`

DEVELOPMENT OF FUEL CELL USING METAL FOAM

HAVINES RAO A/L NAGESVERAM

B092010394

BACHELOR OF MECHANICAL ENGINEERING TECHNOLOGY (AUTOMOTIVE TECHNOLOGY) WITH HONOURS

2024

`

Faculty of Mechanical Technology and Engineering

DEVELOPMENT OF FUEL CELL USING METAL FOAM

Havines Rao a/l Nagesveram

Bachelor of Mechanical Engineering Technology (Automotive Technology) with Honours

2024

`

DEVELOPMENT OF FUEL CELL USING METAL FOAM

HAVINES RAO A/L NAGESVERAM

A thesis submitted
in fulfillment of the requirements for the degree of
Bachelor of Mechanical Engineering Technology Automotive with Honours

Faculty of Mechanical Technology and Engineering

UNIVERSITI TEKNIKAL MALAYSIA MELAKA

2024

UNIVERSITI TEKNIKAL MALAYSIA MELAKA

BORANG PENGESAHAN STATUS LAPORAN PROJEK SARJANA MUDA

TAJUK: Development of Fuel Cell using Metal Foam.

SESI PENGAJIAN: **2023-2024 Semester 1**

Saya **HAVINES RAO A/L NAGESVERAM**

mengaku membenarkan tesis ini disimpan di Perpustakaan Universiti Teknikal Malaysia Melaka (UTeM) dengan syarat-syarat kegunaan seperti berikut:

1. Tesis adalah hak milik Universiti Teknikal Malaysia Melaka dan penulis.
2. Perpustakaan Universiti Teknikal Malaysia Melaka dibenarkan membuat salinan untuk tujuan pengajian sahaja dengan izin penulis.
3. Perpustakaan dibenarkan membuat salinan tesis ini sebagai bahan pertukaran antara institusi pengajian tinggi.
4. **Sila tandakan (✓)

☑	TERHAD	(Mengandungi maklumat yang berdarjah keselamatan atau kepentingan Malaysia sebagaimana yang termaktub dalam AKTA RAHSIA RASMI 1972)
☐	SULIT	(Mengandungi maklumat TERHAD yang telah ditentukan oleh organisasi/badan di mana penyelidikan dijalankan)
☐	TIDAK TERHAD	

Disahkan oleh:

Alamat Tetap:

NO.14 JALAN KLLN 6
TAMAN KOPERATIF,SUNGAI CHUA
43000,KAJANG,SELANGOR

Tarikh: 10/01/2024

Cop Rasmi:
DR FADHILAH BINTI SHIKH ANUAR
PENSYARAH KANAN
FAKULTI TEKNOLOGI & KEJURUTERAAN MEKANIKAL
UNIVERSITI TEKNIKAL MALAYSIA MELAKA

Tarikh: 09/02/2024

** Jika tesis ini SULIT atau TERHAD, sila lampirkan surat daripada pihak berkuasa/organisasi berkenaan dengan menyatakan sekali sebab dan tempoh laporan PSM ini perlu dikelaskan sebagai SULIT atau TERHAD.

`

DECLARATION

I declare that this project entitled "Development of Fuel Cell using Metal Foam " is the result of my own research except as cited in the references. The project report has not been accepted for any degree and is not concurrently submitted in candidature of any other degree.

Signature	:	
Name	:	Havines Rao A/L Nagesveram
Date	:	10/1/2024

`

APPROVAL

I hereby declare that I have checked this thesis and in my opinion, this thesis is adequate in terms of scope and quality for the award of the Bachelor of Mechanical Engineering Technology (Automotive Technology) with Honours.

Signature : ....

Supervisor Name : Dr. Fadhilah Binti Shikh Anuar

Date : 09/02/2024

`

DEDICATION

To my beloved family and friends,

Thank you for all of the support and belief in my abilities,

and countless sacrifices.

To my honoured supervisor,

Dr. Fadhilah Binti Shikh Anuar and all UTeM lecturers and staffs

Thank you for all of your guidance, expertise and encouragement

To help me complete this project study.

`

ABSTRACT

For clean and efficient energy conversion, fuel cells have emerged as a possible alternative to traditional combustion engines. This research focuses on the creation of a fuel cell with metal foam as a crucial component. Metal foam has unique qualities such as large surface area, great thermal conductivity, and outstanding mechanical strength, making it an attractive choice for improving fuel cell efficiency. The purpose of this study is to look into the feasibility and performance of a metal foam-based fuel cell. Material selection, manufacturing procedures, and performance assessment are all important parts of the research. The conductivity, durability, and compatibility with fuel cell surroundings of appropriate metal foam materials are first discovered. The metal foam is then fabricated into the fuel cell design using different manufacturing processes such as powder metallurgy, foam impregnation, or electrodeposition. The manufacturing technique seeks to maximise the active surface area and gas diffusion capabilities of the metal foam by optimising its structure and shape. Techniques for ensuring excellent electrical conductivity are also being researched. To assess the performance of the metal foam-based fuel cell, comprehensive experimental studies are conducted. The key performance parameters, including power density, efficiency, and durability, are evaluated and compared against conventional fuel cell designs. The impact of metal foam properties, such as pore size, thickness, and surface treatment, on the fuel cell performance is systematically analysed. This study's findings will help to advance our understanding of metal foam's potential as a successful component in fuel cell technology. Metal foam integration's better performance might contribute to greater energy conversion efficiency, decreased system weight, and increased durability. Furthermore, the use of metal foam may offer up new opportunities for fuel cell applications in a variety of industries, such as automotive, aerospace, and stationary power production.

`

ABSTRAK

Untuk penukaran tenaga yang bersih dan cekap, sel bahan api telah muncul sebagai alternatif yang mungkin kepada enjin pembakaran tradisional. Penyelidikan ini memberi tumpuan kepada penciptaan sel bahan api dengan buih logam sebagai komponen penting. Buih logam mempunyai kualiti unik seperti luas permukaan yang besar, kekonduksian terma yang hebat, dan kekuatan mekanikal yang luar biasa, menjadikannya pilihan yang menarik untuk meningkatkan kecekapan sel bahan api. Tujuan kajian ini adalah untuk melihat kebolehlaksanaan dan prestasi sel bahan api berasaskan buih logam. Pemilihan bahan, prosedur pembuatan dan penilaian prestasi adalah semua bahagian penting dalam penyelidikan. Kekonduksian, ketahanan dan keserasian dengan persekitaran sel bahan api bahan buih logam yang sesuai pertama kali ditemui. Buih logam kemudiannya difabrikasi ke dalam reka bentuk sel bahan api menggunakan proses pembuatan yang berbeza seperti metalurgi serbuk, impregnasi buih, atau elektrodeposisi. Teknik pembuatan bertujuan untuk memaksimumkan luas permukaan aktif dan keupayaan resapan gas buih logam dengan mengoptimumkan struktur dan bentuknya. Teknik untuk memastikan kekonduksian elektrik yang sangat baik juga sedang dikaji. Untuk menilai prestasi sel bahan api berasaskan buih logam, kajian eksperimen komprehensif dijalankan. Parameter prestasi utama, termasuk ketumpatan kuasa, kecekapan dan ketahanan, dinilai dan dibandingkan dengan reka bentuk sel bahan api konvensional. Kesan sifat buih logam, seperti saiz liang, ketebalan, dan rawatan permukaan, pada prestasi sel bahan api dianalisis secara sistematik. Penemuan kajian ini akan membantu memajukan pemahaman kita tentang potensi buih logam sebagai komponen yang berjaya dalam teknologi sel bahan api. Prestasi integrasi buih logam yang lebih baik mungkin menyumbang kepada kecekapan penukaran tenaga yang lebih besar, penurunan berat sistem dan peningkatan ketahanan. Tambahan pula, penggunaan buih logam mungkin menawarkan peluang baharu untuk aplikasi sel bahan api dalam pelbagai industri, seperti automotif, aeroangkasa dan pengeluaran kuasa pegun.

ACKNOWLEDGEMENTS

First and foremost, I would like to extend my deepest appreciation to my project supervisor Dr. Fadhilah Binti Shikh Anuar from Universiti Teknikal Malaysia Melaka (UTeM) for her constituent supervision, support and encouragement towards the completion of this study. Her insightful feedback and continuous encouragement have been instrumental in shaping the direction and quality of this study.

I would like to express my sincere gratitude to everyone who have been associated in this paper of study. Their assistance was crucial in gathering appropriate information and data in enhancing the report's findings. Sincere appreciation is extended to my parents, siblings, and friends for their unflagging encouragement, patience, and motivation during the course of my education. They have been a never-ending source of inspiration because of their love, tolerance, and faith in my skills. I would want to thank everyone who has indirectly contributed to my work but has been crucial in shaping my academic experience. Your help, in any manner, is much appreciated.

Last but not least, I wish to thank Universiti Teknikal Malaysia Melaka (UTeM) for its assistance and resources. The infrastructure in terms of buildings, library resources, and technological advancements has made study much easier.

`

TABLE OF CONTENTS

`

`

LIST OF TABLES

TABLE **TITLE** **PAGE**

`

LIST OF FIGURES

`

`

LIST OF SYMBOLS AND ABBREVIATIONS

PEM	-	Proton Exchange Membrane
CHP	-	Combined Heat and Power Systems
SOFC	-	Solid Oxide Fuel Cell
MCFC	-	Molten Carbonate Fuel Cell
PAFC	-	Phosphoric Acid Fuel Cell
AFC	-	Alkaline Fuel Cell
DMFC	-	Direct Methanol Fuel Cell
PEMFC	-	Proton Exchange Membrane Fuel Cell
PFSA	-	Perfluorosulfonic Acid Polymer
BPP	-	Bipolar Plate
MEA	-	Membrane Electrode Assembly
GDL	-	Gas Diffusion Layer
PTFE	-	Polytetrafluoroethylene
PPI	-	Pores Per Inch
LT PEMFC	-	The Low Temperature PEM Fuel Cell
HT PEMFC	-	High Temperature PEM Fuel Cell
SLM	-	Selective Laser Melting
AM	-	Additive Manufacturing
CAD	-	Computer-Aided Design
°C	-	Degree Celsius
%	-	Percentage
cm	-	Centimetre
mm	-	Millimetre
V	-	Voltage
µm	-	micrometre
mL	-	millilitre
mW	-	milliwatts
W	-	Watts

`

LIST OF APPENDICES

`

CHAPTER 1

INTRODUCTION

1.1 Background

Human's main concerns are to secure freshwater and sustainable energy resources while also protecting the environment. Renewable energy sources are environmental friendly and have low or no impacts on the environment. The development of environmental friendly and efficient energy conversion devices is an essential necessity for the efficient use of renewable energy resources. One of the most effective way and environmentally friendly methods of producing electricity is by using fuel cell. Fuel cell has the ability to deliver high power density while operating in low temperatures. A fuel cell is basically an electrochemical device that converts the chemical energy to electrical energy. Sir William Grove who is known as the 'father of fuel cell' discovered it in the year 1839. Since then various types of fuel cells have been produced. Those includes the solid oxide, alkaline, and proton exchange membrane (PEM) fuel cell which is being used as the tool in this paper of study.

Fuel cells are used in a wide range of applications, from powering cars, trucks and buses, to generating electricity for homes, buildings and off-grid remote locations. One of the major challenges in the development of fuel cells is to increase their efficiency and reduce their cost. One way to achieve this is by using metal foam as a substrate for the fuel cell. Metal foam is a light-weight, porous material that has a large surface area-to-volume ratio, high thermal conductivity, and good mechanical properties. These properties make it an ideal material to be used in fuel cells.

`

1.2 Problem Statement

The current fuel cell technology faces challenges related to the cost of raw materials and the lack of durability. Considering precious metals like platinum and iridium are commonly used as catalysts in fuel cells and some types of water electrolysers. The initial cost of fuel cells and electrolysers can be expensive. This hefty cost has stopped some from investing in hydrogen fuel cell technology. These prices must be minimised in order to make hydrogen fuel cells an accessible fuel source for everyone.

Thus, metal foam is therefore employed in fuel cell applications. They have shown promising results in terms of efficiency, durability, and cost-effectiveness. Its high surface area-to-volume ratio and strong thermal conductivity makes it beneficial to be used as a catalyst support that allows for a better efficiency in the chemical processes that occurs within the fuel cell. Besides that, metal foam can improve the distribution of reactants and products within the fuel cell. It can boost overall performance and lowering the possibility of hotspots or other operational concerns. Its compact design and light weight make it ideal to be used as portable or mobile fuel cell systems.

1.3 Research Objective

The main aim of this research is to develop a fuel cell using metal foam.The work includes using cad software to design the metal foam and producing it using the 3d metal printer. Specifically, the objectives are as follows:

a) To design a fuel cell system using metal foam.

b) To fabricate the metal foam using the 3D metal printer.

c) To test the capability and performance of the Fuel Cell System.

`

1.4 Scope of Research

The scope of this research are as follows:

- To develop a fuel cell system by using metal foam as the distributor in fuel cell.

- To design the metal foam by using the Solidworks software.

- To fabricate the metal foam by using the stainless steel material and producing it by using the 3D Selective Laser Melting machine (SLM printer).

- To test the performance of the Proton Exchange Membrane Fuel Cell by analyzing the power output of the fuel cell.

`

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

To ensure the success of a product, several factors should be extensively explored and analysed. The project will be changed in light of the collected data in order to continue operating efficiently and to achieve the design's purpose. Researchers analysed all data or information acquired from numerous sources during their inquiry to reach the best possible outcome. This is done to ensure that the design fulfils all the standard criteria and functions as intended to design and fabricate the fuel cell using metal foam. The type of fuel cell that will be used in this project is the Proton Exchange Membrane (PEM) fuel cell and the metal foam that is designed will act as the flow distributor in the cell. Thus, this chapter will discuss all the related development aspects and information's regarding the PEM fuel cell and the open cell metal foam.

2.1.1 Fuel Cell System

Figure 2.1 represents the basic structure of a fuel cell. The fuel cell consists of the anode, the cathode, and the electrolyte. The anode is where hydrogen enters the fuel cell. Two ions and two electrons are separated from the hydrogen molecule. Ions flow through the electrolyte to the cathode while electrons go through an external circuit, providing an electrical current. The cathode is where oxygen is introduced to the fuel cell, and it combines with the ions and electrons from the anode to form water and heat. As long as fuel (typically hydrogen) is provided to the anode and oxygen is given to the cathode, the fuel cell generates electrical power. Water and heat are byproducts of the fuel cell process that may be used in

`

a variety of ways. Fuel cells are well-known for their great efficiency, minimal emissions, and silent operation.

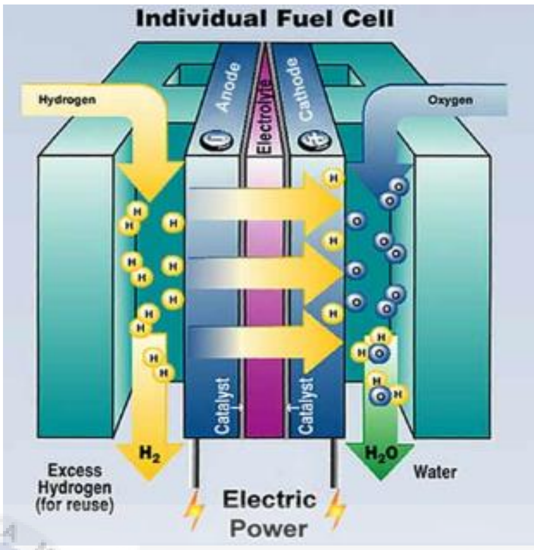


Figure 2. 1 Basic Structure of fuel cell (Professor Shapley, 2011)

Fuel cell systems are alternative energy systems that generate electricity by using hydrogen. They are intended to transform hydrogen and oxygen's chemical energy into electricity, water, and heat. There are six systems that is involved in the operation of a fuel cell as shown in Figure 2.2. First is the fuel cell stack. This is the main component of the fuel cell system. It consists of multiple cells depending on the applications to generate electricity from hydrogen and oxygen. Next is the fuel storage system. In this system is where the hydrogen which act as the fuel is stored in compressed or liquefied form. Then, is the air intake system where it supplies necessary oxygen to the fuel cell stack. Adding on is the power conditioning unit where it controls and converts the direct current produced by the fuel cell into appropriate voltage and current for its respective application. Then comes the thermal management system where it controls the temperature of the fuel cell stack to ensure efficient and safe operation of the fuel cell. Lastly is the auxiliary power systems. This system provides power for auxiliary functions such as pumps, fans and control systems.

`

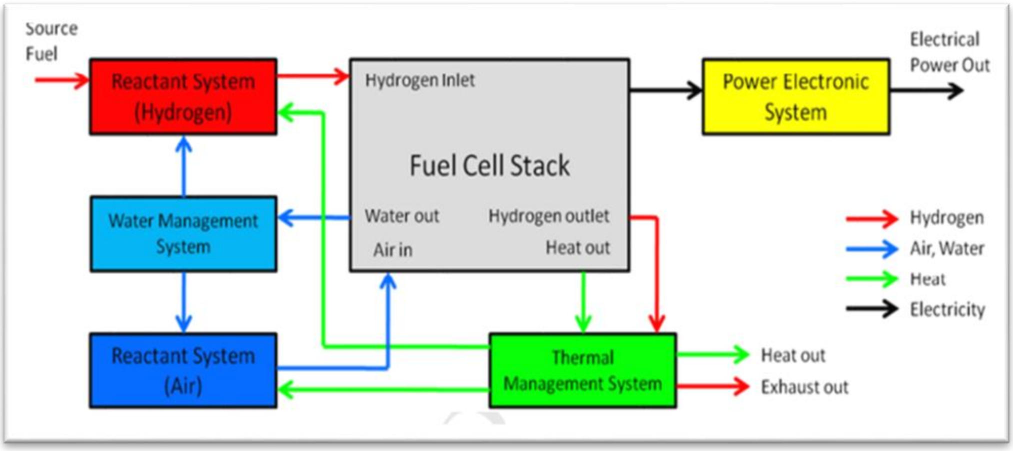


Figure 2. 2 Schematic Diagram of Fuel Cell system (Daud, Rosli, Majlan, Hamid, & Mohamed, 2017)

2.1.2 Types of Fuel Cells

The development of fuel cells over the last century has been heavily influenced by external factors. Fuel cells were seen as an attractive means for the generation of power because the efficiency of other technologies were very poor (M & Fuller, 2002). Fuel cells are electrochemical devices that transform the chemical energy contained in fuels such as hydrogen directly to electrical energy. They are classified according to the electrolyte utilised. Its efficiency in electrical energy conversion may approach 60% and overall 80% in co-generation of electrical and thermal energies, with more than 90% decrease in main pollutant emissions. (Wang, Chen, Mishler, Cho, & Adroher, 2011). There are several types of fuel cells, each with distinct characteristics and operating principles. The first type is the Solid Oxide Fuel Cell (SOFC). The electrolyte used is a dense ceramic oxide electrolyte and has high operating temperature which is around 500°C-1000°C.It is mainly used for stationary power generation, combined heat and power (CHP) systems, and certain transportation applications.

The Molten Carbonate Fuel Cell (MCFC) comes next. The MCFC runs at high temperatures (between 650°C and 750°C) with a molten carbonate salt combination as the

`

electrolyte. It may run on a range of fuels such as natural gas, biogas, and coal gas. MCFCs are well-known for their excellent efficiency and tolerance of some degrees of fuel contaminants. They're often found in large-scale stationary power producing applications including industrial and utility power plants.

The Phosphoric Acid Fuel Cell (PAFC) comes next. The PAFC runs at low temperatures (150°C to 200°C) and uses phosphoric acid as the electrolyte. It may be powered by reformed natural gas or hydrogen. Because of their high efficiency and dependability, PAFCs are ideal for stationary power production applications such as hospitals and schools.

The third type is the Alkaline Fuel Cell (AFC). The AFC uses a solution of potassium hydroxide or sodium hydroxide as the electrolyte. It operates at low temperatures and is primarily used in niche applications, such as space exploration and underwater vehicles. AFCs have high efficiency and good tolerance to carbon dioxide, but they require pure hydrogen and are not widely commercialized.

There's also the Direct Methanol Fuel Cell (DMFC), which transforms methanol fuel directly into energy without the use of an external reformer. The electrolyte is commonly a polymer membrane similar to that used in PEMFCs. DMFCs are portable and may find use in portable electronics and small-scale power generation. However, they encounter methanol crossover issues and have a lower energy density than hydrogen fuel cells.

The Proton Exchange Membrane Fuel Cell (PEMFC), which will be employed in this investigation, is the final one. As the electrolyte in the PEMFC, a solid polymer electrolyte membrane, generally formed of a perfluorosulfonic acid polymer, is used. It can start up quickly and works at relatively low temperatures (usually below 100°C). PEMFCs are small, have a high power density, and are efficient. They are widely employed in transportation applications like as automobiles and buses.

`

2.1.3 PEM Fuel Cell

A fuel cell always consists of two electrodes, an anode and a cathode at the both ends. Then there is the current collector plate which is known as the compression plate. It is made up of aluminium alloy that is used to fix and monitor the entire electrolysis process of the cell. The bipolar plate (BPP) is attached next to the collector plate. This bipolar plate needs to be low in resistance and high in mechanical, thermal and chemical stability. This is because the main function of the bipolar plate is to help in the heat transfer process. Then there is membrane electrode assembly known as the MEA plane. In this MEA plane there is sealing, gas diffusion layer (GDL) and the Proton Exchange Membrane (PEM). The sealing is used for the fluid channellings process in the cells. The gas diffusion layer will act as an electronic conductor between MEA (membrane electrode assembly) and bipolar plates (BPP) to ensure efficient mass transfer of fluids and gasses is being supplied between the electrodes and BPP. Lastly is the the proton exchange membrane, also known as the polymer electrolyte membrane. It is the most crucial component in the operation of a fuel cell. Its main function is to allow the transfer of hydrogen ions (protons) from the anode to the cathode of the fuel cell.

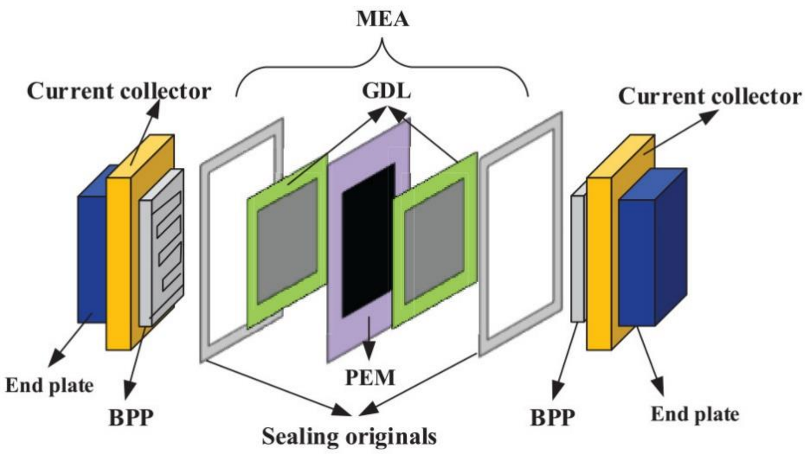


Figure 2.3 Component and Parts of the PEM Fuel Cell (Lv, Ji, Liu, & Zhang, 2020)

`

Proton Exchange Membrane fuel cells (PEM fuel cells) are devices that generate electricity through an electrochemical reaction between hydrogen gas and oxygen. The reaction takes place within a fuel cell stack, which consists of individual fuel cell units. Each fuel cell unit consists of an anode, a cathode, and a proton exchange membrane. Proton exchange membrane fuel cells are promising devices for a range of energy-conversion technologies.

However, due to the high cost of balancing durability, performance, and materials, they have limited market penetration. This is due to the cost includes the machine flow channels in the fuel cell is high (Tsai, et al., 2012). Besides that, because of the ribs and channels, the concentration distribution of reactants and the temperature distribution inside electrodes are not uniform throughout the membrane electrode assembly (MEA plane). This causes an uneven rate distribution of electrochemical processes, reducing catalyst utilisation and cell longevity. Another factor for the restricted availability of PEM fuel cells is the size and weight of the bipolar plates (graphite). Bipolar plates contribute significantly to the overall weight and volume of a single cell, accounting for up to 50% of total weight and volume. (Chung-Jen, et al., 2012). Recently, new types of flow-fields such as porous metallic powder metal micro-coil, and metal-foam have been introduced in bipolar plates (Park, et al., 2019). By replacing the traditional channel rib construction with a porous structure, these flow-fields provide advantages such as homogeneous reactant distribution and efficient water removal. However, metals have some drawbacks in the PEMFC operation condition because they are likely to corrode in acidic conditions. Therefore, new materials with novel, non-metallic structures are needed to enhance performance of the membrane electrode assembly (Park, et al., 2019).

Another significant component for mass transport in PEMFCs is the gas diffusion layer (GDL). It transports reactants from the bipolar plate channel to the catalyst layer and

`

eliminates water formed outside the catalyst layer. In addition, the GDL connects electron transport, and provides mechanical support to the membrane electrode assembly (MEA) (Zhang, Advani, & Prasad, 2008). Current GDL materials, such as carbon cloth or paper, have had little success because they do not fulfil long-term fuel cell performance, durability, or cost criteria (Zhang, Advani, & Prasad, 2008). Furthermore, classic GDLs are frequently made hydrophobic by coating them with Polytetrafluoroethylene (PTFE), which adds 5% to 30% to their weight while lowering their electrical and thermal conductivities.In addition, GDLs composed of carbon cloth or carbon paper are compressed, which reduces their thickness and reduces porosity and permeability by up to 50%. These circumstances also restrict the GDL's and, as a result, the fuel cell's longevity (Zhang, Advani, & Prasad, 2008).

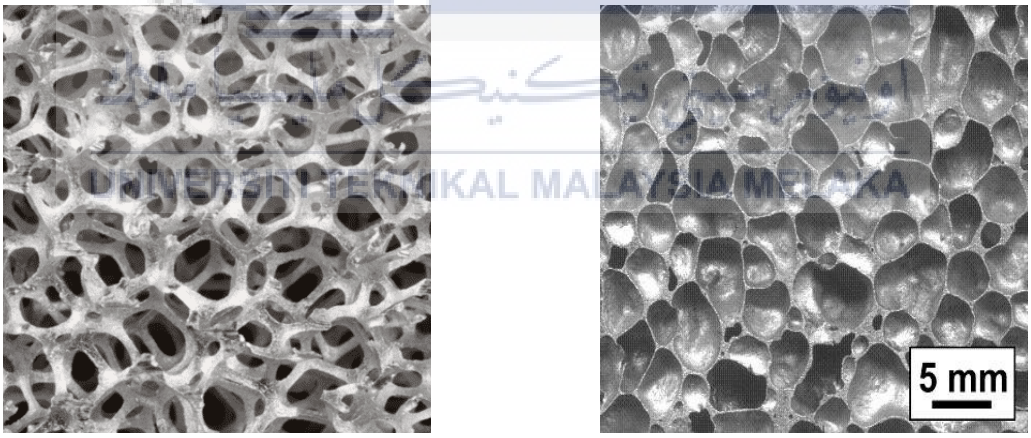
To distribute reactants more evenly and better utilize the whole area of the MEA, flow channels are usually machined on the surfaces of the bipolar plates. Serpentine, column, and interdigitated flow fields are commonly used today. Recent studies indicated that the flow field design significantly affects cell performance (Tsai, et al., 2012). Poorly designed flow fields can cause in efficient water removal and hinder reactant transport. (Wu, et al., 2018). In the traditional ones, the volume of the gas distribution layer (GDL) under the ribs is typically compressed by 10% to 20% in volume. While increasing the electric conductivity, it also reduces the porosity and permeability of the GDL, causing gas transport to be hampered. This results in reducing the efficiency of the fuel cell and causes the fuel cell to not produce the desired amount of energy.

Therefore, new materials with novel, non-metallic structures are needed to enhance performance of the membrane electrode assembly. Thus, recently metal foam has been employed as a GDL in PEMFC (Park, et al., 2019).

`

2.1.4 Open Cell Metal Foam in Fuel Cell

Metal foam is a novel material with exceptional qualities that may be used in a variety of applications. Metal foam has superior mechanical qualities, is lightweight, and has a high strength-to-stiffness ratio. Metal foam's complicated structure improves surface area per unit volume. This is an excellent feature for heat transfer or thermal management applications such as heat exchangers. By altering the properties of metal foam, such as permeability, pore size, pores per inch (PPI), and so on, the metal foam may establish a unique interaction with the fluid that flows through it, leading to a variety of findings. There are two kinds of metal foam as seen in Figure 2.4, the first type is an open cell, whereas the second is a closed cell. Because the cells are not closed, fluid may easily flow from one to the next in the open cell metal foam. The closed-cell metal foam is composed of continuous cell walls that produce discrete portions to differentiate one cell from the next.



(a) (b)

Figure 2.4 Metal Foams (a) open cell (b) closed cell (Sathurusinghe.S, Herath,S,R, & Herath,K,R, 2012)

Open-cell metal foam is an innovative material that has potential applications in fuel cell technology. Open cell metal foam has been investigated for use in fuel cell applications due to its high surface area, high porosity, and excellent heat and mass transfer properties.

`

The use of open cell metal foam as a current collector in fuel cells can enhance the transport of reactants to the catalyst layer and the removal of products from the electrode surface.

A small number of researchers have investigated the use of metal foam for cooling of fuel cells. Vazifeshenas, Sedighi, and Shakeri (2019) have investigated the influence of metal foam with varied porosities introduced in the PEM cooling channel on stack performance. The findings demonstrated that using metal foam boosted heat transmission and pressure decrease. Fluid flow and heat transfer were simulated in a 15 cm × 15 cm square area of fuel-cell cooling plates with various flow forms, including straight, serpentine with repeated passes, and metal foam, by Seyed Ali, Ebrahim, Elnaz, and Chinonyelum M, (2021). Metal foam is the best cooling strategy in terms of maximum surface temperature, temperature homogeneity, and pressure reduction, according to the data.

On the other hand, Srouji, Zheng, Dross, Turhan, and Mench (2012) studied the performance of a PEMFC with an open cell flow field architecture and a parallel rib channel design. The result shows that under the same operating circumstances the open-cell flow field design outperformed the standard channel design in terms of peak power. Furthermore, due to homogenous compression, open-cell designs offer low area-specific resistance and contact resistance.

Due to its low density and simplicity of manufacture as compared to typical graphite bipolar plates, open-cell foam has recently been investigated for PEMFC components, either as flow distributors or as gas diffusion layers. Many studies on the performance of open-cell metal foam flow fields in fuel cells have been published (Tatyana & Olga, 2021). The performance of open flow field designs in saturated and oversaturated humid environments was examined. According to the findings, the open-cell architectural flow field design displayed lower mass transport resistance in both saturated and oversaturated conditions than the serpentine channel design. Furthermore, the open cell structure maintained regular

`

humidity and allowed for quick oxygen diffusion. The use of metal foam as the flow fields has improved connections with the gas diffusion layer (GDL) via its network of ribs, resulting in reduced electrical resistance. Furthermore, its high permeability and foam structure aid in the equal distribution of reactant gases while minimising pressure loss (Tsai, et al., 2012).

The use of open cell metal foam as a current collector in fuel cells can improve performance and reduce the overall cost. However, there are still challenges to overcome in the use of metal foams in fuel cells. The corrosion resistance of the foam material must be ensured, as fuel cells operate in harsh environments. The foam structure must also be optimized to achieve optimal performance while maintaining mechanical stability. Overall, the use of open cell metal foam in fuel cell applications shows promise in improving performance and reducing cost. Further research is needed to optimize the use of this material for various fuel cell types and operating conditions.

2.2 Design of Using Metal Foam in Fuel Cell System

Figure 2.5 shows an example of the schematic diagram of PEM fuel cell with foam flow plate as the flow distribution (Baroutaji, Carton, Stokes, & Olabi, 2014). For the PEM fuel cells, details concerning the design of the fuel cell stack by using metal foam are rarely released or provided to the public. The designs, and hence the design requirements, are heavily influenced by the application. In this study the main design criteria that need to be taken into consideration is the operating conditions, durability, and cost.

Based on the research done by Barbir & S, (2007) water management plays a crucial role in the operation of a fuel cell stack. Water is essential to the operation of a fuel cell stack. The ionic conductivity of the membrane is a major effect of its hydration state. Even though water is generated in the cathode, some water must be supplied into the fuel cell to keep the membrane from drying out. This is where the gas diffusion layer in the membrane electrode assembly plays the vital role. It must be sufficiently porous to allow flow of both reactant gases and product water in the fuel cell in order to prevent the membrane from drying.

For the operating conditions, it is preferable to operate with low relative humidity of the gases at the stack input because it simplifies the system humidification of reactant gases and water recovery. The Low Temperature PEM fuel cells (LT PEMFC) may operate at room temperature, but the normal working temperature is between 60°C and 80°C. To lower the size of the heat rejection equipment, much research and development on high-temperature membranes is being conducted. Vazifeshenas, Sedighi, & Shakeri, (2019) conducted a study and find out that by using the metal foam in the as the flow field helps to increase the rate of heat transfer and pressure drop which enables the operating temperature of the fuel cell to be in control.

On the other hand, the High Temperature PEM fuel cells (HT PEMFC) can operate up to 120°C to 140°C. Based on the research conducted by Chung-, Ying-, Chien, Yi, & Kan, (2016), the application of metal foams as the flow field improves gas convection and gas diffusion. It also increases the operating temperature and improves the cell performance. They also found out that when the fuel cell temperature increases, the performance rate increases by 10%. The porous structure of metal foam can effectively reduce the contact resistance between the flow plate and carbon paper which results in higher performance rate by 20% when 0.6 V current density metal foam is being used compared to the costly conventional graphite plate.

`

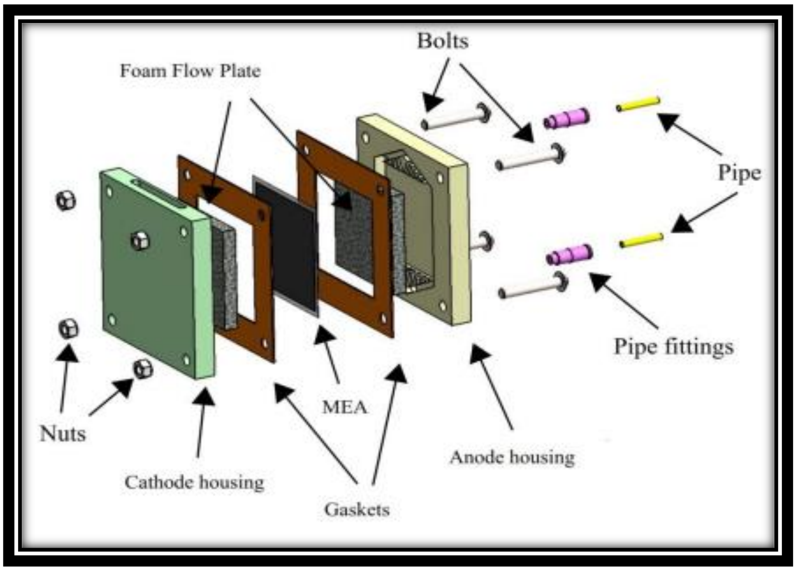


Figure 2.5 Schematic Diagram of PEM Fuel Cell with Foam Flow Plate (Baroutaji, Carton, Stokes, & Olabi, 2014)

2.3 Fabrication of Open Cell Metal Foam in Fuel Cell

2.3.1 Selective Laser Melting 3D Printing

In this project, the additive manufacturing method that was chosen to be used for 3D printing is the selective laser melting (SLM) method. This method is categorized under powder bed fusion technique that is famous and commonly used in additive manufacturing. SLM is considered as the most versatile among most additive manufacturing (AM) process because it can process a wide range of different materials. The SLM method uses a high powered laser beam to selectively melt metal powder. The melted metal powder is then fused together layer-by layer in a molecular level until the desired model is completely printed. Various metal powders comprising of various material can be used in this method. The main types of metals include stainless steel, aluminium, titanium, copper, nickel and many other. These metals have to exist in atomized powder form to be able to use in this process. This technology is also proven to produce near net shape parts with relative densities up to 99.9%.

`

This enables the process of building functional components with near-perfect density, yielding realizable economic benefits. When using this method, several process parameters must be carefully adjusted to produce defect-free parts such as the level of laser power, the laser beam diameter, the scan speed as well as the possible layer thickness (from 20 µm to 120 µm) (Bedmar, Riquelme, Rodrigo, Torres, & Rams, 2021). Furthermore, SLM does not have the need to acquire part-specific tooling and pre-production costs is low when dealing with series identical materials. The Figure 2.6 illustrates the principle working of the SLM process and the steps by which the process can be broken down. First, the 3D CAD volume model is decomposed into layers and transferred to the selective laser melting machine. A powder material (particle fraction 10-45 µm) is then deposited as a defined thin layer on the substrate. The geometric information of each layer is transferred to the powder bed by a laser beam. There, an area intended to contain solid material is scanned under an inert atmosphere (nitrogen or argon), leaving a solid layer of the part to be manufactured. After thinning the substrate by one-layer thickness, the process steps are repeated until the part is complete (Gokuldoss , Kolla, & Eckert , 2017).

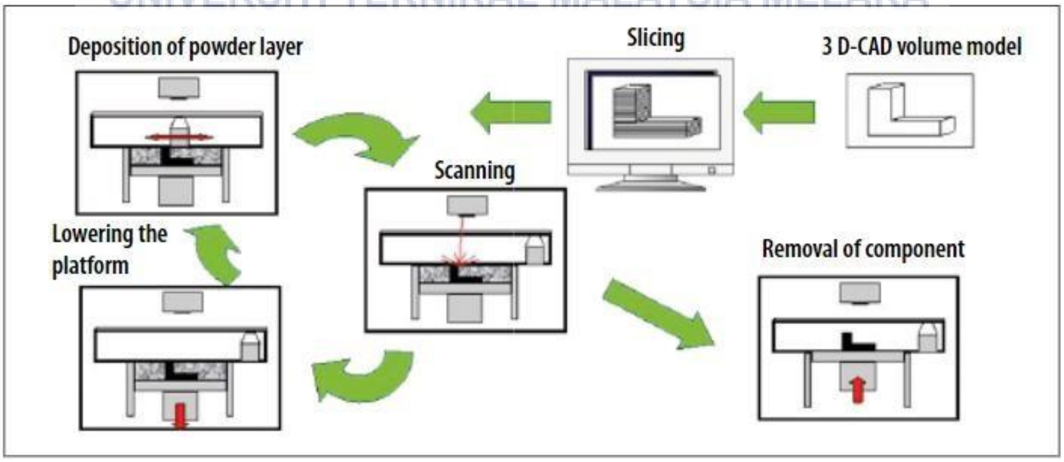


Figure 2.6 Working Principle of SLM machine (Chou, 2018)

`

2.3.2 Nickel Metal Foam

Based on the experiment made by Chung-Jen, et al., (2012), the metal foam that was used is made up of nickel with pore size of about 0.58mm. Because of corrosive environment in the PEM fuel cell, the metal foam needs to be coated with corrosion-resistant material and needs to be hydrophobic. This needs to be done to ensure the metal foam can facilitate water removal process in the cell. Thus they have decided to coat the metal foam with Polytetrafluoroethylene (PTFE) to enhance water removal and corrosion protection. The metal foam that was used has a porosity in the range of 95-98% which is acceptable in order to provide a large surface area for the reaction to occur. In order to increase the electrical conductivity, the metal foam was then compressed. As a result, the porosity of the metal foam decreases.Figure 2.7 shows the metal foam without PTFE coatings and with PTFE coatings.

(a) (b)

Figure 2.7 a) Metal foam without PTFE coatings, b) Metal foam with PTFE coatings (Chung-Jen, et al., 2012)

In terms of comparison with the traditionally graphite plate, the performances are almost the same in the low current density region. But in the intermediate to the high

`

current density regions, the metal foam cell out-performs the graphite flow channel plate cell.

2.3.3 Nitride Metal Foam

Recently, nitride-coated metal foams have been success fully used as the flow fields in the fuel cells. Based on the experiment carried out by Chung-, Ying-, Chien, Yi, & Kan,the potential application of nitride-coated metal foams towards fuel cell is investigated. In this experiment the metal foam that is used has a pore size of 0.8 mm approximately. The type of metal bipolar plates used in this work are made of aluminium alloy. The experiment make use of a membrane electrode assembly (MEA) that is commercially accessible. The size of the MEA's reaction area is 25 cm^2, and the operating temperatures are from 140°C to 200°C. In this experiment the outcome is similar to (Chung-Jen, et al., 2012).This is because it requires to be coated due to the corrosive environment in the fuel cell. Thus the metal foams and the bipolar plates is coated and porosity of the metal reduces after it is being compressed. But using nitrite material as metal foams really shows some boost in the efficiency. The fuel cell shows better performance, with approximately 20% higher compared to the traditionally graphite fuel cell.

2.4 Performance of Open Cell Metal Foam in Fuel Cell

2.4.1 Performance of Nickel and Nitride Metal Foam

Based on previous study, it is true that using metal foams as a flow distributor really does enhance the efficiency and durability of the fuel cells (Kumar & Reddy, 2003).This is because metal foams have large surface area for reaction and excellent heat transfer properties which can improve the rate of reaction and prevent overheating in fuel cells. However, the actual performance of metal foam in fuel cells depends on the specific design and operational conditions of the system (Tsai, et al., 2012). This can be proven when the experiments involving nickel and nitrite as the metal foam is being used. Both of these material shows efficiency but the rate of reaction of nickel is slow compare to nitrite. This can be due to the flow fields and design. But in terms of gas diffusion nickel has provided a better response rate. There is a better rate in uniformity in concentration distribution of reactant gases (Chung-Jen, et al., 2012). If the gas diffusion rates are too low, the fuel cell may not be able to produce enough power to meet the demand. This can result in a lack of power supply, which can lead to the shutdown of critical systems or even complete system failure. (Huu, et al., 2021).

For the fuel cell temperature, both shows some increase and efficiency. But nitrite material has a better performance and increases by about 10% with every increase of 10°C in cell temperature. But for nickel material the performance decreases as the cell temperature goes up. This can be due to the humidification where relatively low external humidification is applied when there is an increase rate of reaction. Thus it becomes less hydrated and its proton conductivity gets low (Chung-Jen, et al., 2012). Monitoring the fuel cell temperature is one of the most important aspects in the operation of fuel cells. This is because it influences the performance of proton exchange membrane fuel cells (PEMFCs). Since fuel cells operate at a specific range of temperatures, typically between 60°C and 100°C. If the temperature goes outside this range, the fuel cell's performance and efficiency can be affected, and it could even lead to damage or failure. Thermal management may increase PEMFC efficiency and minimise irreversible internal damage such as membrane breakdown. (Chen, et al., 2022).

`

2.4.2 Performance of Metal Foam with Different Parameters and Specifications

Table 2.1 shows the Experimental Optimization of Metal Foam Structural Parameters specification in order to improve the performance Proton Exchange Membrane Fuel Cell (Wang, et al., 2022). In this experiment, nine distinct types of cases were investigated using varied structural characteristics (pore density, thickness, compression ratio) as the cathode flow field in an open-cathode PEMFC. Measurements of polarisation curves and power density curves are used to examine cell performance and internal losses. Pore diameters of 20 PPI, 40 PPI, 60 PPI, and 80 PPI were examined with various thicknesses ranging from 3mm to 5mm.

Table 2.1: Experimental Optimization of Metal Foam Structural Parameters (Wang, et al., 2022)

Samples	Pores per inch/PPI	Initial Thickness(mm)	Thickness after compression(mm)	Compression Ratio	Porosity(%)
CASE 1	20	5	3	5:3	95
CASE 2	40	5	3	5:3	95
CASE 3	60	5	3	5:3	95
CASE 4	80	5	3	5:3	95
CASE 5	40	4	2.4	4:2:4	95
CASE 6	40	3	1.8	3:1:8	95
CASE 7	40	5	1.2	2:1:2	95
CASE 8	40	3	2.4	3:2:4	96.3
CASE 9	40	5	2.4	5:2:4	93.8

In terms of the influence of metal foam pore density, the cell performance initially increases and then decreases as the metal foam pore density increases, achieving its peak performance at 40 PPI. The metal foam's pore density is a crucial component in cell performance. The study discovered that when the metal foam pore density increases, cell performance rises first due to increased pressure drop and then declines due to decreased reactant flow into the reaction zone. By optimising the pore density, the maximum power density is increased by 49.8% (Wang, et al., 2022).

The results of the thickness effect shows that increasing the thickness of the metal foam improves cell performance significantly. This is because as the thickness of the metal foam rises, more air enters the foam zone to participate in the electrochemical process, improving cell performance (Wang, et al., 2022). In this experiment, the cell with 3 mm thickness metal foam had the highest maximum power of the fuel cell.

Adding on, metal foam must be compressed to an adequate flow field thickness to optimise mechanical strength and conductivity. In this experiment, raising the compression ratio first improves cell performance before decreasing it. At a current density of 0.8 A cm^2, metal foam with a compression ratio of 4:2.4 delivers the maximum power density (Wang, et al., 2022). Metal foam compression ratio optimisation leads in a 7.3% increase in cell performance. A slight increase in the compression ratio of the metal foam increases cell performance, but raising the compression ratio further has an influence on cell performance (Wang, et al., 2022).

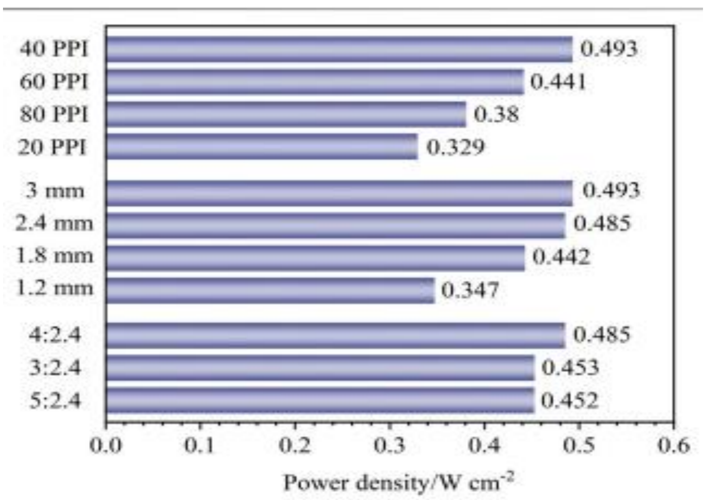


Figure 2.8 Summary of maximum power density for different cases. (Wang, et al., 2022)

CHAPTER 3

METHODOLOGY

3.1 Introduction

This chapter provides a description of the methods that were utilised in this study to investigate the performance of the fuel cell that was developed by using 3D printed metal foam. The primary areas of attention were on the behaviour of the fuel cell and the metal foam. For the fuel cell, the operating temperature and the output power voltage were studied, whereas for the metal foam, the pore density and also the thickness of the metal foam were analysed. The process began with an investigation and research on the mechanical characteristics of the fuel cell's membrane electrode assembly (MEA) that included the gas diffusion layer (GDL). This was done because the metal foam that was being developed by using 3D printing would act as the flow channels in the gas diffusion layer of the membrane electrode assembly (MEA).

`

3.2 Flowchart

In the beginning stages of the project, various information was gathered by doing a literature study from researchers. It was an important stage that assisted in getting the project off to a solid start. The era of experimentation came next. All of the technical work was carried out at this location. It began with monitoring on the performance of fuel cell and also the open cell metal foam. After the trials were finished, the method for collecting data began, and it began with monitoring on the performance of fuel cell and the open cell metal foam. Testing on the output power, pore density of the metal foam, porosity and the thickness of the metal foam was conducted. After that, the gathered data was analysed and spoken about in order to arrive at a conclusion.

`

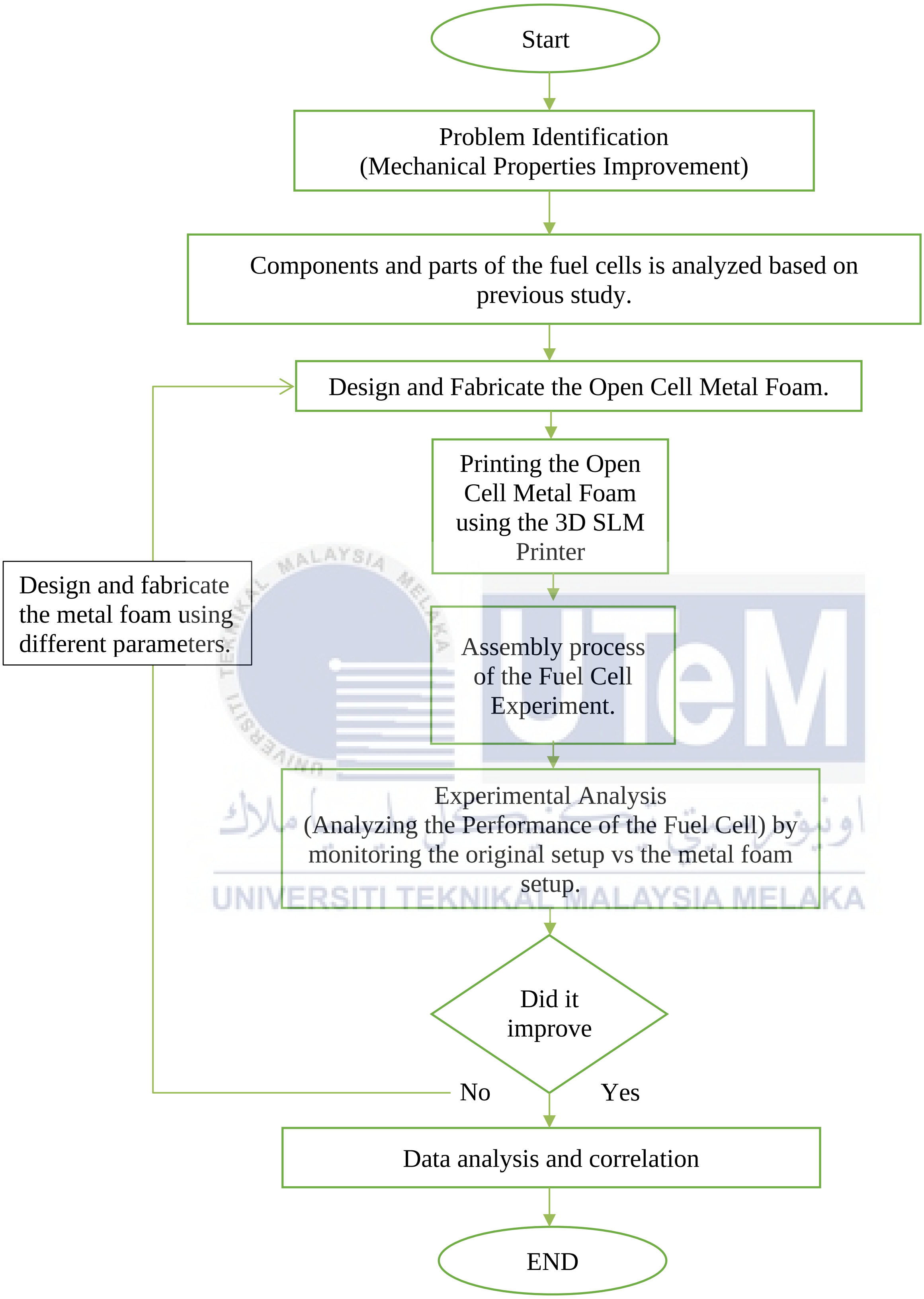


Figure 3.1 Experiment flowchart

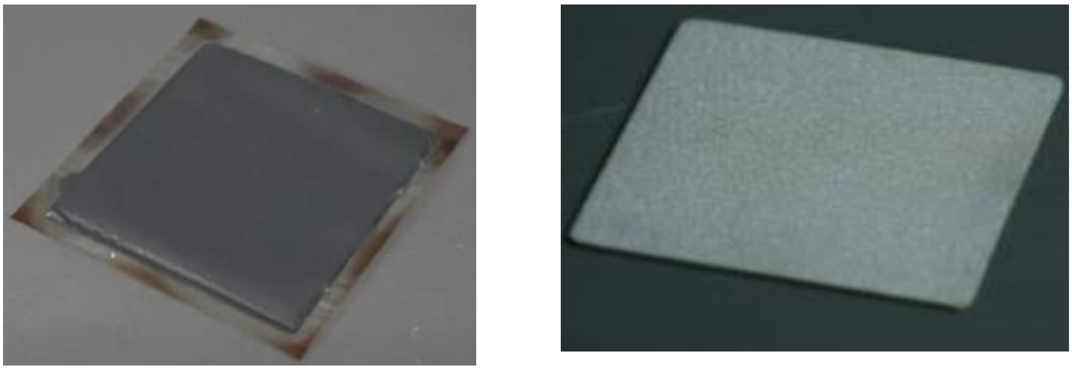
`

3.3 Electrolytic Fuel Cell

In this study, an electrolytic fuel cell was used as the main component in the experiment. This electrolytic fuel cell came with a membrane electrode assembly (MEA) which was examined and tested by dismantling the fuel cell using the proper tools at first. Then, the gas diffusion layer material in the membrane electrode assembly (MEA) was removed and altered with the printed open cell metal foam. This electrolytic cell also came with the anode and the cathode side where the connection of power source was connected in order to run the cell. Figure 3.2 shows the electrolytic fuel cell that was used in this study and Figure 3.3 shows the proton exchange membrane (PEM) and the gas diffusion layer (GDL) in the fuel cell.

Figure 3.2 Electrolytic Fuel Cell

`



(a) (b)

Figure 3.3 (a) Proton Exchange Membrane (b) Gas Diffusion Layer

3.4 Design of Fuel Cell

After carrying out the research on the electrolytic fuel cell, a suitable design was drawn using the SolidWorks 2023 software as shown in Figure 3.4. This design came from the recommendations from various sources such as research studies and journals that were conducted. Table 3.1 shows the components and parts with their estimated specifications based on the existing electrolytic PEM fuel cell.

`

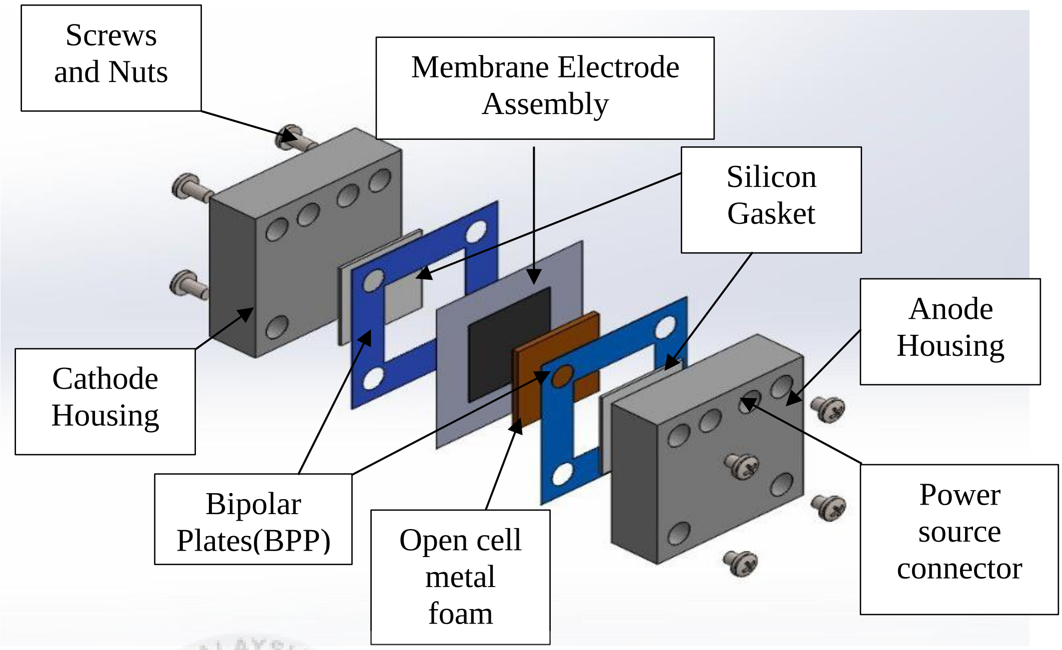


Figure 3.4 Design of the PEM Electrolytic Fuel Cell

Table 3. 1 The Specifications of the component and parts of the Fuel Cell.

Component/Parts	Material	Dimensions (mm)
Proton Exchange Membrane	Polymer	30 x 30 x 1
Open Cell Metal Foam	Stainless Steel Metal Foam	30 x 30 x 6
Bipolar Plates (BPP)	Titanium	30 x 30 x 1
Gaskets	Silicon	30 x 30 x 1
Cathode Housing	Aluminium	54 x 54x 17
Anode Housing	Aluminium	54 x 54x 17

`

3.5 Fabrication of Open Cell Metal Foam

3.5.1 Design of Metal Foam

The open cell metal foam was designed using SolidWorks 2023 software. It was produced using the Selective Laser Melting Ermaksan 3D printing (SLM machine). The important aspects such as the dimensions, porosity, and the material were studied before designing. The dimensions included (30 x 30 x 6) ,(30 x 30 x 8),(30 x 30 x 10) mm and the size of the pore of the metal foam was set to 0.8mm at first to analyze the performance.The smallest thickness of metal foam was set to 6mm because any thickness below causes the metal foam to brittle and damage when removing the support.Thus,metal foam with 6 mm thickness was choosen as the minimum thickness. The material that was chosen was stainless steel because it had good mechanical strength. The gas diffusion layer (GDL) in a PEM fuel cell needed to withstand compression forces during assembly and maintain structural integrity during operation. Therefore, stainless steel was suitable to be used as the material of the open cell metal foam. Besides that, it also had good thermal and electric conductivity which allowed mass transport of electrons while preventing the build-up of excessive heat during operation. Stainless steel exhibited excellent corrosion resistance, which was crucial in the harsh operating conditions of a PEM fuel cell. The gas diffusion layer (GDL) was exposed to the electrolyte, which typically contained an acidic environment, and stainless steel's corrosion resistance ensured the gas diffusion layer (GDL)'s durability over an extended period. The Figure 3.5 showed the open cell metal foam that had been designed using the open cell metal foam using the SolidWorks 2023 software.

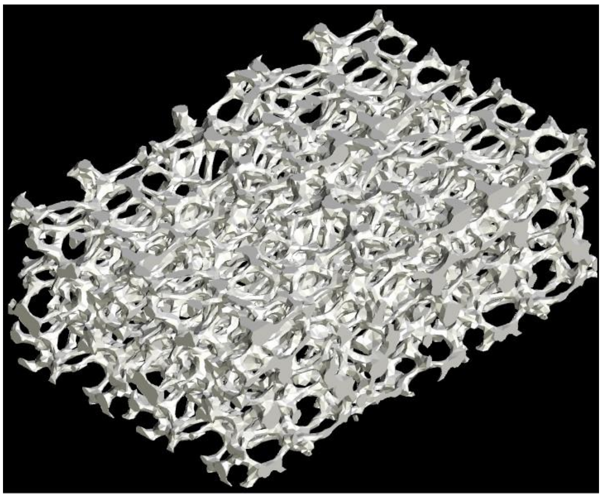


Figure 3.5 Design of the Open Cell Metal Foam using SolidWorks 2023 software

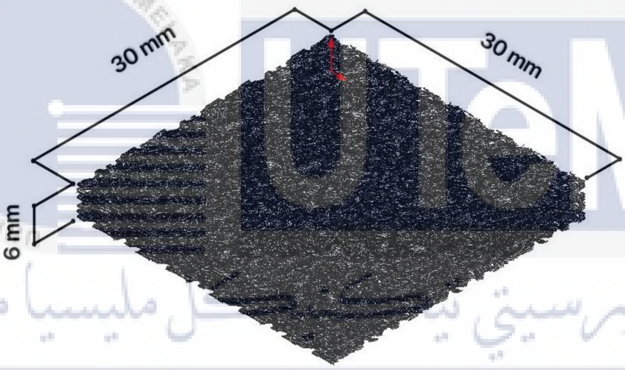


Figure 3.6 Dimension 30 x 30 x 6 (mm) of the open cell metal foam using SolidWorks 2023 software.

`

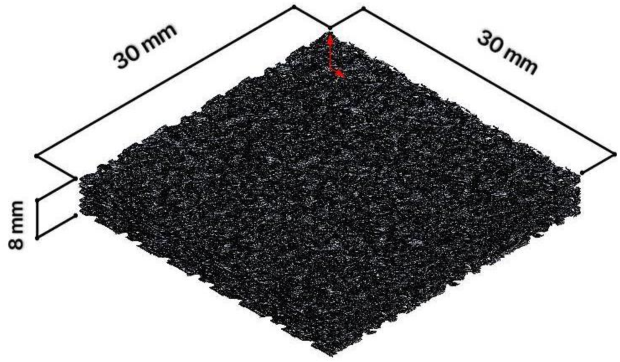


Figure 3.7 Dimension 30 x 30 x 8 (mm) of the open cell metal foam using SolidWorks 2023 software.

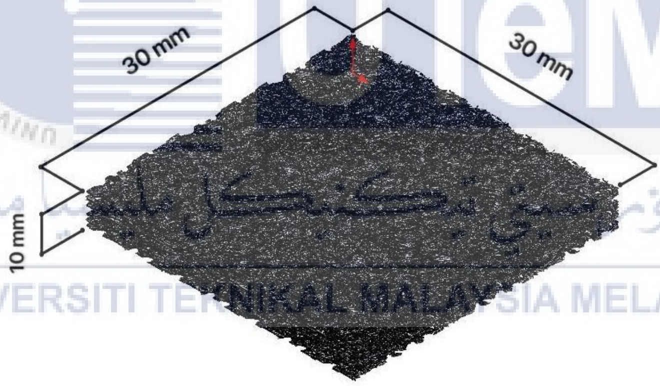


Figure 3.8 The dimension 30 x 30 x 10 (mm) of the open cell metal foam using SolidWorks 2023 software.

After designing process is complete, the STL file is imported to the Materialise Magics Print 25.02 software as shown in Figure 3.9 in order to undergo the support process of the metal foam. This process is being done in order to prevent hanging of material when the specimen is printed out. In this process, all three dimensions of the X, Y and Z plane is checked to make sure it is within 100 mm when it is printing. It helps to maintain stability, accuracy, and material optimization while allowing for the printing of complex and detailed structures. The printing angle of orientation was set to 10 degree (tilt) in order to reduce the chances of warping and damage to the metal foam.

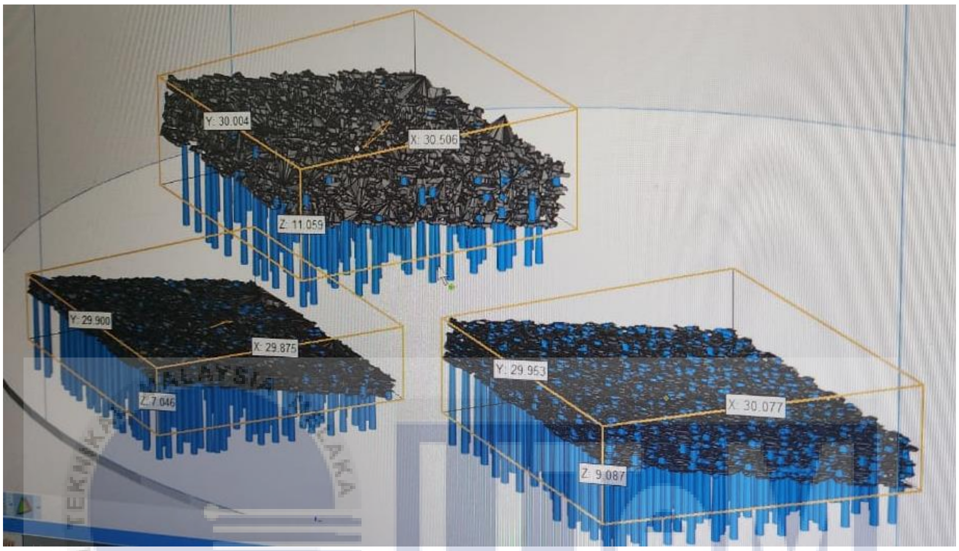


Figure 3.9 Support process using Materialise Magics Print 25.02 Software

3.6 Selective Laser Melting Printing (SLM)

The Selective Laser Melting Printer (SLM printer) used to conduct this project was the “Ermakson Enavision 120”, as shown in Figure 3.10, that was situated in the technology campus of UTEM in the FTKMP section. This machine also had to be calibrated to default parameters at first to analyse the material behaviour of the open cell metal foam when it was printed.

`

Figure 3.10 ENAVISION 120 3D-printer at FTKMP faculty, Campus Technology, Utem, 2023.

This printer is still new as the production year is only in year 2022 and the innovative features of the machine assure consistent and dependable outcomes.Table 3.2 is the specifications of the Ermakson Enavision 120-3D printer. Since the metal foam specimen is very detailing, this machine is suitable to be used because of its precise layer-by-layer deposition method allows the fabrication of complicated shapes and detailed features while wasting as little material as possible. Users can also have total control over the process by being able to optimize machine settings depending on part shape and unique production demands.

`

Table 3.2 Specifications of the ERMAKSON ENVASION 120-3D printer.

Machine Name	Additive Manufacturing Machine	
TYPE	ENAVISON 120	
PRODUCTION YEAR	2022	
SERIAL NUMBER	0030882-ERH	
VOLTAGE	220/240	V-3Ph/N/PE
FREQUENCY	50/60	Hz
NORMINAL POWER	4.5	Kw
NET FUSE	20	A
TOTAL WEIGHT	1000	kg

The parameters values in Table 3.3 is the standard calibration parameters of the Ermakson Enavision 120-3D printer . At first,these parameters were used as the guideline while printing the metal foam speciemen.Then the parameters are increased and tested individually on how each parameter differences makes an impact on the open cell metal foam produced.The laser parameters variances is also increased according to the default parameters of the SLM machine. These values are acquired by increasing the minimum default parameters to a certain extent to investigate the effects brought upon these variances.

Table 3.3 Standard calibration parameters of the SLM printer

Laser parameters	Parameter values
Laser power	300 W
Hatch distance	0.12 mm
Scan speed	3000 mm/s
Layer thickness	0.05 mm

`

Table 3.4 and Table 3.5 below shows the printer setting that was set for the scanning and support process during printing. The laser power and speed is often utilised during the scanning process to selectively melt a tiny layer of powder to generate a cross-section of the printed product. Lowering the laser intensity during scanning allows for greater control of the amount of heat delivered to the material, minimising excessive melting and allowing for better control of particle fusion. Besides that, scanning with lower laser power can produce finer details and greater resolution in the printed product. This is critical for recreating complicated features such as metal foams precisely, especially in places where accuracy is required.

Table 3.4 Printer Setting that was set for scanning during the printing process

Laser parameters	Parameter values
Laser power	130 W
Hatch distance	0.1 mm
Scan speed	900 mm/s
Layer thickness	0.04 mm

Table 3.5 Printer Setting that was for support set during the printing process.

Laser parameters	Parameter values
Laser power	240 W
Hatch distance	0.1 mm
Scan speed	1000 mm/s
Layer thickness	0.04 mm

Figure 3.11 shows the sperical Ermak S316L-A11 powder that is used for printing the metal foam specimen.This S316 stainless powder is made from stainless steel grade 316L

which a low-carbon form of stainless steel with additional molybdenum for corrosion resistance. Spherical powders are used for additive manufacturing because they have a more uniform particle shape, resulting in better flowability and packing density during the printing process. The spherical form also helps the printed items achieve better resolution and finer detail. S316 L-A11 powder is particularly intended for use with laser-based powder bed fusion (PBF-LB) 3D printing technology. It is designed to have great processability, the ability to manufacture complicated geometries with high precision, and robust mechanical qualities in the final printed items. Overall, the Spherical Ermak S316 L-A11 powder is a high-quality material that is suitable for printing stainless steel material types of specimen as it has a very high and precise form of detailing a specimen.

Figure 3.11 Spherical Ermak S316 L-A11 Powder

Figure 3.12 shows the nitrogen gas (N_2) that was used to control the atmosphere during the printing process. nitrogen gas is utilized to produce a regulated atmosphere. It aids in the prevention of oxidation of sensitive materials and lowers the danger of undesirable reactions during printing. It lowers the level of humidity and oxygen inside the production chamber. During the printing process, the humidity needs to below 10.00 Rh and the oxygen must be below 0.2%. This is to ensure material stability and to ensure safety issues such as discoloration and combustion from taking place during printing. Besides that, nitrogen gas is also important in order to control the temperature during the printing process in order to prevent the specimen from experiencing warping and material shrinkage from happening.

Figure 3.12 HIQ Nitrogen 5.0 Zero Gas Tank in Utem at FTKMP faculty, Campus Technology, Utem, 2023

3.7 Experiment Preparation

In this study, the fuel cell was tested on the output power voltage and the operating temperature in order to measure the efficiency when metal foam was being used as the flow channels in the membrane electrode assembly (MEA). Thus a suitable experiment set up was needed in order to measure the performance of it. The experiment set up consisted of several equipments and apparatusas listed in Table 3.6.

Table 3.6 Apparatus and Equipments

APPARATUS/EQUIPMENTS	USAGE
Electrolytic Pem Fuell Cell 	Main component of the experiment. To test the performance and capabilities by connecting the cathode and anode housing to the power source.
Electrolysis Kit 	Separates the hydrogen and oxygen at the cathode and anode. To measure the level of conductivity of the hydrogen level at the end .
Ammeter 	To measure the current flow produced by the fuel cell during operations in order to test its performance.

APPARATUS/EQUIPMENTS	USAGE
Voltmeter 	To measure the output voltage of the fuel cell during operations in order to test its performance.
Tubes 	Used to connect the fuel cell and the electrolytic fuel cell kit for the flow of hydrogen and oxygen during the operations.
Power Source 	To supply power source to the electrolysis fuel cell kit for movement of hydrogen and oxygen molecules in the cathode and anode side in order to test the fuel cell operations.Ouput voltage is 12V and output current is 2A.

APPARATUS/EQUIPMENTS	USAGE
Wires/Cables 	To allow electric current to flow in the circuit and transmitting signals and power between various components.
Airflow Control Valves 	Act as a medium to control the flow of hydrogen (H_2) gas and oxygen (O_2) gas during operations.
WATER (H20) 	Plays a crucial role as an electrolyte and source of ions for the electrochemical reactions that occur at the electrodes.To provide Hydrogen gas (H_2) and oxygen gas (O_2) during the operations.
Hydrochloride Solution (NaOH) 	Only use when needed and two tablespoon is enough to mix with water in order to increase the conductivity of electricity during the testing operations.

`

3.8 Experiment Set-Up

This experiment set up was very important to ensure the fuel cell could be tested and was working when a load was connected.The electrolysis kit is tested by using water (H2O) at first.When power is supplied to the kit,the hydrogen, (H_2) molecules will discharge at the anode and the oxygen, (O_2) molecules will discharged at the cathode.The gas from anode (hydrogen) and cathode(oxygen) will flow through the tubes to the cathode and anode side of the fuel cell.The fuel cell abosrbs the gases in the form of energy and produces an output power to run the load.

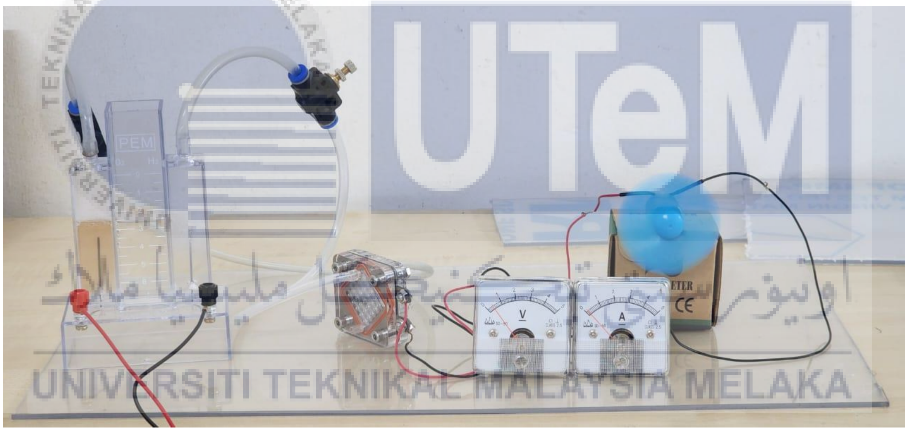


Figure 3.13 Basic Experiment set-up of the Electrolytic Fuel Cell kit.

3.9 Collection of Data

In this study, main factor that is analysed in this study is the fuel cell's operating conditions such as the voltage, current and the power output. These data are collected by analysing the output behaviour of the fuel cell by comparing the original output power of fuel cell with different specifications of metal foams that is designed and printed in order to replace the MEA membrane in the fuel cell.

`

Since electrical power is the product of voltage and current, thus the formula given is as follows:

$$\text{Power Output} = \text{Voltage(V)}.\text{Current(I)}$$

Output power of the fuel cell compared to an existing fuel cell kit. This will be done by comparing the output power voltage of the modified version of fuel cell with metal foam with the standard operating fuel cell. Besides that, this study also focuses on designing a suitable open cell metal foam to be used as the flow distributor in the membrane electrode assembly (MEA) plane based on the specifications set. These specifications are actually figured out and analysed based on previous journals in order to improve the fuel cells durability.

`

CHAPTER 4

RESULTS & DISCUSSION

This chapter presents the findings and analysis of the research conducted to explore the impact of using the open cell metal foam as the gas diffusion layer in the membrane of the fuel cell with various specifications in terms of the dimensions and the size.The 3D printed open cell metal foam will act as the flow channels and distributor when the fuel cell is operating.This study also mainly focuses on the output behaviour of the fuel cell by monitoring and analyzing the operating conditions involving voltage (V),current(I) and power (P) towards the efficiency of the fuel cell.This was done by comparing the the modified version of fuel cell with metal foam with the original version of fuel cell that consist of gas diffusion layer in the membrane electrode assembly.

4.1 Results on the 3D printed open cell metal foam.

The open cell metal foam specimen was printed by using the S316 stainless steel powder under the guideline parameter settings as mentioned in (table 3.4 and table 3.5). Figure 4.3 below shows the stainless steel printed open cell metal foam.The metal foam consist of three various dimensions in terms of the thickness.The dimension for length and width was printed based on the dimension of the membrane electrode assembly in the fuel cell (30 x 30) mm.For the thickness,adjustments was made in order to enhance the diffusion of gases that flows through the membrane and the metal foam.The three printed open cell metal foam consist of three different type of thickness all ranging up to 10mm.Thus,the dimensions for the open cell metal foams are (30 x 30 x 6) mm,(30 x 30 x 8) mm and (30 x 30 x10) mm respectively.

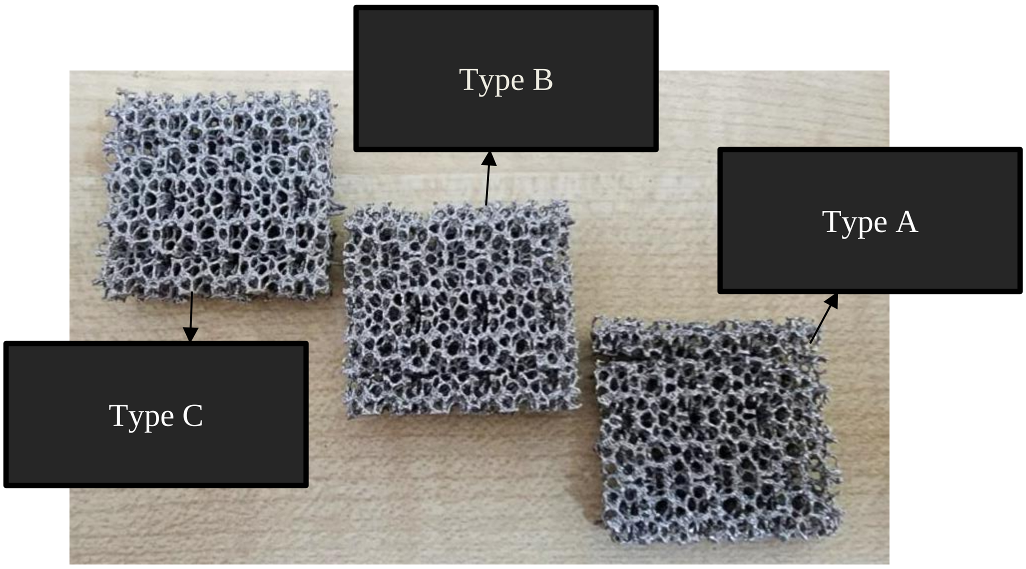


Figure 4.1 3D printed open cell metal foam

(A) 30 x 30 x 6 (mm) (B) 30 x 30 x 8 (mm) (C) 30 x 30 x 10 (mm)

4.2 Results on the PPI and Porosity

Open-cell metal foam is a one-of-a-kind material having a three-dimensional linked network of metal struts or ligaments, resulting in a sponge-like or foam-like structure. The density of the foam structure is often described in terms of "pores per inch" (PPI). PPI is the number of pores or voids per linear inch of material. These pores are the open gaps between the connecting metal struts in the context of open-cell metal foam. The PPI value is an important quantity because it affects the porosity of the foam, which effects material qualities including permeability, thermal conductivity, and mechanical strength. The production procedure for stainless steel open-cell metal foam involves the creation of a metallic matrix with a specified number of linked spaces. These spaces contribute to the foam's open-cell structure. The PPI value is an important component influencing the performance of metal foam. Since the length of the metal foam that is produced is fixed to 30mm which is equals to 1.18 inch. Thus, the formula given is as below:

`

$$\text{Pores per inch (PPI)} = \frac{\text{Number of Pores}}{\text{Measured Length (in)}}$$

The results for the pores per inch was calculated based on the formula and the results is as shown in table 4.1.Since all metal foams have the same dimension of length based on the fuel cell membrane,therefore the length value is fixed as 30 (mm).Type A metal foam consist of the smallest value of thickness which is 6mm.The number of pores was 7 and the PPI value obtain is 6PPI.Type B metal foam has a thickness of 8 (mm) and the number of pores calculated was 10PPI.Hence by reffering to the formula given the pores per inch value obtain is at 8PPI.The third metal foam is the type C where the thickness is the at 10 (mm) which is the thickest compared to the other two metal foams that is printed.The number pores calculated is 12 and the PPI value obtain is at 10PPI which is the highest compared to the other two printed metal foams.Based on the research done by (B Buonomo, A di Pasqua, D Ercole, & O Manca, 2019) on the effect of PPI values of metal foams showed that metal foams with higher pores per inch value should provide a better efficiency during operations.Table 4.1 shows the tabulated data on the reults of pores per inch value (PPI) on metal foams.

Table 4.1 Results on the Pores per Inch (PPI) value of the metal foams.

Type	Length (mm)	Thickness (mm)	Number of Pores	PPI value (inches)
A	30	6	7	6
B	30	8	10	8
C	30	10	12	10

`

Porosity of metal foam used in fuel cells can have a substantial influence on the fuel cell's performance and operation. Porosity allows gases like hydrogen and oxygen to diffuse through the metal foam structure more easily. This is especially important in fuel cells, where effective gas diffusion to electrode surfaces is required for electrochemical reactions to occur. However, the porosity of a given material also depends on the size and volume. Since the metal foams dimensions are small in value, the porosity values are also small in range. Porosity is basically the volume percentage of empty spaces or pores inside the material as opposed to the overall volume of the foam. It is a measurement of how much of the material consists of empty spaces. Mathematically, porosity is defined as the ratio of the volume of pores to the total volume of the metal foams. The formula is as follows:

$$\text{Porosity } (\Phi) = \frac{\text{Volume of pores}(\text{cm}^3)}{\text{Total volume of metal foam } (\text{cm}^3)}$$

The volume of pores is calculated by using the submerged technique. This was done by taking the initial volume of water and the submerged volume of water when the metal foam is placed in it. The difference between the initial and the submerged volume of the water shows the volume of pores of the metal foam. Table 4.2 shows the results of the volume of pores of the metal foams that was calculated using the formula. The formula is shown as follows:

$$\text{Volume of pore (Vp)} = \text{Initial Volume(mL)} - \text{Submerged Volume(mL)}$$

Table 4.2 Volume of pore of the metal foams.

Dimension	Initial volume of solution (mL)	Submerged reading of volume (mL)	Volume of pore (cm^3)
3 x 3 x 0.6 (cm)	2	2.2	0.2
3 x 3 x 0.8 (cm)	2	2.3	0.3
3 x 3 x 1 (cm)	2	0.3	0.3

Metal foam with (3 x 3 x 0.6) cm has the volume of pore of 2cm^3 and the total volume is 5.4 cm^3.Thus the porosity of this specimen is calculated as follows:

$$\text{Porosity } (\Phi) = \frac{0.2\text{cm}^3}{5.4\text{ cm}^3}$$

$$= 0.037$$

$$\text{Porosity } (\Phi) = 0.037 \text{ x } 100\%$$

$$= 3.7\%$$

A porosity value of 3.7 % indicates that voids or pores make up around 3.7% of the material's total volume. This shows that this is the level of porosity that will allow the diffusion of gases in the metal foams when it is operating. Metal foam with (3 x 3 x 0.8) cm has the volume of pore of 0.3cm^3 and the total volume is 7. 2cm^3.The porosity is calculated by:

$$\text{Porosity } (\Phi) = \frac{0.3\text{cm}^3}{7.2\text{cm}^3}$$

$$= 0.0416$$

$$\text{Porosity } (\Phi) = 0.042 \text{ x } 100\%$$

$$= 4.16\%$$

`

This shows that that the thickness does influence the porosity value. The 4.6% of porosity shows that the metal foam is made of 4.6% of pores of the total volume of the specimen. The last specimen of metal foam as the total volume of $9cm^3$ and $0.3cm^3$ for the total volume of pore. Thus the porosity is as follows:

$$\text{Porosity } (\Phi) = \frac{0.3\text{cm}^3}{9\text{cm}^3}$$

$$= 0.0333$$

$$\text{Porosity } (\Phi) = 0.033 \text{ x } 100\%$$

$$= \ 3.33\%$$

Based on all the calculations of porosity that has been made, metal foam with (3 x 3 x 0.8) cm has the highest percentage of porosity value which is at 4.16% compared to the other two metal foams. When the porosity value is high, it indicates that a greater proportion of the metal foam is composed of empty spaces. Metal foam with (3 x 3 x 1) cm has the same volume of pore has the metal foam with (3 x 3 x 0.8) cm but due to its thickness and dimensions the porosity value is slightly low. Table 4.3 shows the results on the porosity of the metal foams. The reasons why the percentage of porosity of the metal foams are small in values is because the dimension's metal foam that is printed. The metal foams are printed and designed based on the membrane electrode assembly dimensions of the PEM Fuel Cell. Hence, it need to be fitted correctly in order to be tested to determine the effectiveness of using these printed metal foams as the flow channels.

Table 4. 3 Results on the porosity of metal foams.

Metal Foam	Volume of pore (cm^3)	Total Volume (cm^3)	Porosity (%)
3 x 3 x 0.6 (cm)	0.2	5.4	3.7
3 x 3 x 0.8 (cm)	0.3	7.2	4.16
3 x 3 x 1 (cm)	0.3	9	3.33

4.3 Testing results of the fuel cell

Fuel cell is an electrochemical device that turns the chemical energy of a fuel into electricity via an oxidising agent reaction. The basic idea requires the employment of an electrolyte to allow ions to travel between the cell's anode and cathode. The most popular forms of fuel cells employ hydrogen as the fuel, and the electrochemical interaction with oxygen (from the air) results in the production of electricity, water, and heat as by products. The output efficiency of fuel cell is measured by observing the voltage, current and the power output of the fuel cell while it is operating. Since, the pace at which work or energy is exchanged in an electrical circuit is referred to power, the power output is calculated by using Ohm’s Law, (P=VI). Besides that, the amount of water solution needed to spin the load was also measured during each fuel cell operations in order to obtain the most efficient fuel cell.

4.3.1 Testing using fuel cell without metal foam

First the original fuel cell without any modification was tested in order to observe its operating conditions. The experiment set up for this testing is as shown in Figure 4.2. In this testing the fuel cell needed at least 5ml of the water solution in order to provide some voltage and current output in order to run the load. The voltage and current was measured by using the voltmeter and ammeter. The fuel cell has an output voltage of 0.3 V and current stays at 0.2 A while operating. Thus, based on the formula of the electrical power, the output power can be calculated by:

$$\text{Power Output, P} = \text{Voltage(V)}.\text{Current(I)}$$

$$\text{Power Output, P} = 0.4\ \text{V}\ .\ \ 0.2\ \text{A}$$

$$= 0.08\ \text{W}$$

$$= 80\ \text{mW}$$

Since this is an electrolytic proton exchange membrane (PEM) fuel cell used for experiments, the results obtain in this testing is acceptable because the actual operating conditions for the fuel cell ranges from 0.3 V to 0.5 V.

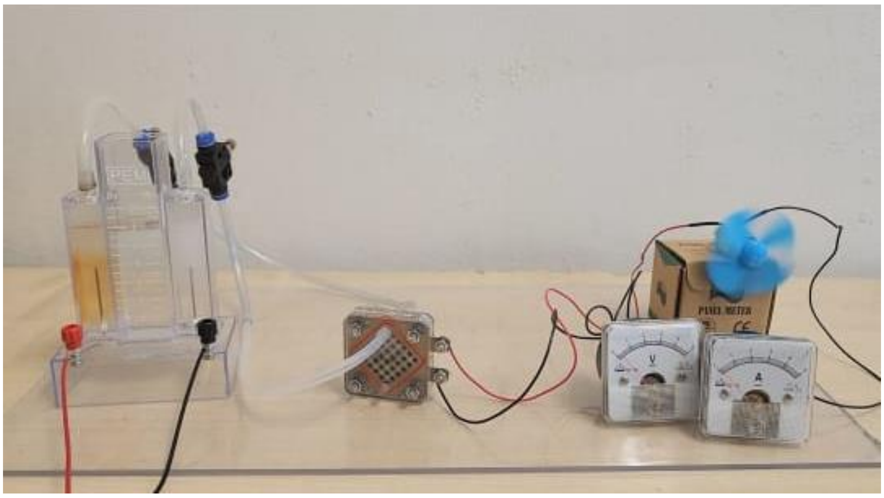


Figure 4. 2 Testing of the original Fuel cell

`

4.3.2 Testing of fuel cell using metal foam with 6 (mm) thickness.

The next testing is done by using the metal foam with 6 (mm) thickness acting as the flow distributor in the fuel cell. The experiment set up for this testing is shown in Figure 4.3. The 3D printed metal foam was inserted in between the MEA membrane and the plate housing of the fuel cell as shown in Figure 4.4. In this testing the fuel cell only needed 3ml of the water solution in order to produce voltage and current output in order to run the load. The voltage and current was measured by using the voltmeter and ammeter. The fuel cell has an output voltage of 0.7 V and current stays at 0.5 A while operating. Thus, based on the formula of the electrical power, the output power was calculated by using the formula:

$$\text{Power Output, P} = \text{Voltage(V)}.\text{Current(I)}$$

$$\text{Power Output, P} = 0.7\ \text{V}\ .\ 0.5\ \text{A}$$

$$= 0.35\ \text{W}$$

$$= 350\ \text{mW}$$

In this testing, the values of the output voltage, current and power efficiency are higher compared to the original fuel cell testing that was made. The voltage and current measured is 0.7 V and 0.5 A. The power output obtain is 0.35W which is equivalent to 350 milliwatts.

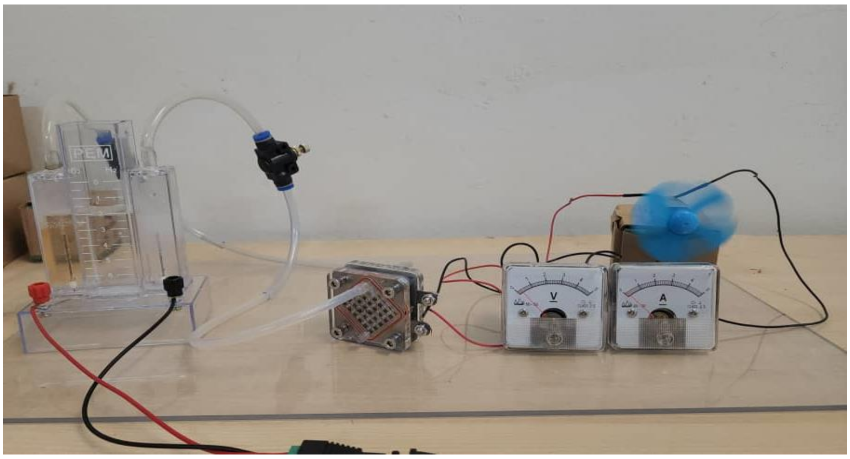


Figure 4.3 Experiment testing of 30 x 30 x 6 (mm) of the 3D printed open cell metal foam in testing.

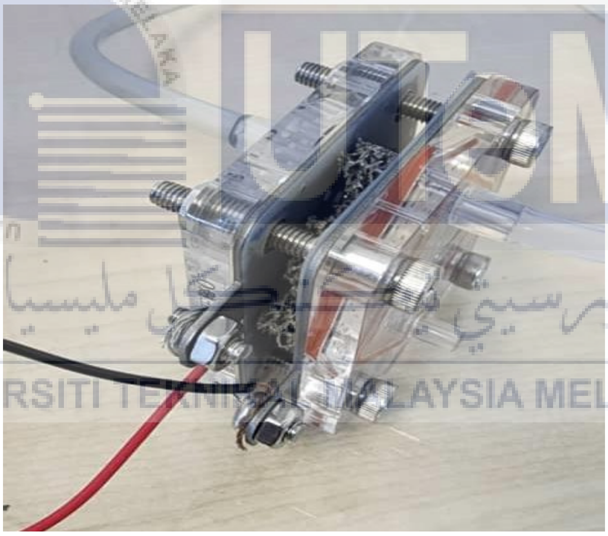


Figure 4.4 Testing the fuel cell with the 30 x 30 x 6 (mm) metal foam as the distributor and flow channels.

4.3.3 Testing of fuel cell using metal foam with 8 (mm) thickness

In this testing the metal foam with dimension (30 x 30 x 8) mm was used. The amount of water solution needed to run the load ranges from 4ml to 5ml. The fuel cell has an output voltage of 0.3 V and current stays at 0.2 A while operating. Thus, based on the formula of the electrical power, the output power was calculated by using the formula:

$$\text{Power Output, P} = \text{Voltage(V)}.\,\text{Current(I)}$$

$$\text{Power Output, P} = 0.3\ \text{V} \,.\, 0.2\ \text{A}$$

$$= 0.06\ \text{W}$$

$$= 60\ \text{mW}$$

The results obtain in this testing is similar to the results obtain using the original fuel cell. The output voltage is 0.03 V and the output power is 0.06 W. Thus, we can say that the efficiency of the operating conditions in this testing produces the same output with the original fuel cell testing that was made.

4.3.4 Testing of fuel cell using metal foam with 10 mm thickness.

The final testing that was carried out is by using the (30 x 30 x 10) mm open cell metal foam. This metal foam has the largest thickness compared to the other two metal foams that was printed. During this testing, the contact between the membrane and the metal foam had some minor gaps in between due to its thickness. Because of its thickness, this fuel cell requires at least 5ml to 6 ml in order to provide some energy output to run the load. This is because the large surface area of the metal foam that is in contact with the membrane requires higher amount of diffusion of gases to flow through in order to produce the energy output. Consequently, during this testing the voltage output was 0.4 V and the current 0.3 A. The power output during this testing is calculate as follows:

`

$$\text{Power Output, P} = \text{Voltage(V)} . \text{Current(I)}$$

$$\text{Power Output, P} = 0.4\ \text{V} . 0.3\ \text{A}$$

$$= 0.12\ \text{W}$$

$$= 120\ \text{mW}$$

The results obtain in this testing is higher compared to the original fuel cell and the fuel cell with 0.8 mm metal foam thickness. But, the amount of water solution needed to produce the output energy is the highest compared to all the testing that was conducted. This can be due to the thickness of the metal foam which is 10mm and has a large surface area so more diffusion of gases of H_2 and O_2 molecules is needed to discharge at the cathode and anode side of the fuel cell.

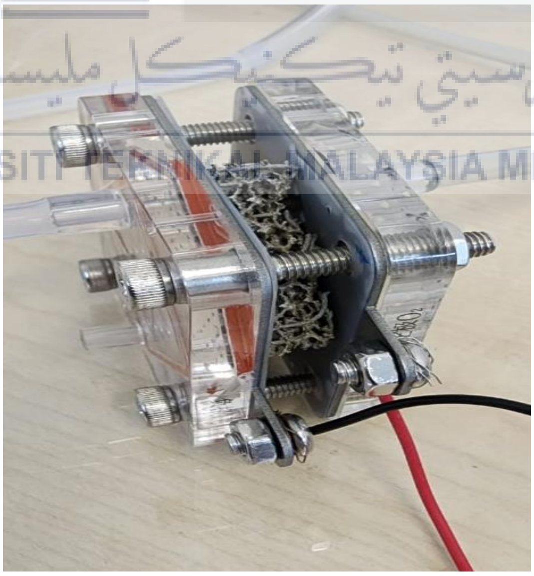


Figure 4.5 Testing the fuel cell with the 30 x 30 x10 (mm) metal foam as the distributor and flow channels.

`

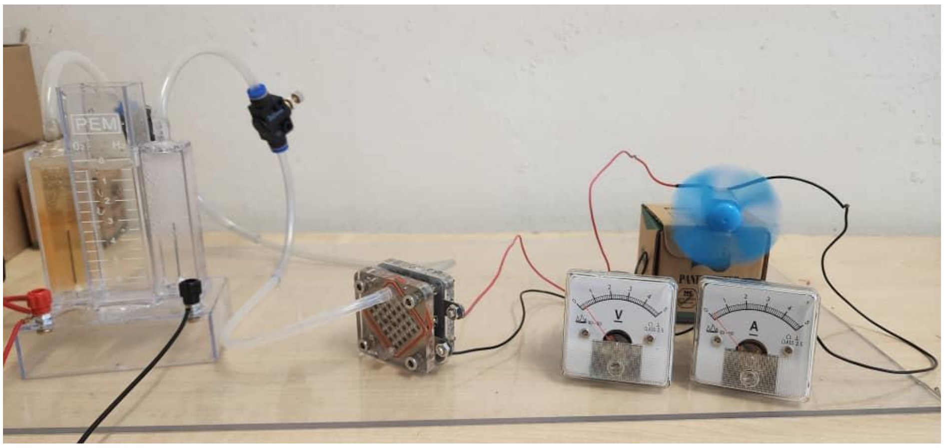


Figure 4.6 Experiment testing of the 30 x 30 x 10 (mm) 3D - printed open cell metal foam.

4.4 Summary on the Fuel Cell Testing

In summary, the results obtain from all the testing that was conducted varies according to its respective specifications. Table 4.4 shows the results on the amount of solution needed for the fuel cell to spin the load. In this results, the relationship between the amount of solution needed and the effectiveness of the fuel cell was observed. Based on the results, metal foam with (30 x 30 x 6) mm needs the lowest amount of solution which is 3mL in order to spin the load compared to the other specifications of fuel cell types. This can be due to the effectiveness of the metal foam to create a better contact with membrane in order to attract the electrons and to allow diffusion of gases in the fuel cell. The fuel cell without metal foam needs at least 4mL in order to spin the load and for the metal foam with (30 x 30 x 8) mm and (30 x 30 x 10) mm needs at least 5mL of the solution to run the load. This can be due to the thickness of the metal foam which doesn’t really provide a great contact with the membrane electrode assembly of the fuel cell during the testing.

`

Table 4.4 Amount of solution needed for the fuel cell to spin the load.

Metal Fom	3 (mL) solution	4 (mL) solution	5 (mL) solution	6 (mL) solution
	Load Spin (Yes/No)	Load Spin (Yes/No)	Load Spin (Yes/No)	Load Spin (Yes/No)
Without metal foam	No	Yes	Yes	Yes
30 x 30 x 6 (mm)	Yes	Yes	Yes	Yes
30 x 30 x 8 (mm)	No	No	Yes	Yes
30 x 30 x 10 (mm)	No	No	Yes	Yes

The table 4.5 shows the summary of results that includes the voltage, current and power that was obtain during each type of fuel cell testing. The results of the power output are small in values because this testing involves electrolysis process which occurs in the electrolysis kit. During electrolysis high amount of energy is needed to discharge the hydorgen (H_2) and oxygen (O_2) molecules at the cathode and anode side of the electrolyte. Thus most of the output energy that is produced by the power source will be loss during this reaction. Besides that, power loss also occurs when the gases are diffused in cathode and anode plate of the fuel cell before it produces an actual output energy to run the load. As a consequence, the voltage, current and power values obtain during all the testing are small in values. But, the efficiency of the fuel cell can be seen when each results offer various output during testing.

Table 4. 5 Summary of the results on the fuel cell

Metal Foam	Amount of solution needed to run the load (mL)	Voltage (V)	Current (A)	Output Power (W)
Without metal foam	4 to 5	0.4	0.2	0.08
30 x 30 x 6 (mm)	3	0.7	0.5	0.35
30 x 30 x 8 (mm)	5 to 6	0.3	0.2	0.06
30 x 30 x 10 (mm)	5 to 6	0.4	0.3	0.12

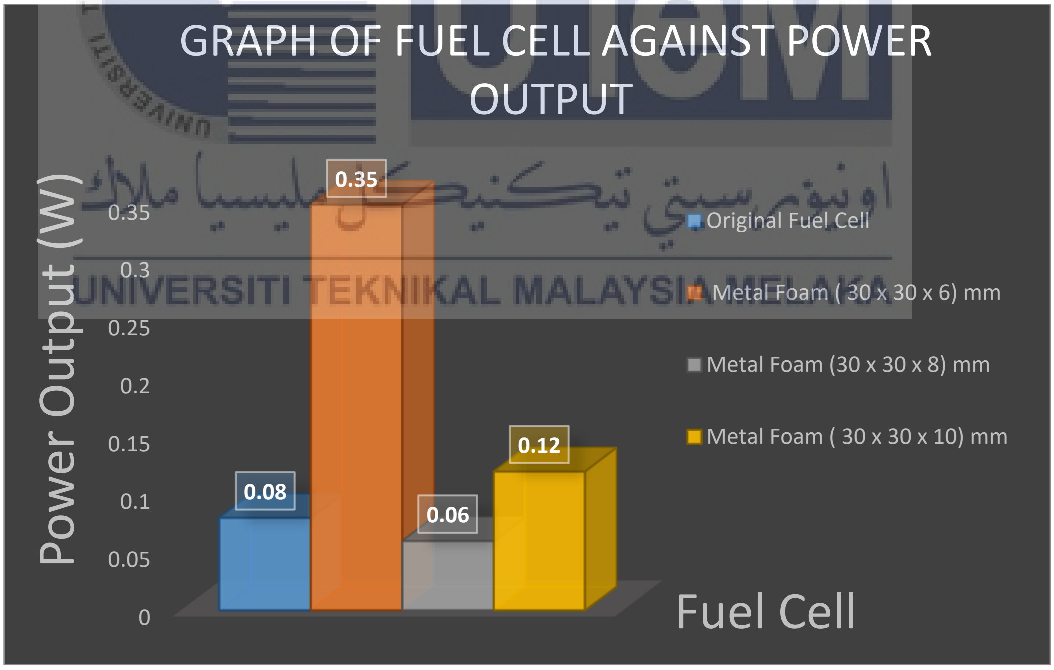


Figure 4.7. Graph results on the power output of the fuel cells.

`

Based on the summary of results, testing that was carried out using the 3D printed metal foams have shown higher efficiency in terms of providing high output power compared to the fuel cell without metal foam. The most efficient result that is obtain was when the (30 x 30 x 6) mm of the 3D printed metal foam was used as the distributor and flow channels in the fuel cell. During this testing the voltage output is 0.7 V and the current obtained is 0.5. A which is the highest and the amount of water solution needed to run the load was only 3ml.This shows that the rate transfer of energy during this testing is the fastest and most efficient. This can be due to the thickness of the metal foam which plays a vital role in the diffusion of gases in the fuel cell. The small and thin surface area of the metal foam creates a better surface contact with the membrane and forces the rate of diffusion of gases to be fast which produces the highest power output voltage compared to the other fuel cell testing that was conducted. The testing of using (30 x 30 x 10) mm metal foam showed that the surface area of the metal foam plays an important role on the rate of diffusion of gases. This can be seen when 5 mL to 6 mL of water solution is needed to run the load when this testing was conducted. The thickness of this metal foam requires more solution in order to diffuse to the anode and cathode plate of the fuel cell in order to provide sufficient amount of energy to run the load.

`

CHAPTER 5

CONCLUSION AND RECOMMENDATIONS

5.1 Conclusion

The research conducted has managed to successfully achieve its objectives where the 3D printed open cell metal foam was succesfully used in the fuel cell system in order to test the capability and performances of the fuel cell system. Based on the results of this study,it can be concluded that metal foams can act as the flow channels and distributor in the fuel cell during operations.The power output values obtain in this study during each testing shows that the metal foams does influence the output power and efficiency of the fuel cell during the operation.Howewer,the main factor that influenced small output values is the electrolysis process that was carried out in order to obtain the hydrogen (H_2) and oxygen (O_2) molecues.High rate of energy was used during this reaction which results in high power loss during the testing that contributes in small output values.This is because,this is the safest method that can be used to obtain the hydrogen gas (H_2) and oxygen gas (O_2) in order to test the capability of PEM fuel cell since hydrogen gas is highly explosive towards surroundings.

Based on the results,metal foam that have smaller surface areas creates a better contact with the membrane and provides higher output power.This can be seen when the metal foam with (30 x 30 x 6) mm that was used in the fuel cell produced the highest output values in terms of voltage,current and power compared to all the other testings that was made. At the same time the ppi values of the metal foam also plays a vital role in the results. The metal foam with (30 x 30 x 10) mm has the highest pores per inch value compared to the other metal foams which allows more diffusion of gases but takes time to convert and produce the energy.Thus,the amount of water solution that is needed is high and ranges from

`

5mL to 6mL in order to provide the energy output to run the load during the testing.In terms of the porosity of the metal foam,the effectiveness cant be seen much.This can be due to the small range of values in the dimension and the size of the metal foams that was printed. That being so,the specifications of metal foams in terms of material, size,ppi value and the porosity should be analysed and studied at first in order to obtain the most effcient results during testing the fuel cell.

Based on the testing that was carried out,it is safe to say that the stainless steel open cell metal foam with (30 x 30 x 6) mm offers a suitable replacement to the gas diffusion layers (GDL) in the membrane electrode assembly (MEA) of the fuel cell.The purpose of this study is to demonstrate on the behaviour of the fuel cell when metal foams are used as the flow channels.Therefore,for experimenting purpose the electrolytic PEM fuel cell was choosen as the tool to be tested and the results were shown in this paper.

5.2 Recommendations

The research reccomendations in this study is to understand the behaviour of fuel cell much more in detail by conducting more testings on the fuel cell and see if it is compatible when metal foams are being used as the flow channles in the membrane electrode assembly (MEA) of the fuel cell.Therefore there are several proposals of testings for future studies regarding the behaviour of the fuel cell. Listed below are ideas that can be employed for upcoming research:

1. Conducting thermal performance assestments by examining the thermal properties of metal foams and their impact on heat dissipation and see how the changes occur with the traditional fuel cell.This can be done by using thermal imaging and

`

temperature measurements to analyze how metal foams influence thermal management within the fuel cell and comparing those results with traditional setups.

2. Besides that, conduct gas cross over evaluation.This is to make sure the metal foams that is being used prevents the gas crossover effectively.This can be done by assesing the presence of gas crossover through the metal foam channels. Ensure that the chosen metal foam material acts as an efficient barrier by maintaining the purity of reactant gases under operating conditions.At the same time when conducting the testing make sure there is no gaps between the metal foams and the membrane of the fuel cell.If large metal foam thickness is being used make sure the housing of the fuel cell fits perfectly to prevent the gases from emitting to the surroundings.
3. Carry out modelling and simulation in order to predict and understand the behaviour of fuel cell with metal foams.This can be done by using computational models and simulations to stimulate the elctrochemical and thermal process within the fuel cell.Validate the model analysis with the experimental data and use it as the guideline.
4. Use the PEM Fuel Cell stack system if there is enough cost in order to examine and study in detail the behaviour of fuel cell.This is because these stack PEM Fuel Cells are the ones that will be used in vehicles and power generation systems.Use this Fuel Stack System as the tool and modify the flow channels and distributors in the system with the suitable 3D printed metal foams.

The recomendations stated will eventually enhance the research on developing metal foams in the fuel cell systems and will certainly boost the ongoing research and development aim which is to improve the efficiency, durability, and cost-effectiveness of PEMFC technology in different applications.

`

REFERENCES

Barbir, F., & S, Y. (2007). Status and development of PEM fuel cell technology. *INTERNATIONAL JOURNAL OF ENERGY RESEARCH*, 369-378.

Bedmar, J., Riquelme, A., Rodrigo, P., Torres, B., & Rams, J. (2021). Comparison of Different Additive Manufacturing Methods for. *Materials* , 6504.

B Buonomo, A di Pasqua, D Ercole, & O Manca. (2019). The effect of PPI on thermal parameters in compact heat exchangers with aluminum foam. *Journal of Physics: Conference Series*.

Baroutaji, A., Carton, J. G., Stokes, J., & Olabi, A. G. (2014). Design and development of proton exchange membrane fuel cell using open pore cellular foam as flow plate material. *Journal of Energy Challenges and Mechanics*, article 7.

Chen, X., Xu, J., Fang, Y., Li, W., Ding, Y., Wang, X., & Tu, Z. (2022). Temperature and humidity management of PEM fuel cell power system using multi-input and multi-output fuzzy method. *Applied Thermal Engineering*, 117865.

Chou, S. C. (2018). *Evaluation of Laser Powder Bed Fusion (LPBF) Fabricated A356.* Montreal,Quebac,Canada: Department of Mining and Materials Engineering,MCGILL University.

Chung-, J., Ying-, J., Chien, -J., Yi, -H., & Kan, -R. (2016). Application of metal foams to high temperature. *International Journal of Hydrogen Energy Volume 41*, 16196-16204.

Chung-Jen, T., Bin Tsang, T., Zhong-Sheng, L., Tien-Chun, C., Wen-Chen, C., & Shih-Kun, L. (2012). Author's personal copy A PEM fuel cell with metal foam as flow distributor. *Energy Conversion and Management*, 14-21.

Daud, W. R., Rosli, R. E., Majlan, E. H., Hamid, S. A., & Mohamed, R. (2017). PEM fuel cell system control: A review. *Renewable Energy*, 8.

Gokuldoss , P. K., Kolla, S., & Eckert , J. (2017). Additive Manufacturing Processes: Selective Laser Melting, Electron Beam Melting and Binder Jetting—Selection Guidelines. *Materials 2017*, 672.

Huu, L., Jeasu, H., Xuan, L., Sangseok, Y., Young, -M., & Duc, D. (2021). Review of the Durability of Polymer Electrolyte Membrane. *Energies* , 1-34.

Kumar , A., & Reddy, R. (2003). Modeling of polymer electrolyte membrane fuel cell with metalfoam in the flow-field of the bipolar/end plates. *Journal of Power Sources*, 54-62.

Lv, Y., Ji, Q., Liu, Y., & Zhang, J. (2020). Data-driven sensitivity analysis of contact resistance to assembly errors for proton-exchange membrane fuel cells. *Measurement and Control*, 1354-1363.

`

M, P. L., & Fuller, T. F. (2002). A Historical Perspective of Fuel Cell Technology. *An ECS Centennial Series Article*, S59-S67.

Park, J. E., Lim, J., Lim, M. S., Kim, S., Kim, O. -H., Lee , D. W., . . . Sung, Y. -E. (2019). Gas diffusion layer/flow-field unified membrane-electrode assembly. *Electrochimica Acta*, 134808.

Professor Shapley. (2011). Fuel Cells. University of Illinois.

SATHURUSINGHE, S. P., HERATH, K. B., & HERATH, S. R. (2012). *ELASTIC PROPERTIES OF OPEN CELL METALLIC FOAMS USING FINITE.* UNIVERSITY OF PERADENIYA,SRI LANKA: Researchgate.

Tatyana, R., & Olga, P. (2021). Determination of oxygen mass transport resistance in proton exchange membrane fuel cells with an open flow field architecture. *Electrochimica Acta*, 138529.

Tsai, B.-T., Tseng, C.-J., Liu, Z.-S., Wang,, C.-H., Lee, C.-I., Yang,, C.-C., & Lo, S.-K. (2012). Effects of flow field design on the performance of a PEM fuel cell with metal foam as the flow distributor. *international journal of hydrogen energy 37* , 13060-13066.

Vazifeshenas, Y., Sedighi, K., & Shakeri, M. (2019). Heat transfer in PEM cooling flow field with high porosity metal foam insert. *Applied Thermal Engineerin*, 81-89.

Wang, Y., Chen, K. S., Mishler, J., Cho, S. C., & Adroher, X. C. (2011). A review of polymer electrolyte membrane fuel cells: Technology, applications,. *Applied Energy*, 981-1007.

Wang, Z., Fan, L., Wu, S., Tongsh, C., Zhang, Y., Yang, Z., . . . Jiao, K. (2022). Experimental Optimization of Metal Foam Structural Parameters to Improve the Performance of Open-Cathode Proton Exchange Membrane Fuel Cell. *Frontiers in Thermal Engineering*.

Wu, Y., Cho, J., Neville, T., Meyer, Q., Zeische, R., Boillat, P., . . . Brett, D. (2018). Effect of serpentine flow-field design on the water management of polymer electrolyte fuel cells: An in-operando neutron radiography study. *Journal of Power Sources*, 254-263.

Zhang, F. -Y., Advani, S. G., & Prasad, A. K. (2008). Performance of a metallic gas diffusion layer. *Journal of Power Sources* , 293-298.

`

APPENDICES

APPENDIX A: PROCESS OF PSM PLANNING IN GANTT CHART

Project Gantt Chart	W1	W2	W3	W4	W5	W6	W7	W8	W9	W10	W11	W12	W13	W14	W15
INTRODUCTION															
Identify problem statement															
Identify objectives of project															
Identify scopes of project															
DEVELOPMENT															
Conduct Researchers															
Literature Review & Methodology															
DESIGN & FABRICATION															
Design adjustments															
3D-printing process															
Checking For Error															
SLM Machine Parameters															
EXPERIMENT TESTING															
Running the experiment															
RESULT AND DATA ANALYSIS															
Collecting Data and Tabulating															
THESIS SUBMISSION															
Completion of thesis and submission															