion resistance and mechanical strength [Chen 2006].

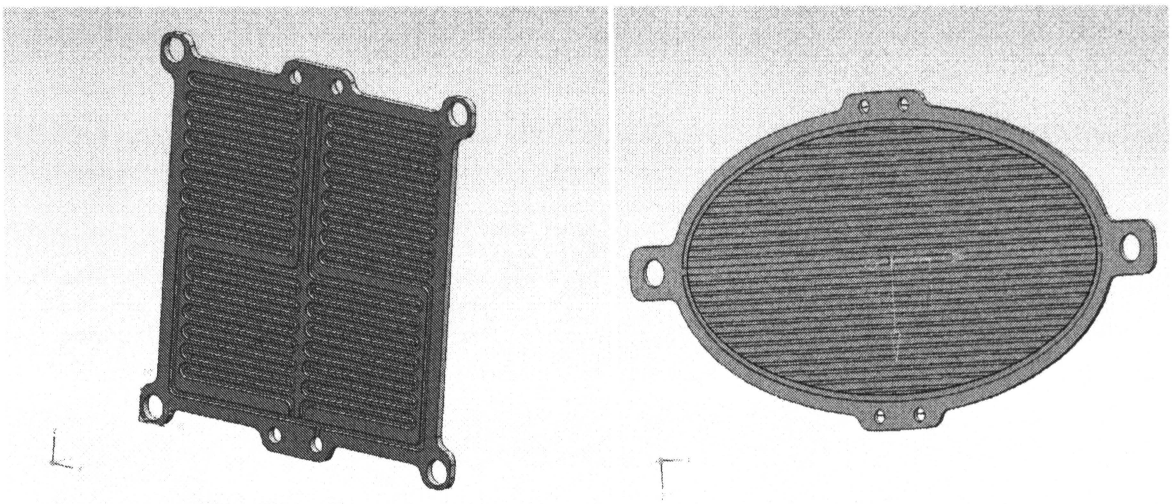


Figure 2.2: Metal bipolar plates designed in square and sphere shapes

Figure 2.2 depicts serpentine and straight groove design of metal bipolar plates that are commonly used in PEM Fuel cells. The advantages of using metal plates are high mechanical strength, good durability, no permeability and cost effectiveness. The disadvantages of using metals as bipolar plates are corrosion in the harsh, acidic environment inside the fuel cells. Some of the corrosion rates for materials in bi-polar plates are as shown in Figure 2.3

Research is being conducted to increase the conductivity in polymers. In polymers, moisture absorption takes place which eventually lead to degradation in electric and mechanic strength. Composite reinforced with larger size of graphite flake constraints the amount moisture absorption initial absorbing speed. This can be explained as difference between large size of graphite flake reinforced to composites and small one makes different interfacial area between graphite flake and polymer resin. For the lower temperature, diffusion process restrained and less moisture absorbed [16]. These results can be a good application to PEMFC bipolar plate.

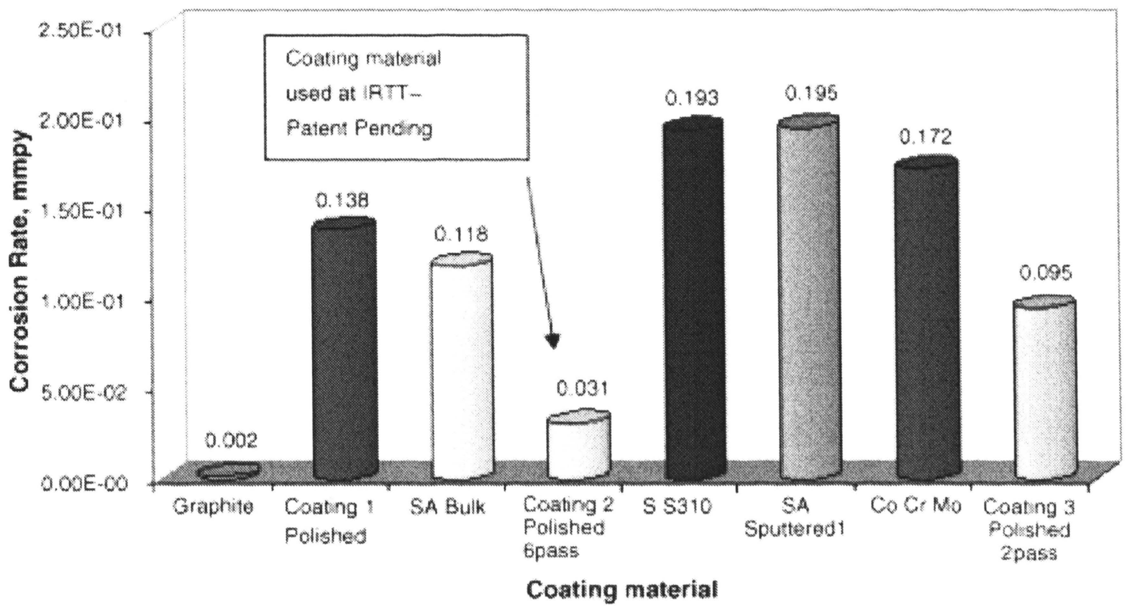


Figure 2.3: Corrosion rates for different materials and coatings in 0.5M Na2So4 +10ppm HF solutions at 80C [Tawfik 2006]

Although bi-polar plates might not be the most expensive part of the fuel cell, it is definitively an important factor. Apart from bring the backbone of the fuel cell, bi-polar plates facilitate water and thermal management. The designs for bi-polar plates are virtually endless. There are many flow field patterns and lot of research is being done as to which type of flow field would yield maximum fluidity of gases. The approach taken is to have the least number of fasteners. This lowers the manufacturing and assembly costs.

The common flow field designs used are pin type, straight, serpentine and multiple serpentine.

For an air breathing fuel cell, the entire surface of the cathode must be exposed to exterior device to allow enough oxygen to reach catalyst area. During long discharge cycles, the oxygen demand of fuel cells will not be met unless there is a very large exposed area [8].

3. TESTING PROCEDURE

3.1. GREEN LIGHT G40 TEST STATION

This test station (Figure 3.1) has a power range of 1-50W. It has fully automated safety features and is capable of unattended operation. This particular model is optionally configured for high temperature PEM research also. Some of the features are as follows

- Standard anode flow range (0.015-1.5nlpm)
- Standard cathode flow range (0.025-2.5nlpm)
- Optional fuel cell enclosure
- Automatic N_2 purge on shut down
- Integrated fume hood with H_2 sensor
- 2 separate PID loops for cell endplate heaters
- Optional liquid cell cooling capability
- DMFC operation available
- Optional humidifier gas by pass
- Ceramic hydrogen burn out

3.2. TEST FUEL CELL

The fuel cell used in these experiments was a commercially obtained PEM fuel cell from Horizon Fuel cell technologies. It is rated at 20W and is labeled as H20. There are thirteen cells in series. The stack is designed to operate optimally at 55^0C, but it was observed to reach higher temperatures during normal function. This is function of varying parameters such as presence of blower, humidity and ambient temperature.

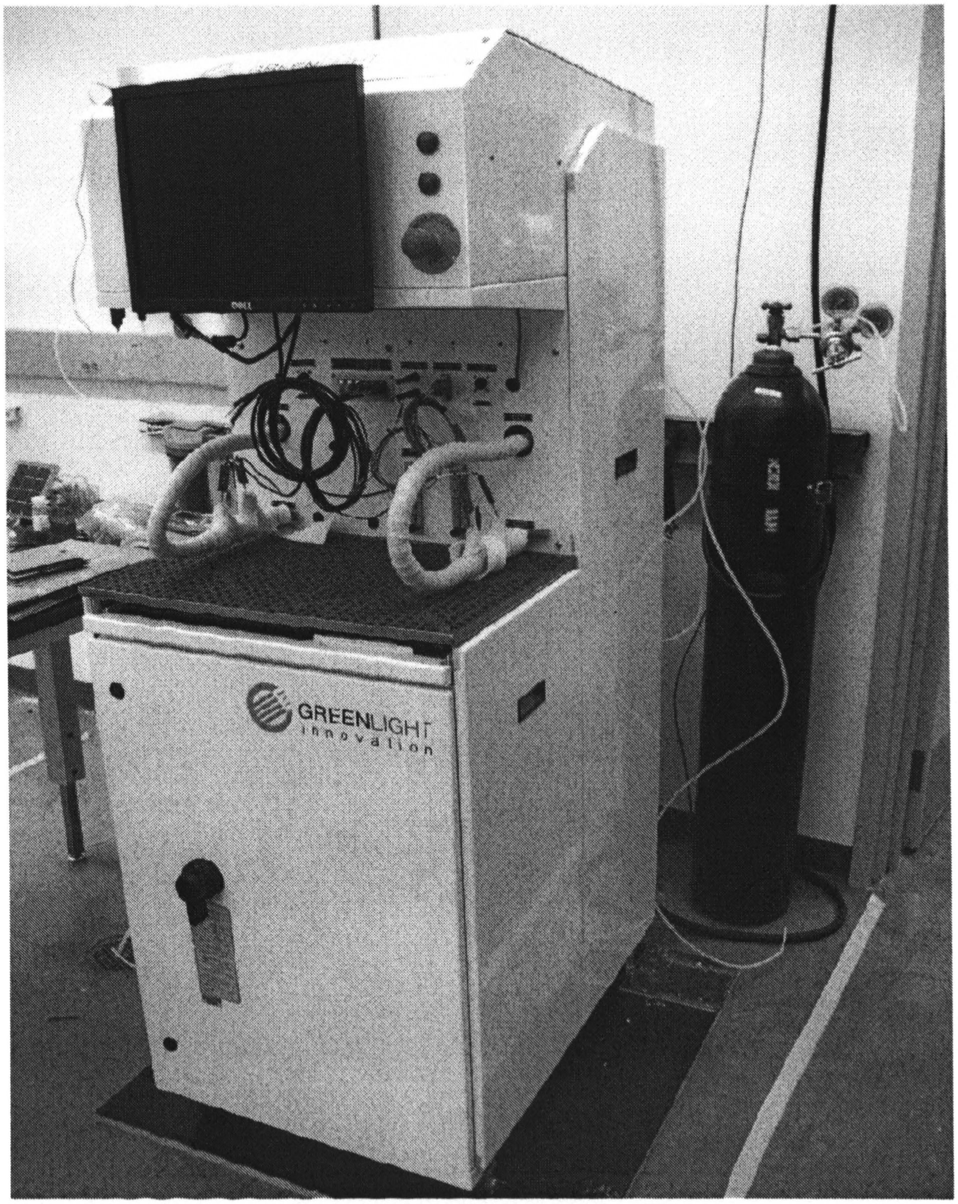


Figure 3.1: The Greenlight G40 fuel cell test station: The test station comes with Hyware interface for running tests.

Originally the fuel cell had a blower but it was removed for experimentation purposes. The inlet pressure is rated between 3 and 9 psi but the fuel cell was operated consistently at 7psi for all tests. The bipolar plates are made of graphite for this fuel cell. As shown in figure, the fuel cell uses open cathode geometry for movement of air. This type of cathode structure can be used for forced convection by the use of a fan.

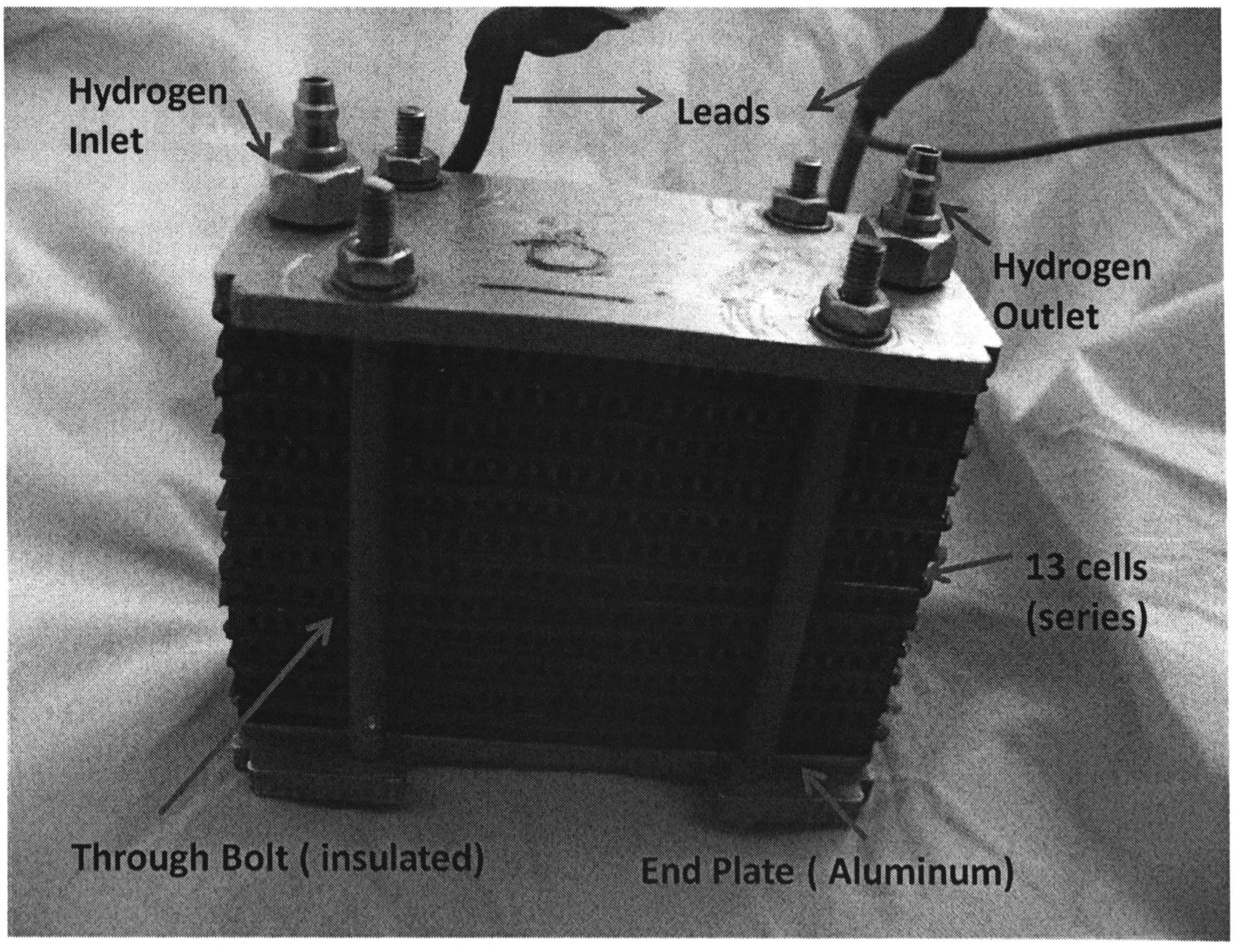


Figure 3.2: 20W test fuel cell with vertical air channels on cathode side

3.3. OPEN CATHODE GEOMETRY

Open cathode geometry is advantageous for portable power sources as they operate silently while achieving high energy density without parasitic loads. It can also be manufactured at low cost. There are many design options for an open breathing cathode. Bussayajarn [2009] explored parallel slit, circular opening and oblique slit.

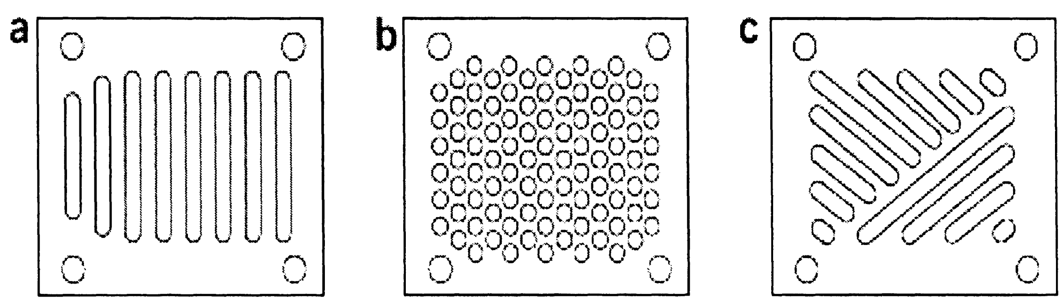


Figure 3.3: Three different cathode designs(a) parallel slit (b) circular opening and (c)oblique slit [Bussayajarn 2009]

The parallel slits were 2mm apart having a hydraulic diameter, a term commonly used when handling flow in non circular tubes and channels, of 7.47mm. The circular openings had shortest rib distance of 0.87mm with hydraulic diameter of 4.29mm. The oblique had rib geometry of 1.67mm with hydraulic diameter of 7.91mm. The test conditions were carried out at 24^0C and 60% relative humidity. The hydrogen inlet pressure was 1.2bar and the fuel cell was operated with dead end at anode.

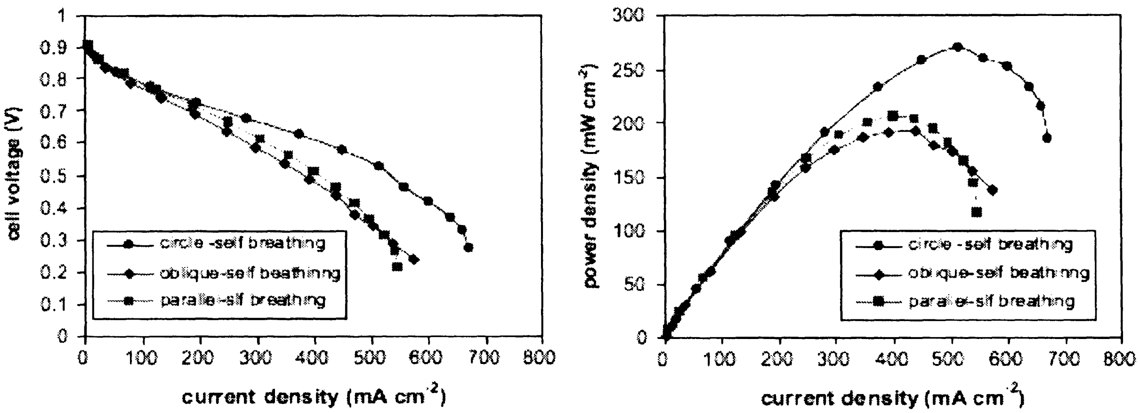


Figure 3.4 : Cell performance of different cathode designs for self breathing with dead end operation [Bussayajarn 2009]

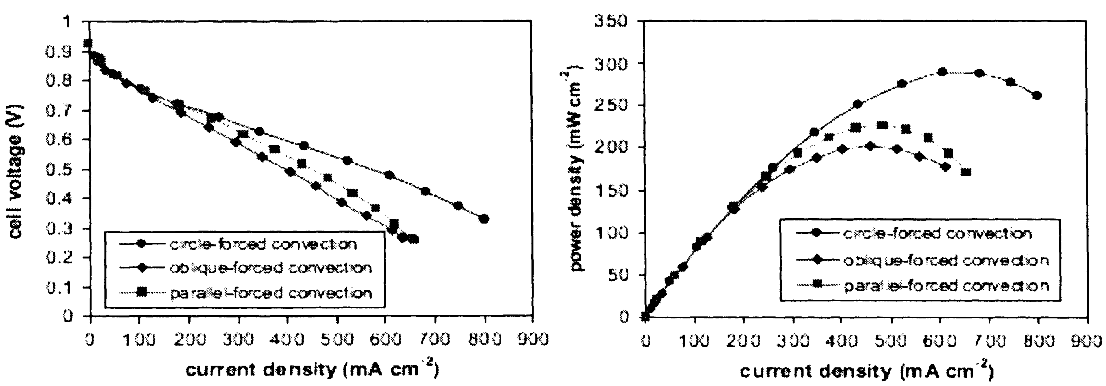


Figure 3.5: Cell performance of different cathode designs for under forced convection [Bussayajarn 2009]

The result of the research done shows performance of open cathode designs in parallel, circular and oblique slit form. Under self breathing condition, circular opening design shows the best performance and highest limit current density, while the cell performance of the parallel and oblique slits are very similar[2]. The fuel cell which is used for tests in the experiments performed here are parallel grooves. They are not slits but are parallel grooves which allow air to freely move along their cross section.

3.4. ORIENTATION OF THE FUEL CELL

Air is taken directly from the surrounding air by diffusion and natural convection. The structure of the cathode plays a very important part in fuel cell operation. Improved cell performance, slightly lower cell temperatures at high current density, smaller cell voltage fluctuation and less liquid water saturation imply that the convection on the surface of the cell is improved when the cell is vertically oriented. Enhanced convection removes heat and water more effectively from the cell and simultaneously brings more fresh oxygen to the cell [8].

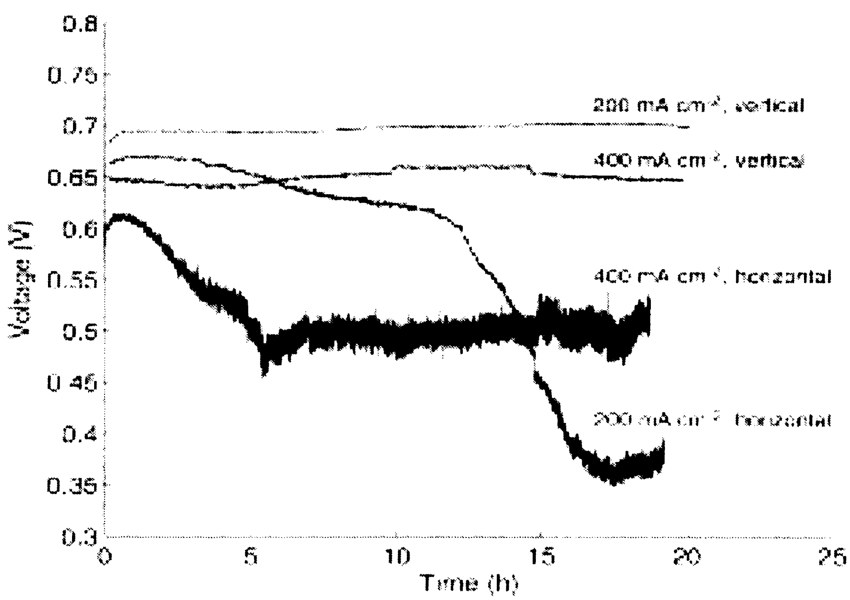


Figure 3.6: Voltage, current density and cell orientation with long term time measurements [Hottinen 2004]

The test fuel cell was operated in vertical and horizontal operation. The vertical air channel orientation had a peak power output of 17.22W and the horizontal air channel orientation had a peak power output of 11.30W as shown in Figure 3.7.

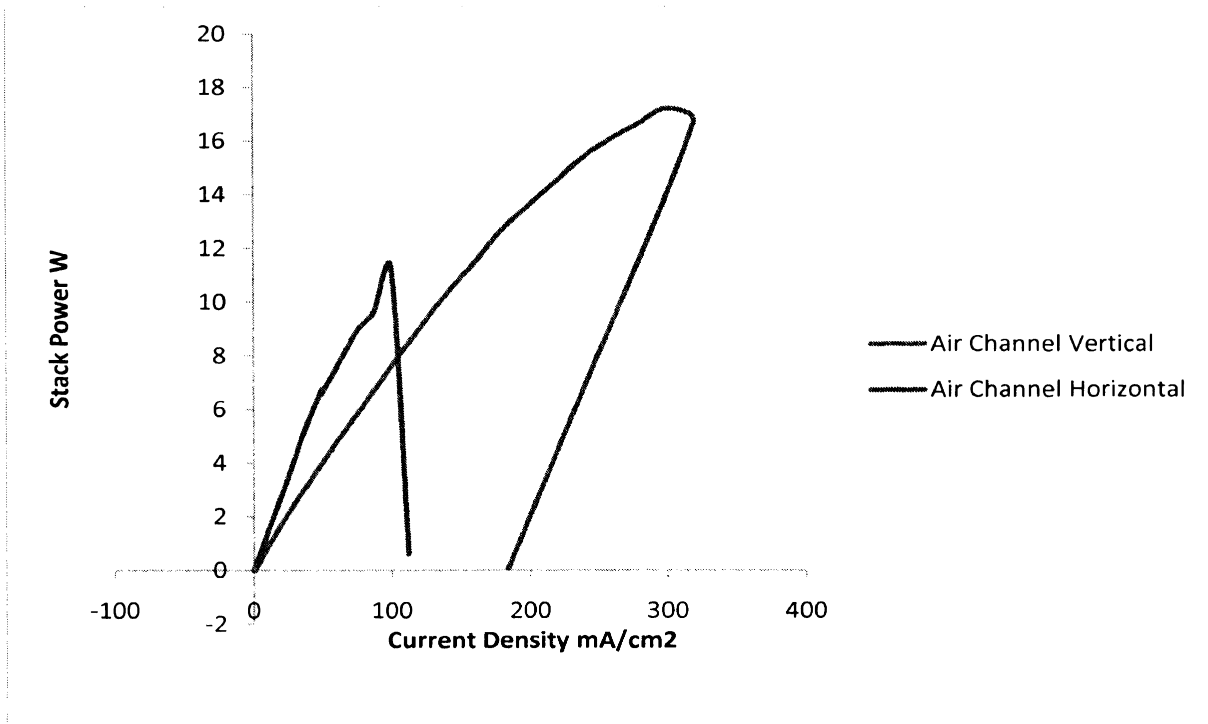


Figure 3.7: Horizontal air channel performance compared with vertical air channel performance of free air breathing fuel cell

The results strongly indicate that vertical position of the fuel cell is better for operation. Vertical positioning with blower attached had the best yielding polarization curve. Using this result, further experiments were conducted with vertical positioning.

4. RESEARCH METHODOLOGY

With the high energy density of the fuel cells and formation of water at the cathode side, the movement of air is inside the fuel cell is very necessary. Although large scale fuel cell systems can afford to use a blower, the small, portable system can lose considerable amount of power feeding the blower, Thus there is a need for natural-convection air cooling. A packaging enclosure with a pipe mounted on top is designed to create the chimney effect. Tests are conducted to investigate the effect of the chimney for a portable PEM fuel cell.

4.1. ENHANCEMENT OF CONVECTION

Chimney's have only been recently been used to improve the natural air convection cooling of electronic components [9]. Chimneys have also been shown to decrease temperature of transistors operating at 100^0 C by 10% thereby increasing reliability of the system [10].

Incorporating chimney onto a fuel cell for experiments was done as shown in Figure 4.1. The draft of the chimney is caused because of the tendency of hot air to rise. Tests indicate that using a chimney with a fuel cell is very useful after the fuel cell is on and starts heating up. Tests were conducted at start up and after ten minute of operations to observe the difference in cell performance.

As far as the height of the chimney, more height increase air draft in the chimney. But this logic cannot be used when experimenting with chimneys for portable fuel cell. It

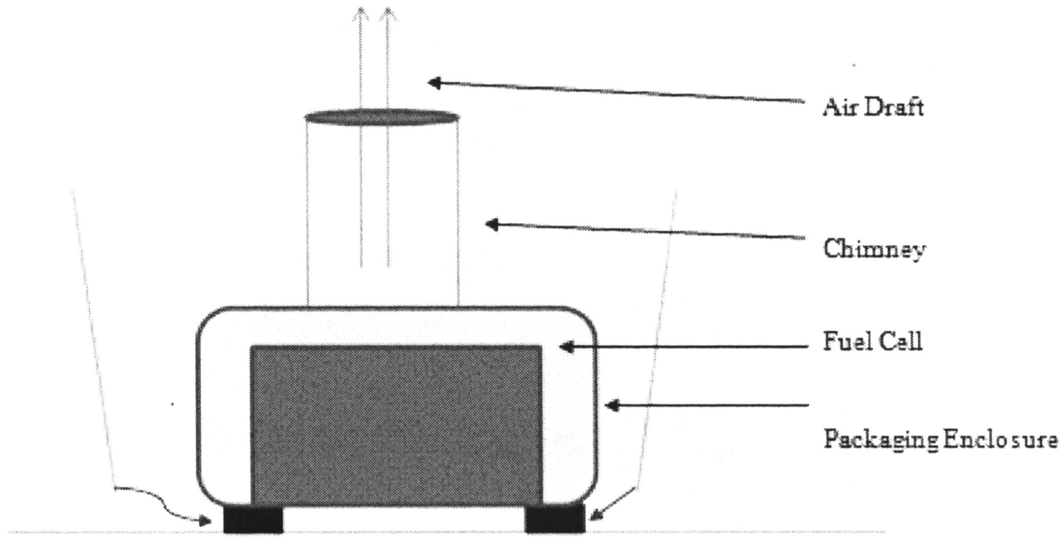
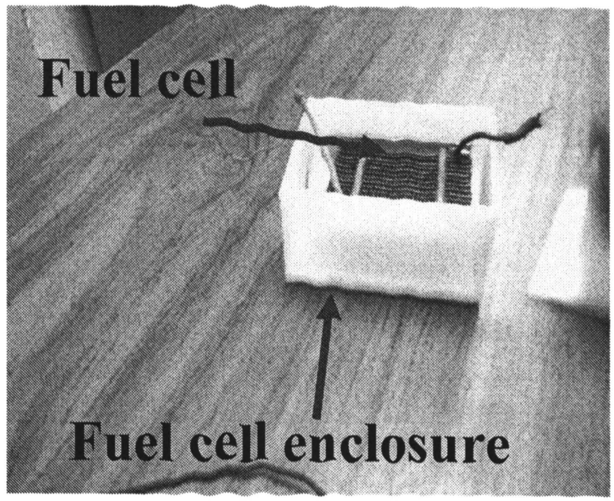


Figure 4.1: Schematic diagram of a fuel cell inside enclosure with chimney

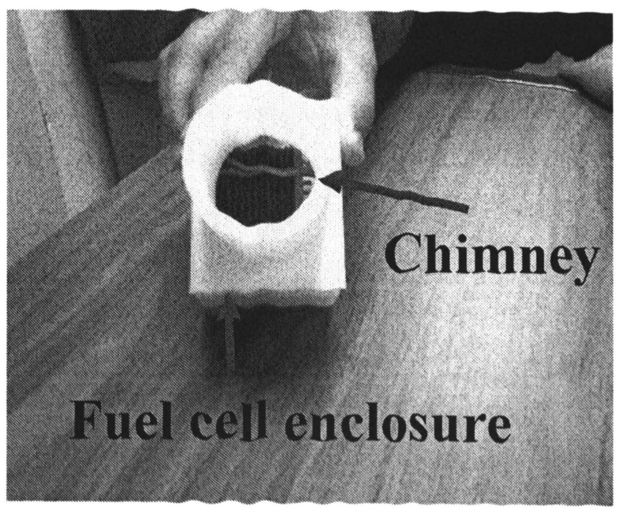
is very important to establish a good height from a manufacturing and portability point of view. In addition, metal chimneys will get warmer outside making it easier for air draft.

Another important factor is the tightness of the fuel cell packaging. The fuel cell should be in an enclosure that ensures adequate air movement. Using this idea, a packaging enclosure and a chimney were designed in Solidworks. The STL files were exported to a Fused Deposition Modeler and the chimneys were built with ABS plastic as shown in figure 4.2.

The fuel cell packaged along with the chimney was tested. Tests were carried out with anode pressure at 7psi and room temperature at 23 ^{o}C. The data was recorded after 10 minutes of operation with no cross air present. The data obtained from the test station is shown in Figure 4.3 and 4.4.



(a)



(b)

Figure 4.2: (a) Vertical air flow fuel cell fitted inside enclosure
(b) Chimney added to enclosure

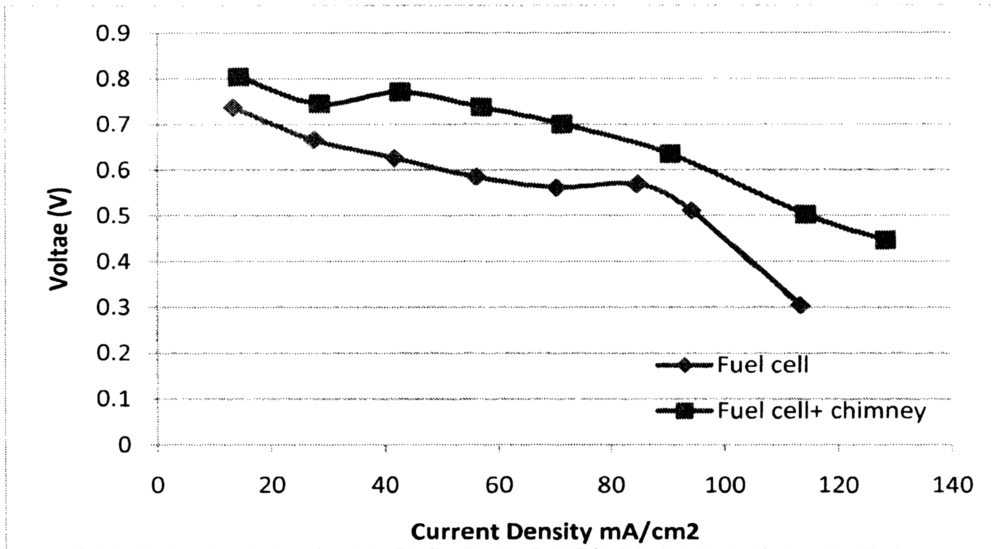


Figure 4.3: Polarization curves of an air breathing fuel cell with chimney and without chimney: There is a peak increase of 21% in voltage of the chimney with fuel cell.

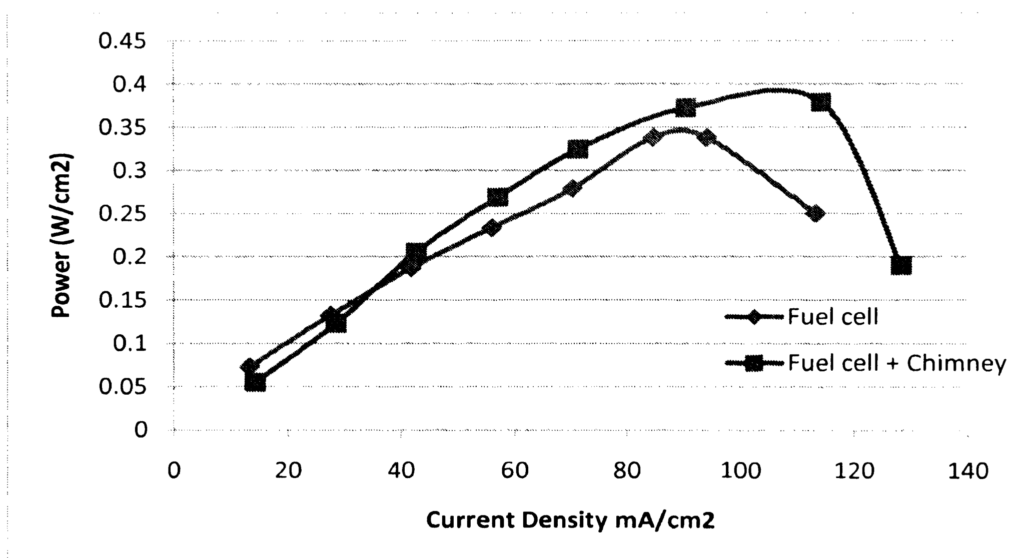


Figure 4.4: Comparison of power densities of air breathing fuel cell with chimney and without chimney: There is a peak increase of 24% in the power density of chimney with fuel cell.

Using the expression [15] given below, it is possible to find the air draft [Q] in the chimney at different temperatures of the fuel cell. The air draft in a chimney is given by

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

where,

Q = volume of air draft (m^3/s)

C_d = 0.65, a discharge coefficient

A = free area of inlet opening (m^2)

g = 9.8(m/s^2), the acceleration due to gravity

h = vertical distance between inlet and outlet midpoints(m)

T_i = Average temperature inside the chimney, K

T_e = External air temperature

Chimneys of different heights were made and the temperature of the Fuel cell was measured with a non contact thermometer gun (pyrometer) with laser sighting. Air draft is shown to increase with increase in chimney height.

4.2. EFFECT OF SLOPE ON CHIMNEY

It was also shown by Kitamura [2004] that increasing the angle of inclination enhances the effects of natural convection and leads to an increase in the airflow rate. The

Table 4.1: Calculations of air draft present in chimney of different 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

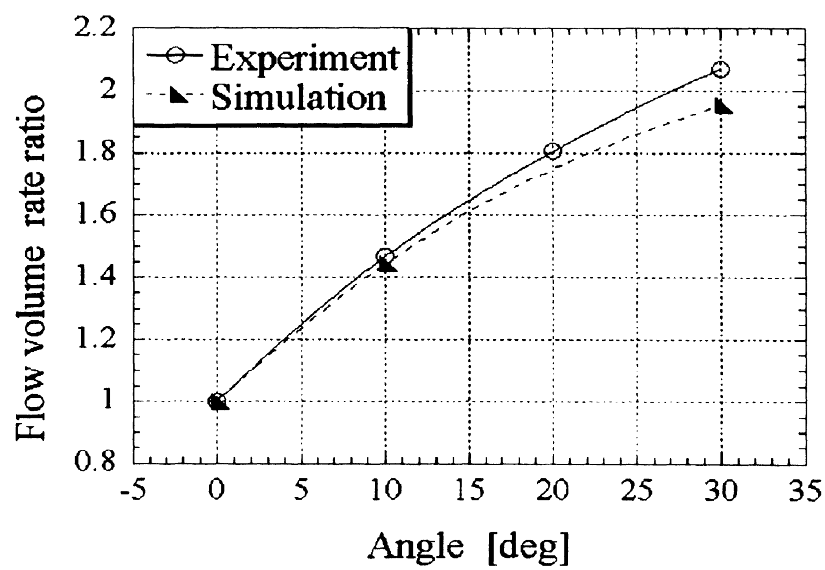


Figure 4.5: Effect of inclination on volume flow ratio [Kitamura 2004]

author performed tests using different angles with test results indicating that higher angle of inclination yields to more volume flow of air as shown in figure 4.5.

Angle of inclination also plays an important role in reducing temperature of the heater surface and the casing of the electronic equipment showed in figure 4.6. The heights of both the chimneys were 16cm and a varying load of 0.8-1 amp was being drawn from the fuel cell for the tests conducted. One of the chimney design was a conventional straight design where as the other chimney had a slant of 30 degrees as shown in the figures 4.7.

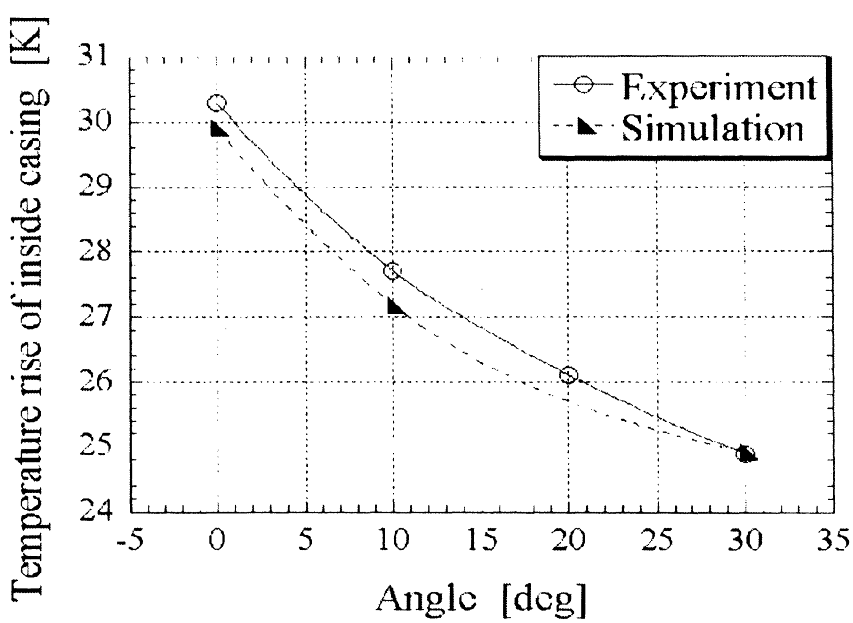
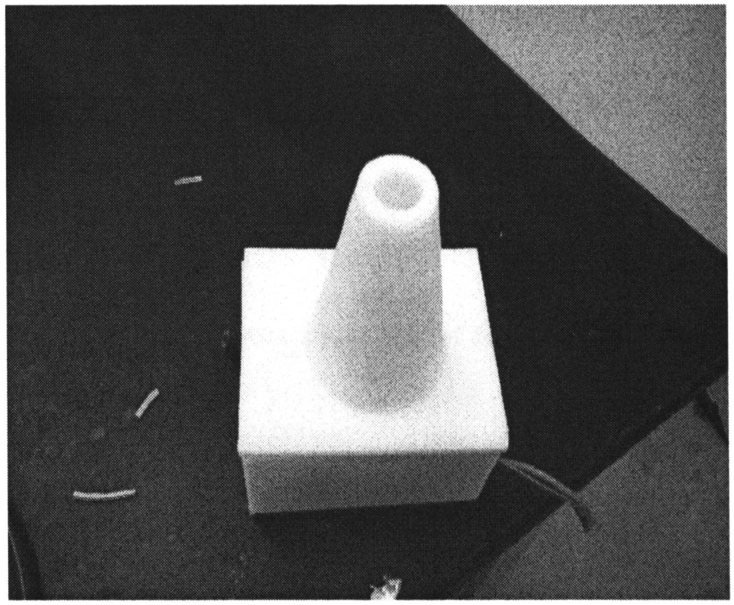


Figure 4.6: Effect of inclination on temperature inside casing [Kitamura 2004]

(a)



(b)

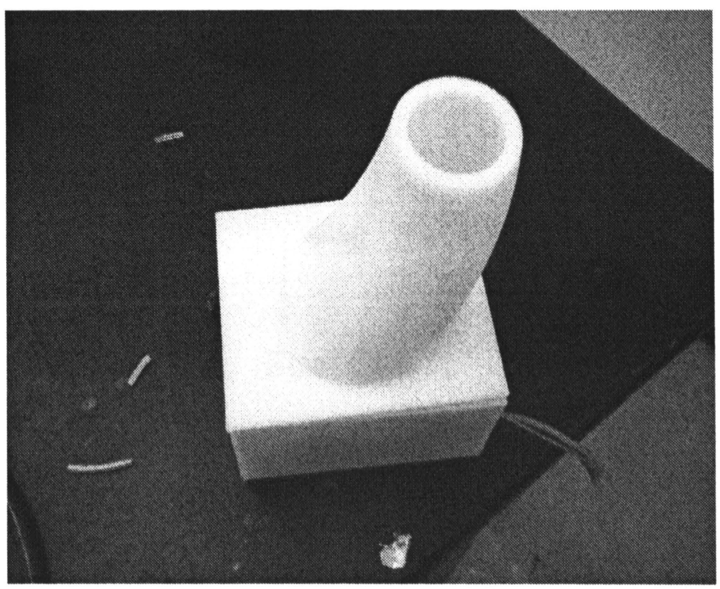


Figure 4.7: Chimney design modeled with the FDM (a) Straight type (b) Slope type

4.3. CHIMNEY WITH CROSS AIR

Another advantage of using a chimney for natural convection is that cross air in the form of wind has a positive impact on the air draft flowing in the chimney. To quantify the extent of impact, an experiment was set up as shown in the Figure 4.8. The anemometer was bought commercially and is able to display current, maximum, and average wind. The chimney height was 16cm for the tests performed. .

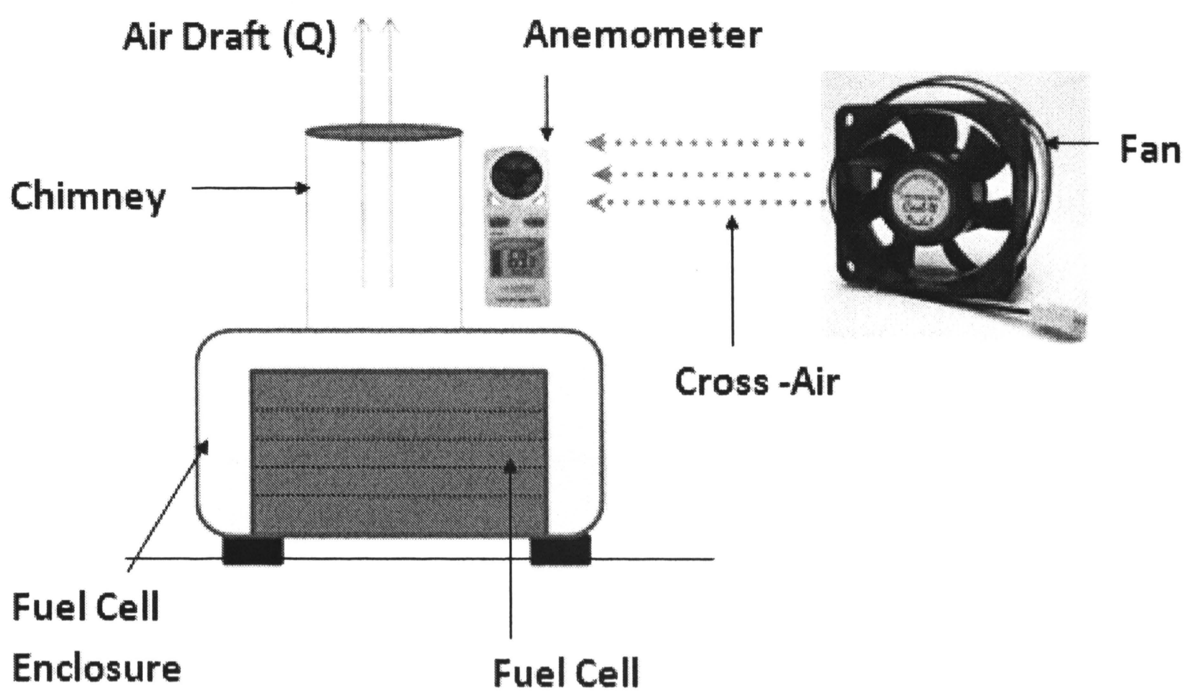


Figure 4.8: Schematic diagram to calculate effect of cross air on fuel with chimney

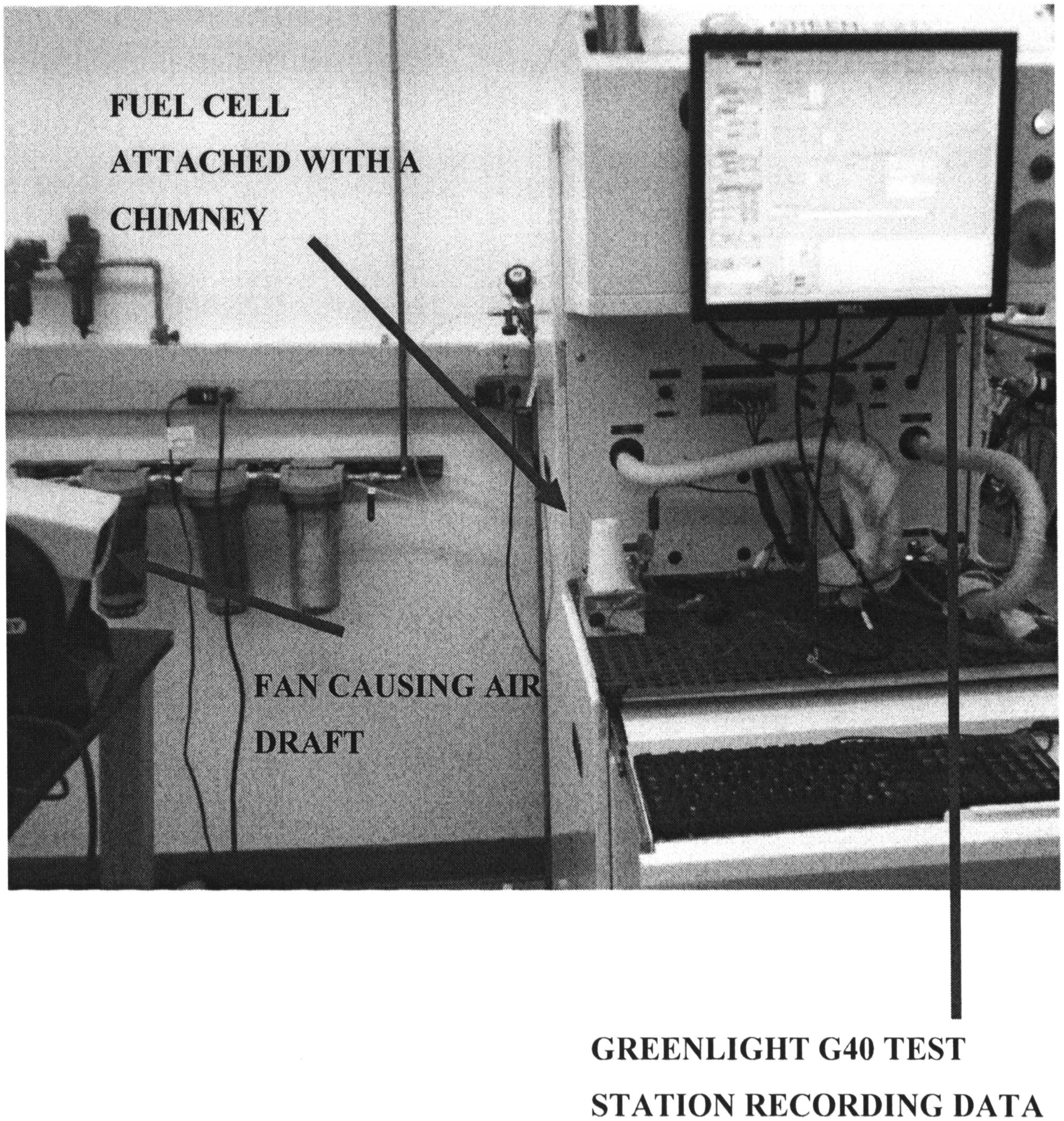


Figure 4.9: Experimental set up to research effect of cross air on a fuel cell with chimney: The fuel cell is placed in the test bay of the Greenlight G40 test station. The probes of the test station are connected to the leads of the fuel cell.

To get a better understanding of wind speed and chimney slope with regard to fuel cell performance, an experiment, as shown in Figure 4.9, was set up. Wind speed was increased by steps of 2mph by controlling the distance of the fan to that of the fuel cell. Care was taken to ensure that the significance of anemometer reading were right to the decimal point. The result obtained is illustrated in the table 4.2 below

Table 4.2: Voltage and current density of straight and slope type chimney under different wind speeds

Wind-Speed	Voltage Straight Chimney	Voltage Slope Chimney	Current Density-Straight Chimney	Current Density-Slope Chimney
0.0	7.274	7.274	57.071	57.012
2.0	7.374	7.374	57.102	57.126
4.0	7.504	7.485	57.723	57.681
6.0	7.504	7.496	58.654	58.964
8.0	7.5	7.5	60.249	60.354
10.0	7.522	7.521	60.914	60.895
12.0	7.522	7.521	61.451	61.631
14.0	7.522	7.521	61.451	61.678
16.0	7.522	7.521	61.451	61.978

Test data indicate that the curve chimney does perform slightly better. A graphical representation is shown in figure 4.10.

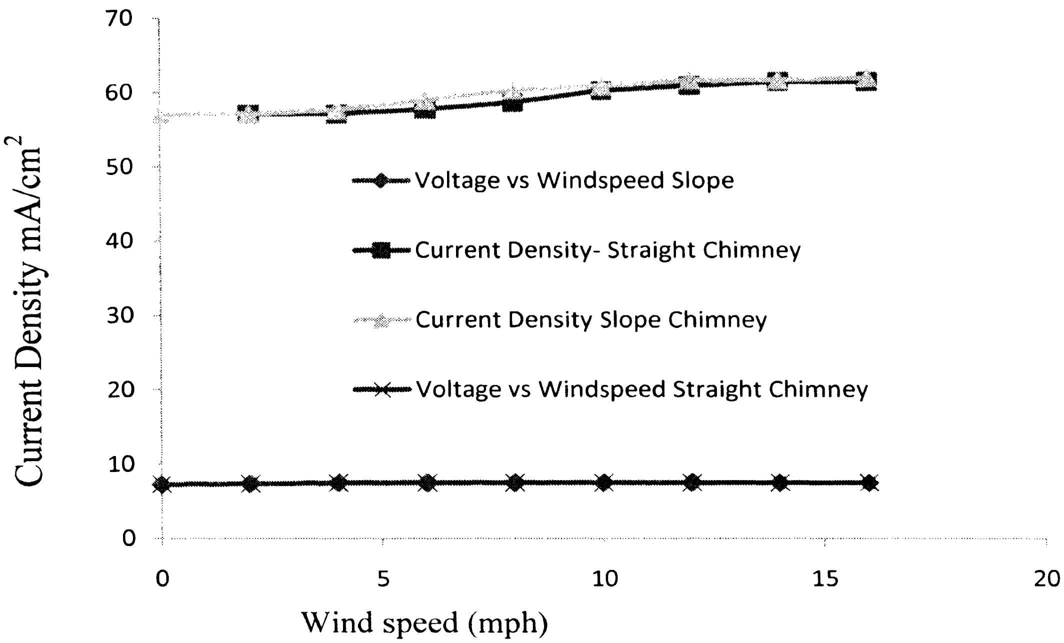


Figure 4.10: Effect of cross air speed on current density for straight and slope chimney designs

4.4. PERFORMANCE OF CHIMNEY IN FUEL CELL IN START UP AND NORMAL CONDITION

Test data has established that chimney functions well in a fuel cell and that any particular design of the chimney does not have a major impact. Effect of cross air acting on a chimney was also tested. Another factor that is very important in the functioning of the chimney is the temperature of the fuel cell. At start up, the fuel cell will be cold. Air-draft will be comparatively less as the ratio of fuel cell temperature to that of the ambient temperature is less.

Therefore, tests were conducted at start up and after ten minutes of fuel cell operation. Voltage and current density was recorded at different load points ranging between 0 to 2.2amps. The load was incremented at steps of 0.2amps.Chimney height was 16cm and cross air was at 6mph.The temperature of the fuel cell after ten minutes of operation was 330K. The results indicated that the fuel cell with chimney had a higher limiting current density than the fuel cell operated all alone. The difference was significant when the data was logged after ten minutes of operation. This indicates that after the fuel cell gets hot natural convection of air gets aided by the presence of chimney. All tests were conducted with the test station and care was taken to ensure that the fuel cell is restored to its normal condition between each run. This was done to ensure that water formation in the cathode side does not interfere with the test results.

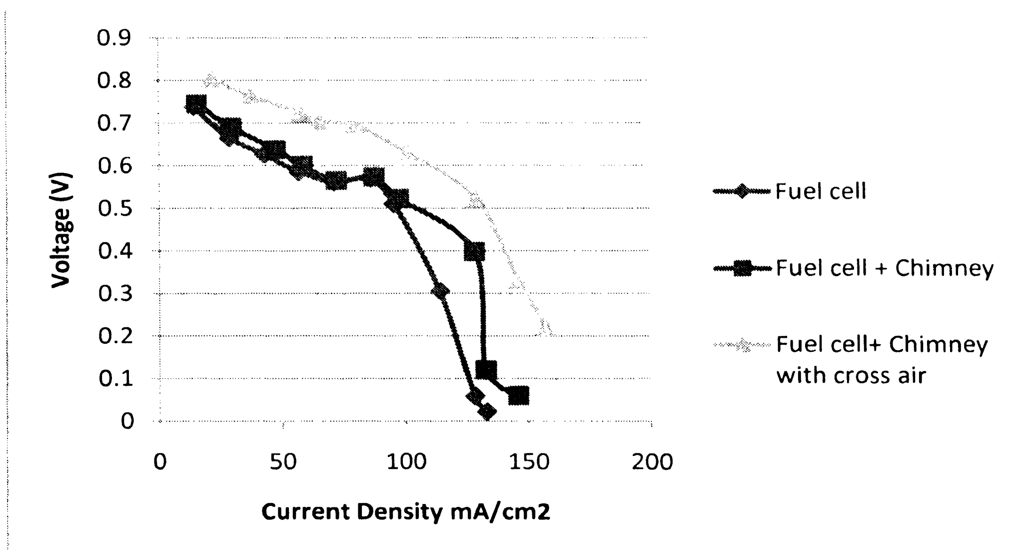


Figure 4.11: Polarization curve of air breathing fuel cell : At start up for only fuel cell, chimney fuel cell, and fuel cell with air draft across chimney at 6mph

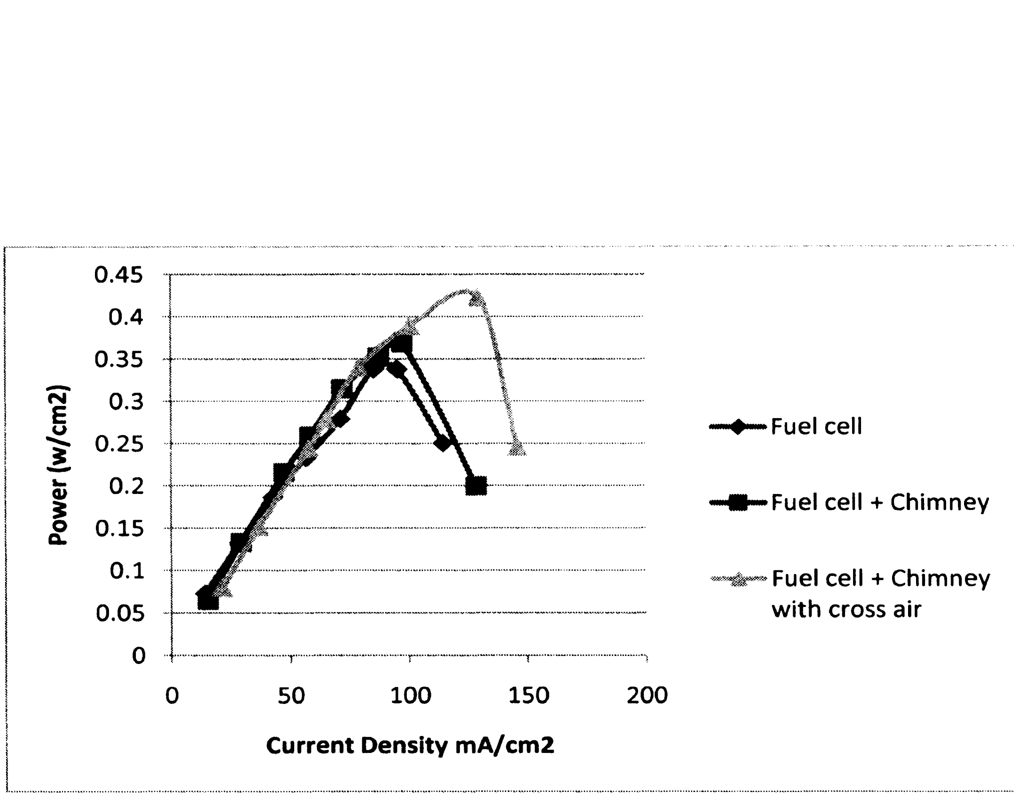


Figure 4.12: Comparison of power densities of fuel cell: At start up for only fuel cell, chimney fuel cell, and fuel cell with air draft across chimney at 6mph

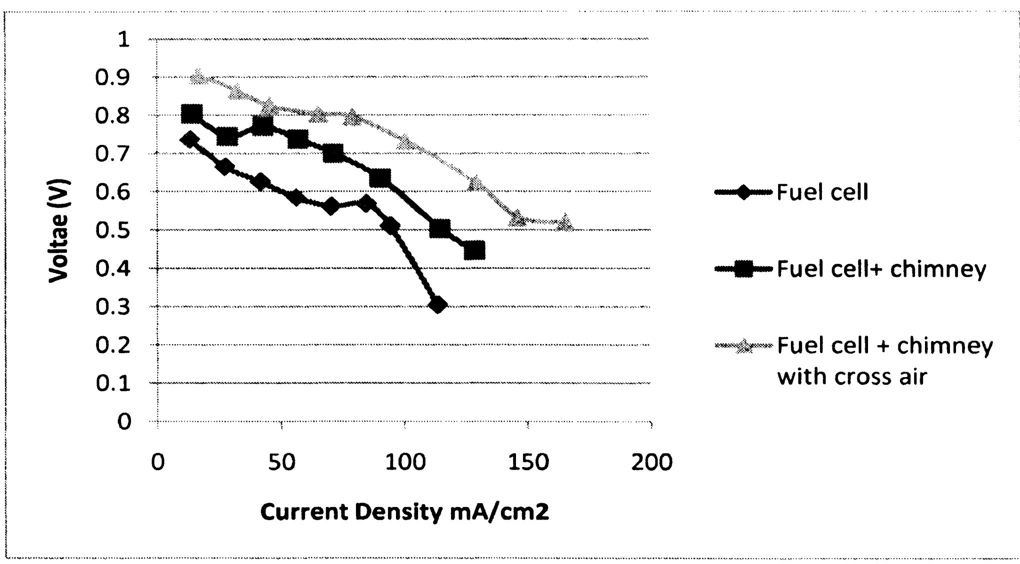


Figure 4.13 Polarization curve after ten minutes operation: For fuel cell only, chimney Fuel cell and chimney fuel cell with air draft. The air draft was at 6mph and the temperature of the fuel cell was recorded to be 330K

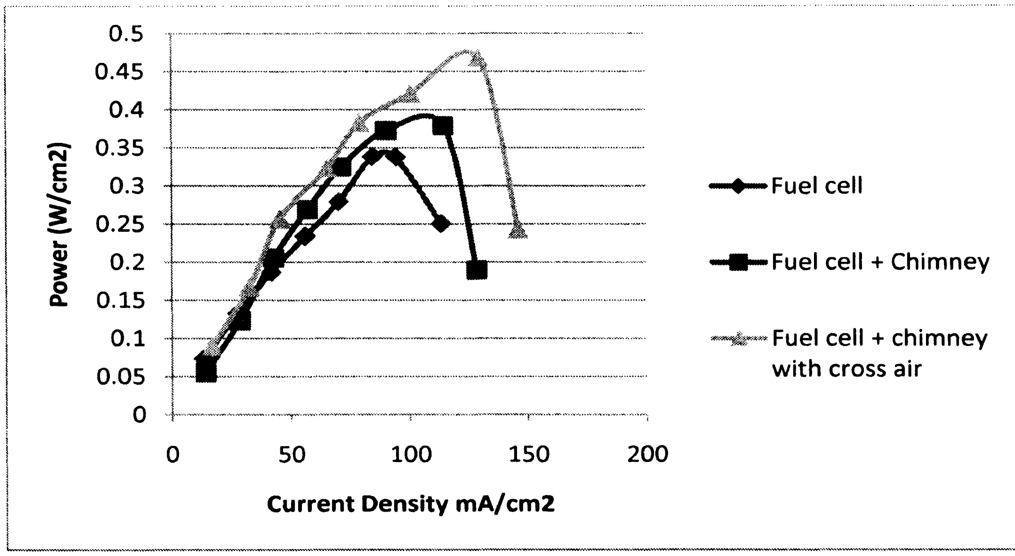


Figure 4.14: Comparison of power densities after ten minutes operation: For fuel cell only, chimney fuel cell and chimney fuel cell with air-draft. The air draft was at 6mph and the temperature of the fuel cell was recorded to be 330K

At start up, the fuel cell with chimney design had an average power density increase of 7.05 % as compared to the fuel cell operating alone. The difference in performance is mostly seen at higher current densities. With the cross air, the average power density increase is 16.89%. After ten minutes, the fuel cell with chimney design had an average power increase of 12.77 % as compared to the fuel cell operating alone. With the cross air, the average power density increased by 27.80%.

4.5. DESIGN OF EXPERIMENT [DOE]

A DOE was conducted to establish a relationship between, chimney height and chimney slope. The experiment was set up as a 3 factor 2 level experiment. The 3 factors taken are

- Chimney height
- Slant of chimney
- Time

Chimney Height: The height of the chimney plays an important role in the ability of the chimney to transfer gases.

Slant of chimney: Kitamura [9] explains how an inclination aids flow of gas. A chimney with a slant of 30 degrees was tested against a straight chimney

When the fuel cell is operated for long periods of time, water gets built up on the cathode side of the fuel cell which causes a change in the fuel cell performance. To avoid this type of noise from creeping into the experiment, each run for the experiment was done after T_R, which is the time taken to dry out the membrane with a fan and also cool down the fuel cell. For the 20W fuel cell, T_R was calculated to be 15min.

The fuel cell was tested for air draft 'Q' with a straight chimney at height 12cm and a 30 degree angle chimney at 12cm height. The experiment was set up as 3 factor 2 levels. The design of experiment was done for two time levels. The first was for testing fuel cell with chimney at start up mode. At start up, the fuel cell will be ambient temperature and will be the point of least air-draft Q. The fuel cell was tested again after T_S, which is the time taken for the fuel cell to reach steady output after T_R. For this fuel cell T_S was found to be 10min. Then the air draft Q was computed.

The levels for the height of the chimney were taken to be 0.1cm and 12cm. 0.1cm refers to no chimney. It is assumed as 0.1 cm to use in the equation. There is still a natural air draft occurring in the fuel in the absence of the chimney as this is an air-breathing vertically oriented fuel cell. The experimental design was set up as shown in Table 4.4.

Table 4.3: Factors and levels for the experiment

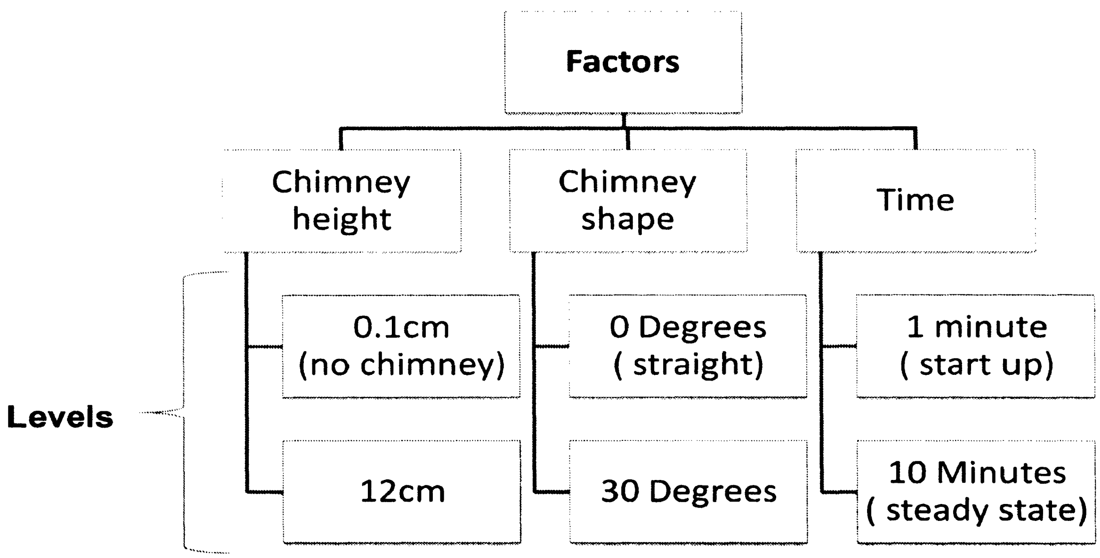


Table 4.4 : Design table for the 3 factor, 2 level experiment

Std	Run	Height	Shape	Time	Q*10^-4 m3/cm
1	1	0.01	0	1	0.3955
5	2	0.01	0	10	1.1366
3	3	0.01	30	1	0.4057
6	4	12	0	10	4.3764
4	5	12	30	1	1.3889
2	6	12	0	1	0.3955
8	7	12	30	10	4.3826
7	8	0.01	30	10	1.1339

Table 4.5: Analysis of variance[ANOVA] for factor models

Source	Sum of Squares	df	Mean Square	F Value	p-value Prob > F	
Model	19.80604	4	4.95151	40.506976	0.0061	**significant**
Height	10.59162	1	10.59162	86.647204	0.0026	
Slant	0.126781	1	0.126781	1.0371638	0.3835	
Time	8.912431	1	8.912431	72.910206	0.0034	
Height*Time	3.788541	1	3.788541	30.993038	0.0114	
Residual	0.366715	3	0.122238			
Cor Total	20.17276	7				

From the ANOVA table , we see that the model is significant and the significant factors are height and time. The interaction between height and time is also a significant effect. This data was obtained by the statistical analysis of the designs using design expert 7.0.2. The scientific explanation deduced is that the height of the chimney plays an important role in the amount of air draft induced. The time is a very significant factor because after start up, the fuel cell heats up and this causes hot air to rise. The shape of the chimney was not significant although it was seen that a sloped chimney does perform marginally better.

The data presented might be biased towards time and height because readings were taken for the fuel cell with no chimney and a 30 degree slope, which is the same run as fuel cell with no chimney. This could be the reason as to why the shape of the chimney is not significant. For the height of chimney at 12cm, it is seen that the shape of the chimney does play a significant role in the amount of natural convection at start up.

Another ANOVA was done ignoring values of chimney at 0.01cms. When the table was analyzed, the factor time had a p-value to 0.0895 and slope had a p-value of 0.4960. The effect of slope of the chimney on the performance of the fuel cell is not certain at this point and is a good area for future work. However, it has been established that height and time are significant factors that increase the efficiency of fuel cell with chimney.

5. CONTROLLING FUEL CELL OUTPUT

The automatic control of PEM fuel cell is the process of actuating at least two families of variables: hydraulic (gas flows) and electric (electron flow). The main task that a control strategy must fulfill is to maintain the chemical kinetics of the redox reaction [12].

The load or electric impedance that is connected to the stack unbalances the electron equilibrium thus forcing the control systems to dynamically adapt the reactants quantities, oxygen and hydrogen [Vega-Leal, 2007]. It is necessary to use the controller in order to use hydrogen efficiently.

The work presented implements an electronic controller which controls the entire system. The controller system consists of a control loop to control the hydrogen flow and is mainly focused on implementation in air-breathing fuel cells. The hydrogen flow ($W_{anode,in}$) when using a stack with closed anode circuit is determined by [Vega-Leal, 2007]

$$W_{anode,in} = K_1(K_2 P_{storage} - P_{anode}) \tag{3}$$

Where W = Gas flow, P = Pressure

A solenoid valve is used to control the flow of hydrogen. The solenoid used is a normally closed type valve. This enables the fuel cell to operate with a sealed end on the anode side. Thus, the fuel cell uses hydrogen efficiently. This control circuit not only controls the hydrogen gas flow, but also stabilizes the output voltage of the fuel cell.

5.1. FUEL CELL OUTPUT CONTROL

A basic block diagram of a portable air breathing PEM fuel cell is as shown in figure 5.1.

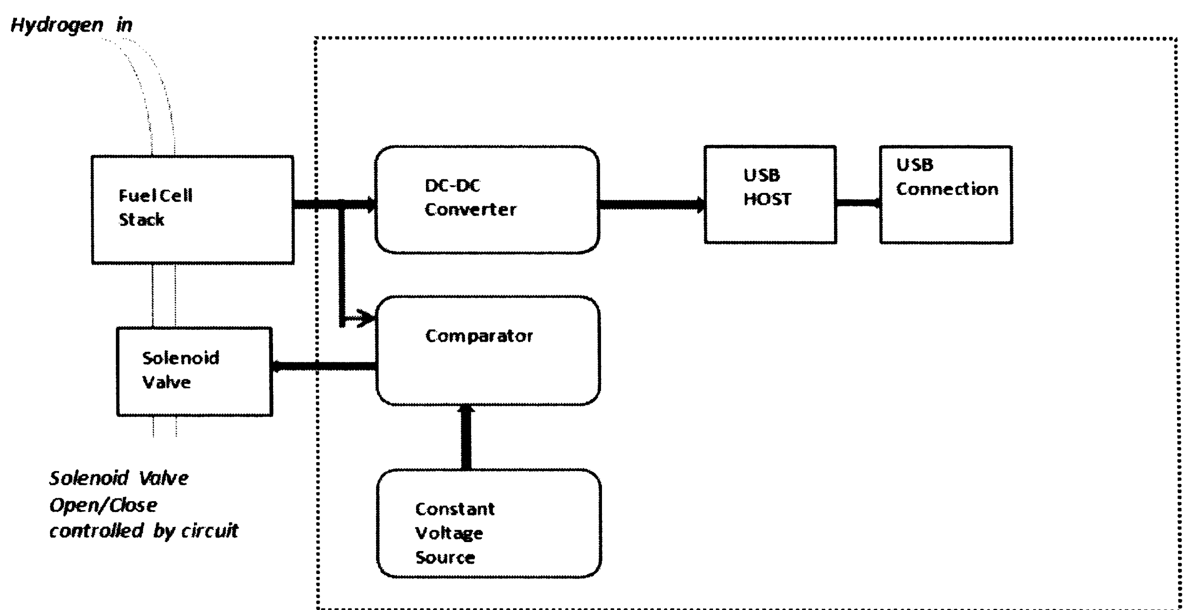


Figure 5.1: Block diagram of fuel cell control circuit actuating flow of hydrogen into the fuel cell

It is almost impossible to get a 100% steady output from a fuel cell. The output of the fuel cell is a function of various parameters, some of which cannot be easily controlled. Therefore to ensure a constant voltage output, a voltage regulator circuit is necessary.

A DC-DC boost converter is used to regulate the output. A solenoid valve can be used to control the purging of hydrogen gas. When the hydrogen in the fuel cell is 'used up' the voltage starts to drop. Once the voltage drops below 3V, the solenoid valve is turned on. This is a normally closed (NC) valve. Thus when the valve is open, old hydrogen is forced out and new hydrogen flows into the system. This in turn increases the output voltage. Once the output increases to 5.5V or more the comparator closes the solenoid valve. This forces the fuel cell to use the hydrogen more efficiently.

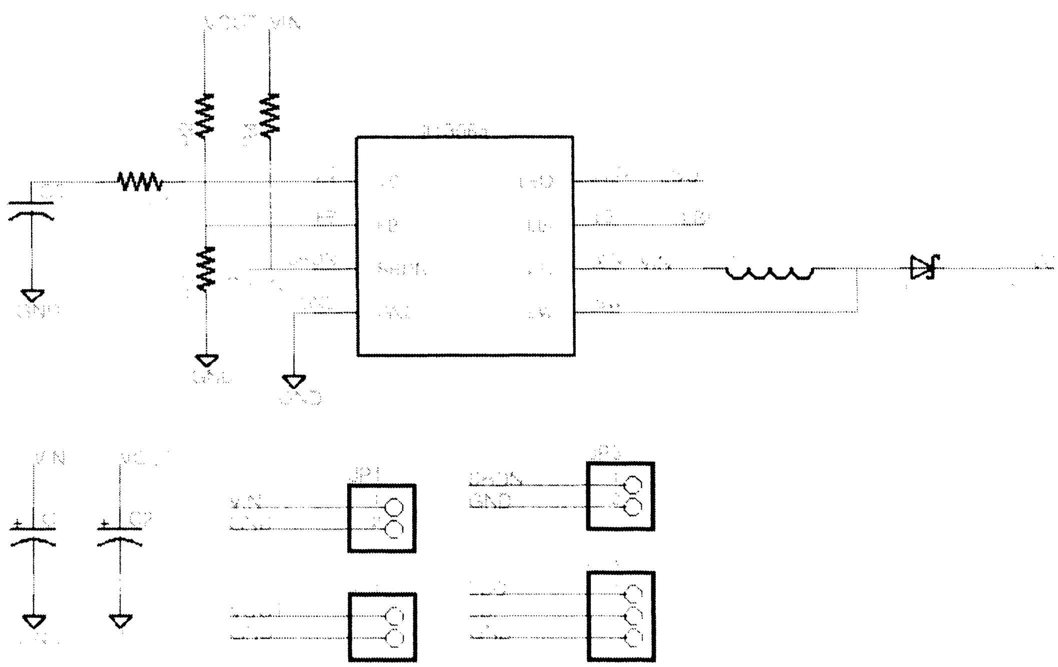


Figure 5.2: Schematic layout of voltage regulation circuit used to give a steady output of 5V

Some of the features of the circuit are as follows

- Uses switching power supply techniques to stabilize the voltage output of the fuel cell
- Senses fuel cell output to control purging of the fuel cell

- Has an efficiency of above 80%
- The output voltage range is within +/- 20mV over the range of fuel cell output voltage
- Standard USB-A connection for many charging application
- USB current limiting circuitry can be added for short circuit/over current protection.

This means that, as long as the fuel cell outputs within the specified limits, the electronic circuit can keep the output steady at 5V. The circuit board layout for the power conditioning part of the circuit is given in figure 5.3

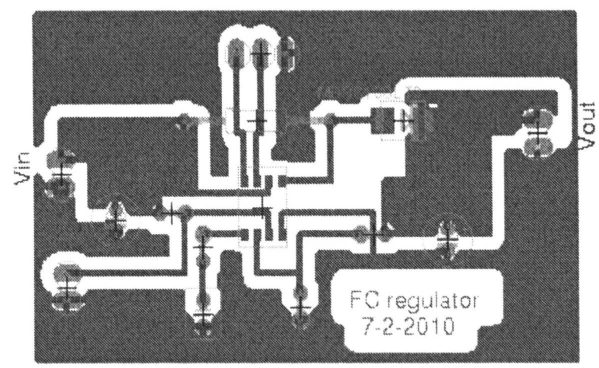


Figure 5.3: Control board layout design for the boost DC-DC converter and voltage regulator

A prototype board, shown in figure, was built in-house with photo lithography and etching equipment. The prototype board that was manufactured is shown in figure 5.4. The prototype which was made was tested yielding the results as shown in Figure 5.5. Smaller loads means greater current USB specifications allowing for 4.75-5.25 Volts output at a maximum of 0.1 Amp per device. 47 Ohms draws slightly more current than the maximum allowable per device. The advantage of having a USB charging port is that many devices have a standard micro-USB charging port. The board was successfully tested to give an steady output of 5V irrespective to changes in the input voltage from the fuel cell.

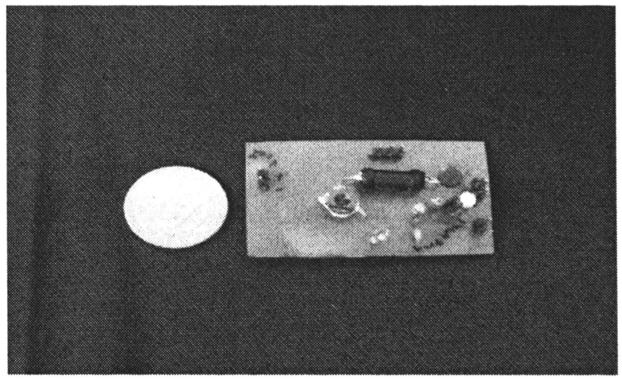


Figure 5.4: First prototype board built in-house with lithography and etching equipment

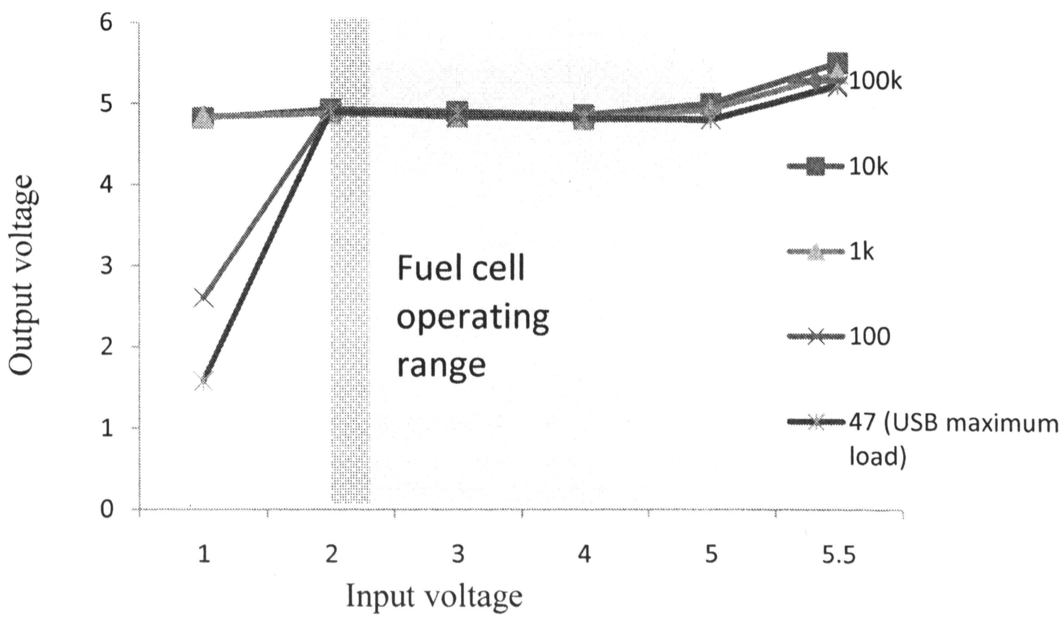


Figure 5.5: Fuel cell voltage regulator output vs. input for various loads

5.2. COST ANALYSIS OF THE CONTROL CIRCUIT

A prototype for the power conditioning circuit was built and tested. All components of the prototype were initially procured as single parts. This drove the cost of the initial prototype up immensely. The total cost excluding assembly for a single prototype manufactured was $286.22.

A cost analysis was done tracking the cost of a single board when manufacturing orders from 10 to 100,000 boards. The cost breakdown is shown in Table 5.1. From the table, it is seen that for orders less than 100, the most expensive component was the circuit board.

As the quantity increases, there is a drastic decrease in component cost. The cost for manufacturing 100 boards is approximately 55% the price of manufacturing ten boards as shown in Figure 5.6. The other main cost factors are USB power controller tube and 220μF Tantalum capacitor. The quotes for the component were acquired from digikey.com and the quote for the board was acquired

The drastic decrease in circuit board cost can be associated to making the masks and tooling for the board. This one time processing is expensive and hence drives the cost of one board very high. However the mask and tooling can be used repetitively for any number of boards making this a onetime cost associated with the initial order of circuit boards. From the point of view of total fuel cell system cost, the control circuit is not expensive if it is manufactured in a bulk quantity of 100 or more. Once the components of the control circuits are acquired, they need to be assembled. The cost breakdown of assembly for each board for different order size is as shown in Table 5.2.

Table 5.1: Fuel cell circuit board components costs based on volume

Parts needed	Cost /Part (10 order)	Cost/ Part (100 order)	Cost/ Part (1000 order)	Cost/ Part (10000 order)	Cost/ Part (100000 order)
IC DC/DC CONV SINGLE CELL 8-SOIC	6.50	3.50	3.50	3.50	3.50
DIODE SCHOTTKY 15V 1A SMB	1.19	0.46	0.41	0.31	0.29
CHOKE RF HI CURRENT 10UH 1.28A	1.33	0.58	0.44	0.42	0.42
CAP TANT LOESR 220UF 6.3V 20%SMD	3.50	2.66	1.24	1.05	1.05
IC USB PWR CTRLR DUAL 16-QSOP	4.28	2.66	2.47	2.39	2.39
CAP 100PF 50V CERAMIC C0G 5%	0.08	5.40	0.46	0.32	0.23
USB Connector	5.00	4.00	0.66	0.66	0.66
Resistors	2.00	0.50	0.04	0.02	0.02
Total (components only)	**23.88**	**19.76**	**9.22**	**8.68**	**8.57**
Printing circuit board	26.24	8.46	5.67	2.20	0.98
Total cost /unit ($)	**50.11**	**28.22**	**14.89**	**10.88**	**9.55**

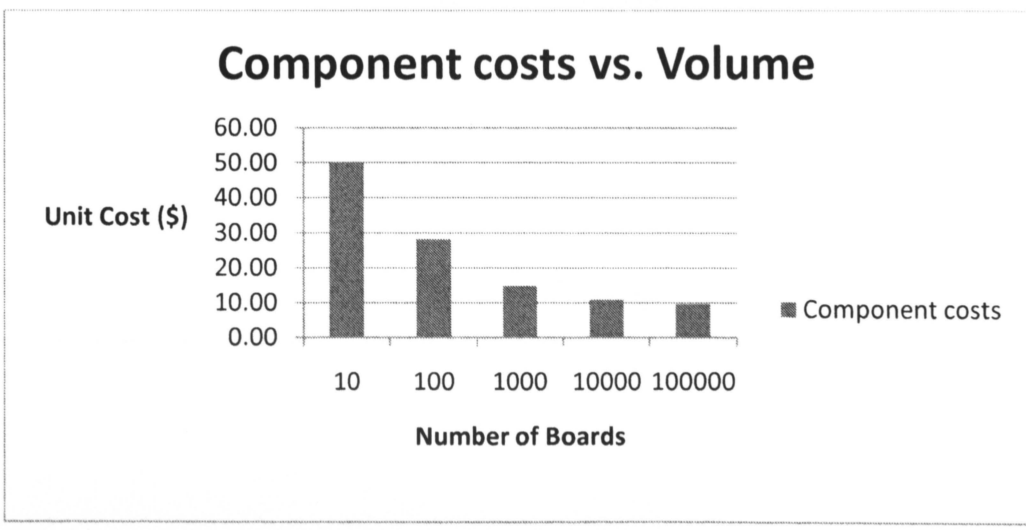


Figure 5.6: Volume to cost comparison chart for the fuel cell control circuit

Table 5.2: Cost of assembly

Number of boards	Total cost ($)	Cost per board ($)
10	815.94	81.59
100	1010.89	10.11
1000	2783.24	2.78
10000	20,506.72	2.05
100000	197,741.47	1.98

The costs shown in table 5.2 are inclusive of testing and part failure. The total cost of the control circuit board is shown in Table 5.3. A graphical representation of total board costs based on volume of purchase is shown in Figure 5.7

Table 5.3: Total cost for manufacturing circuit boards

Number of boards	Component cost/board	Assembly cost/board	Total cost/Board
10	28.62	81.59	110.22
100	28.22	10.10	38.33
1000	14.89	2.78	17.67
10000	10.88	2.05	12.93
100000	9.54	1.97	11.52

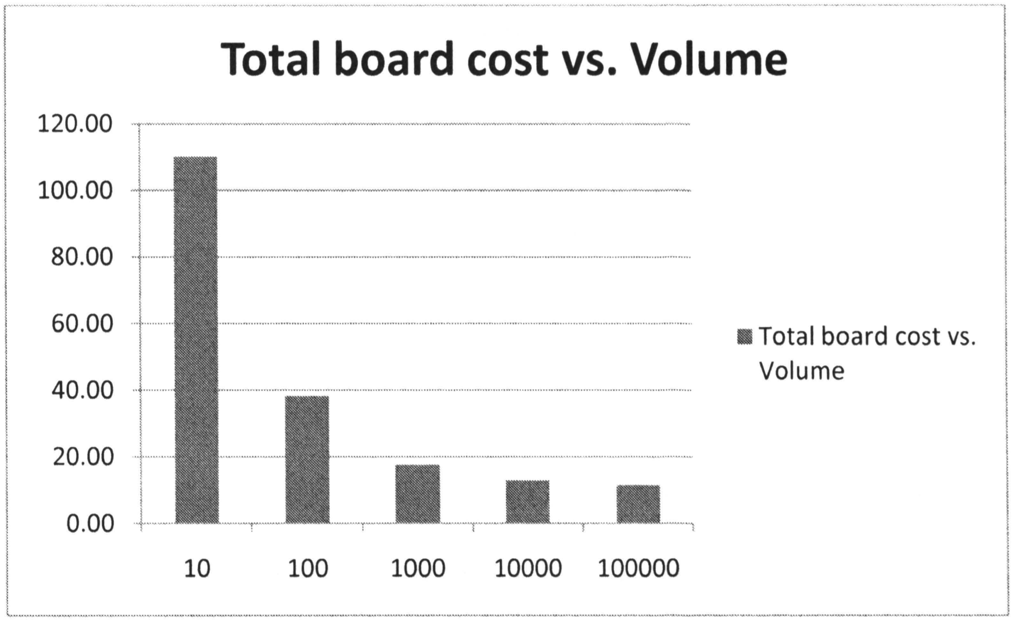


Figure 5.7: Total control circuit board cost based on volume of purchase

6. CONCLUSIONS

The research conducted in this thesis accurately confirms the advantage of using a vertical air channel for an air breathing PEM fuel cell. Furthermore, an innovative air breathing chimney design was tested after steady state time with the fuel cell yielding a 16.89% in the power density. This design was further tested under realistic operating conditions (with cross air acting on the chimney) which further yielded better results. The increase in power density during operation with chimney with cross air was about 27.80%.

A control circuit was designed for an air breathing fuel cell. The working of the control circuit was explained and a functioning prototype was made in the lab and tested. The prototype yielded a stable output of 5V with a variation of 25mV under various loads. A cost analysis was done for this control circuit for different order sizes to shed light on the feasibility of using a control circuit from an economical viewpoint.

BIBLIOGRAPHY

1) Meyers, Jeremy; Helen L. Maynard. "Design considerations for miniaturized PEM fuel cells, 2004.

2) Bussayajarn, Narissara; Han Ming, "Planar air breathing PEMFC with self humidifying MEA and open cathode geometry design for portable applications."2009.

3) Larminie, James; Andrews Dicks, "Fuel Cells Explained."

4) Department of Energy, Roadmap on Manufacturing R&D for the Hydrogen Economy, Washington D.C, 2005.

5) Tawfik, H; Y. Hung, D. Mahajan. "Metal Bipolar plates for PEM Fuel Cells-A Review."

6) Chen, Ssuwei; Fabrication of PEM Fuel Cell Bipolar Plate by Indirect Selective Laser Sintering, Doctor of Philosophy thesis, University of Texas at Austin, 2006.

7) Maeda, K ; T.H.C. Childs, "Laser sintering (SLS) of hard metal powders for abrasion resistant coatings," Journal of Materials Processing Technology 149 (2004) 609–615, 2004.

8) Hottinen, Tero; Olli Himanen, Peter Lund " Effect of Cathode Structure on Planar free air-breathing PEMFC," 2004.

9) Kitamura, Yoji; Masaru Ishizuka. " Chimney Effect on Natural air cooling of Electronic Equipment Under Inclination," 2004.

10) May, G De; M. Wojcik . "Chimney Effect on Natural Convection Cooling of a transistor mounted on a Cooling Fin," 2009.

11) Vega-Leal, P, Alfredo; "Design of control systems for portable PEM fuel cells," 2007.

12) Kordesch, K; G.Simader. Fuel cells and their applications, Ed, VCH publishers, 1996.

13) www.digikey.com , 03/23/2011 , 2030hrs

14) www.pcbassenblydepot.com 03/24/2011 , 2100hrs

15) Andy Walker, National Renewable Energy Laboratory, 06-15-2010, http://www.wbdg.org/resources/naturalventilation.php , Date of access : 03/01/2011

16) Yun, Jin-Chul; Seong-Il Heo, Kyeong-Seok Oh, Kyung-Seop Han* "Degradation of graphite reinforced polymer composites for pemfc bipolar plate after hygrothermal ageing."

VITA

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