CRANFIELD UNIVERSITY

JAYVASSANTH JAYABAL

NUMERICAL MODELLING OF BIPOLAR PLATE IN PEM FUEL CELLS TO ANALYSE THE PRESSURE DROP IN VARIOUS CHANNELS AND DEVELOPMENT OF A NOVEL GEOMETRY OF THE BIPOLAR PLATE

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ABSTRACT

This work centres on comprehending and elevating the performance of Proton Exchange Membrane (PEM) hydrogen fuel cells, with a specific emphasis on minimizing pressure drop in the bipolar plate. Fuel cell efficiency hinges upon core factors, including electrochemical reaction, temperature, and pressure management. Notably, pressure drop within the fuel cell plays a pivotal role in determining overall efficiency and power output.

The study aims to tackle the pressing issue of pressure drop, primarily manifested in the bipolar plate, profoundly affecting the fuel cell's output power. Researchers have pursued ground-breaking designs to curtail pressure drop and augment power output. However, certain advanced designs pose challenges in fabrication, leading to a research gap impeding the development of efficient models. To bridge this gap, the study proposes a novel and straightforward bipolar plate design, demanding minimal external power and eliminating the need for intricate geometries.

Furthermore, apart from pressure drop, fuel cell inefficiencies are compounded by obstacles like inadequate meshing and porosity integrity of the end plates. Consequently, costly platinum and gold-plated end plates are often deployed to achieve superior output performance. The research reveals that velocity variations influence pressure within existing models, furnishing valuable insights for attaining improved efficiencies in fuel cells.

The work presents a comprehensive analysis of PEM fuel cells, with particular attention to the bipolar plate's design and its ramifications on pressure drop. The proposed novel geometry aims to enhance fuel cell performance while addressing challenges linked to complex designs. The research findings offer valuable recommendations for optimizing fuel cell efficiencies, thereby contributing to the advancement of clean energy technologies.

Keywords: Analysis, Bipolar plate, Electrochemical reaction, Geometry, PEM fuel cells, Pressure drop.

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H_2- Hydrogen

ICE – Internal Combustion Engines

MIT- Massachusetts Institute of Technology

O_2- Oxygen

PEMFC – Proton Exchange Membrane Fuel Cells

RR- Redox Reaction

SOFC- Solid Oxide Fuel Cells

1 CHAPTER: INTRODUCTION

Fuel-Cell is an electrochemical cell that turns the chemical energy of hydrogen or any other fuel into electrical energy using the redox reaction mechanism. In fuel cells, redox reactions involve the transfer of electrons between the fuel (e.g., hydrogen) and the oxidizer (e.g., oxygen) to generate electrical energy.(Fan et al., 2022) There are several types of fuel cells, but the most efficient are proton-exchange membrane fuel cells and solid-oxide fuel cells(Tomida et al., 2021). It is primarily being developed to replace conventional mobility systems such as IC engines. These can also be used to propel aircraft and automobiles. These systems are primarily designed to offer sustainable energy that is greener and less harmful to the environment. Climate change is the present major threat to our earth, and it has the potential to destroy our ecology and render our place inhabitable. Pollution from conventional automobiles is one of the many problems impacting our earth.

PEM fuel cells are currently found in a variety of portable devices, including mobile phones and laptop computers. Even if the energy conversion efficiency of PEM fuel cells is higher than that of power plants or internal combustion engines, its optimization is reliant on several sophisticated physical and chemical processes that occur concurrently. These processes have been demonstrated to be highly dependent on the dynamics of the fuel and oxygen fluids within the fuel cell (Solomon et al., 2023)

According to Singla et al. (2021) in today's world, it is vital to reduce our dependency on fossil fuels. Global population and quality of life development have led to significant increases in energy consumption, and until recently, fossil-based fuels have been the primary contributors to satisfying global energy needs.

Xiong et al. (2021) describe that governments have proposed PEMFC R&D and infrastructure development programmes. The United States wants to gradually phase out traditional fossil fuels by depending on the collaborative development of fuel cells, hybrid power, and biofuels, and PEMFC is included in the long-term development plan. The number of PEMFC automobiles and hydrogen refuelling stations will reach 200,000 and 1000, respectively, according to the European Union's "Horizon 2020 Plan". By 2030, the Japanese government intends to have PEMFC vehicles on the market. China recognised PEMFC's immense growth potential as early as 20 years ago, and it is currently classed as one of the country's critical technologies. As a result, continued advancement may lead to the usage of this technology sooner. (Global Hydrogen Review 2021 – Analysis - IEA, 2021)

In the study carried out by Shin et al. (2019) the authors argue that previously centred on electric automobiles (EVs), the fundamental change in transportation caused by climate change has now emerged as a new engine of change. EVs may not be a viable environmental alternative to conventional vehicles since their emissions potential is reliant on how electricity is supplied. HFCVs have the ability to release GHGs depending on how the hydrogen is produced.

The primary objective of this research is to investigate and analyze the bipolar plate, a crucial component of fuel cells, also known as the graphite plate, responsible for facilitating fuel flow within the system. Notably, existing bipolar plate models exhibit a significant pressure drop, resulting in suboptimal electrical output from the fuel cell. To address this issue, the research aims to explore the factors contributing to the observed pressure drop and identify potential design improvements. Through experiments, numerical modeling, and simulations of different bipolar plate geometries, the study will validate and quantify the pressure drop phenomenon. The investigation seeks to provide innovative solutions to enhance the electrical output efficiency of fuel cells and bridge the gap in the current literature on bipolar plate design. Ultimately, the research strives to contribute valuable insights that optimize bipolar plate design, leading to improved performance and efficiency of clean energy technologies.

- Three separate and distinctive designs are presented and developed in this research effort to answer the critical demand for minimising pressure drop in fuel cells. Comparisons with previous studies show that these unique designs outperform the currently existing choices. To assure their efficacy, rigorous validations were performed using detailed numerical simulations and data analysis. The capacity of the channels to create significant pressure drop, increasing mass transport rates and minimising entrapped liquid water over the electrode surface, is the key to their improvement. The research adds to fuel cell technology improvements by giving viable methods to optimise PEM fuel cell performance by efficiently managing pressure drop concerns. (S. J. Hashemi et al., 2021)

Critically, acceptable working limits for hydrogen and water flow inputs were calculated, taking into account energy utilization, cell temperature, channel pressure changes, and current density. It has been established that serpentine designs give a far more even spread of ionic current density, as well as significantly higher electricity production and fuel usage than straight channel layouts (Bhattacharya et al., 2018).

This study is done to compare the working efficiency of current available models to those developed in this research. As a result, new fuel cell models might be created in the future to deliver high electrical output and operational efficiency that can be used both in aviation and automobiles.

2 CHAPTER: LITERATURE REVIEW

2.1 Pem fuel cells and its reliability

(Yilmaz & Ispirli, 2015) The steady state thermal and electrical properties of a hydrogen fuel cell are essential to the overall performance of the device. The boundary conditions that must be satisfied for a hydrogen fuel cell to operate are temperature and pressure regulated by the surrounding environment, fuel cell electrical conductivities, and the diffusion of reactants through the membrane(F. Yang et al., 2023). Therefore, in order for a hydrogen fuel cell to work properly it must satisfy these boundary conditions before it can function. These boundary conditions must be carefully examined in order to ensure that the device operates at maximum efficiency of 60% without any overheating or energy loss occurring(Yilmaz & Ispirli, 2015).

(Cong & Xinghu, n.d.) In 1999, the hydrogen fuel cell used in an MIT(university) car experiment malfunctioned as a result of excessive heat generation within the device. This unfortunate incident resulted in the death of the driver and greatly tarnished the reputation of the hydrogen fuel cell as a reliable source of energy (Cong & Xinghu, n.d.).

In 2001, a hydrogen fuel cell vehicle operated by MIT(university) was involved in a collision that severely damaged the vehicle, and as a result the fuel cell was irreparably damaged and could no longer be operated properly. Once again, this catastrophic event caused many people to question the reliability of the hydrogen fuel cell and called into question the future of the technology (Stephenson, n.d.).

The MIT fuel cell vehicle that was involved in the accident was retired. However, a number of institutions throughout the world are currently pursuing the development of hydrogen fuel cells as a viable alternative to conventional energy sources such as gasoline and electricity. For example, researchers at the University of Notre Dame,USA recently completed a pilot project to evaluate the use of hydrogen fuel cells to power small unmanned aerial drones known as “quadcopters” (H2 TOOLS, 2017)

In 2018, MIT researchers announced the development of a new type of hydrogen fuel cell that is capable of storing large amounts of energy and supplying large amounts of power on demand. This new type of fuel cell could potentially be used as an energy storage system for renewable energy systems, such as wind and solar power (Plug Power Inc, n.d.).

(Alan Jones & Martin Neilson, 2021) In 2017, researchers at Zhejiang Ocean University in China developed a new type of hydrogen fuel cell that is able to store large quantities of energy. This new technology could potentially eliminate the need for batteries in portable electronic devices and electric vehicles. In addition, the new hydrogen fuel cell could also be used to provide power to off-grid communities that do not have access to electricity (Alan Jones & Martin Neilson, 2021).

Hydrogen fuel cell vehicles (FCVs) are a type of electric vehicle that uses a fuel cell instead of a battery to power its electric motor. The development of FCVs is a promising technology that could one day replace traditional internal combustion engines. Although hydrogen fuel cells have many benefits over traditional internal combustion engines, they also have several drawbacks that must be overcome before they can be widely used (Environmental and Energy Study Institute, n.d.).

Stellantis has developed a Hydrogen Fuel Cell Zero Emission solution which combines the advantages of hydrogen fuel cells and electric traction with the absence of both noise and vibrations caused by combustion engines. Several models of battery-powered trolleybus have been in service around the world since the 1950s but more recently, many cities in Europe, North America and Asia have seen a renewed interest in electrically powered buses (Stellantis, n.d.).

These electric buses offer several advantages over traditional diesel buses including lower operating costs, increased passenger comfort and safety and reduced emissions. However, in order to address the increasing demand for zero-emission transportation solutions, bus manufacturers are looking for alternative technologies that can provide the high-speed acceleration and low operational cost associated with conventional diesel buses. Hydrogen fuel cell buses are an attractive option for cities looking to replace their fleet of diesel-powered buses because they do not require any external source of power and are also extremely environmentally friendly (Stellantis, n.d.).

Hydrogen fuel cells have been proposed as an alternative power source for buses, trains, and automobiles. The technological challenges of implementing this technology however are significant because existing fuel cells are large, heavy, and expensive to produce. One solution to this problem is to develop a more compact and lightweight hydrogen fuel cell that can be integrated into a wide range of vehicles and mobile applications (U.S. Energy Information Administration, 2022).

A hydrogen fuel cell bus is one example of such a solution. The bus combines the high-power output of a diesel engine with the zero-emission performance of an electric vehicle. Although the technology is still in its infancy, it has many potential applications and will undoubtedly play a role in the future of transportation (Manoharan et al., 2019)

In 2009, Hyundai Motor Company conducted two field tests of a hydrogen fuel cell bus prototype. The bus was driven on a total of 1,000 kilometers, with an average range of 450 kilometers per fill-up. The top speed of the bus was 130 kilometers per hour. The tests demonstrated the feasibility of using hydrogen fuel cells to power buses. Bipolar plates are a critical component of fuel cells. They are made of a conductive material, such as graphite, and they serve to distribute the reactants (hydrogen and oxygen) and collect the products (water) within the fuel cell. The bipolar plates also help to conduct electricity through the fuel cell. The tests conducted by Hyundai Motor Company showed that the bipolar plates in the hydrogen fuel cell bus prototype were able to effectively distribute the reactants and collect the products. This was essential for the successful operation of the fuel cell and the achievement of the desired range and performance. The tests also showed that the bipolar plates were able to conduct electricity efficiently. This was important for the overall efficiency of the fuel cell. The successful field tests of the hydrogen fuel cell bus prototype by Hyundai Motor Company showed that this technology has the potential to be a viable alternative to traditional combustion engine buses. The use of bipolar plates in fuel cells is an important factor in the performance and efficiency of these vehicles.(OCTA, n.d.).

In 2011, Doosan Mobility Innovation (DMI), a 100% subsidiary of Doosan Group, began development of the next-generation hydrogen fuel cell bus called the Fuel Cell Electric Shuttle (FCES) (Sally French, 2022). The FCES is based on the design of a passenger vehicle currently used by the Korean National Railroad Corporation and incorporates fuel cell technology developed by Ballard Power Systems Inc. In addition to its zero-emission power generation, the FCES was designed to operate as a microgrid, capable of maintaining critical power in a hospital during a power outage or a natural disaster. It has a range of approximately 400 kilometres and a top speed of 160 km/h. As more companies begin developing hydrogen fuel cell buses and bringing them to market, it is likely that we will see an increase in the use of hydrogen in transportation (Guidehouse, 2022).

In 2019, Doosan deployed fuel cell technology to support the temporary hospitals in California during the COVID-19 pandemic. To support this effort, Doosan developed a compact and lightweight portable fuel cell that can sustain power for up to seven hours. This new technology provides doctors with uninterrupted access to power and ensures that hospital staff can continue to provide critical healthcare services during the crisis (Guidehouse, 2022).

2.2 Thermodynamic properties and cooling of fuel cells

(Zhang & Rahman, 2022) Thermodynamic cooling techniques are important for improving the efficiency of fuel cells. This section will describe how thermodynamic cooling techniques can be used to improve the thermal efficiency of fuel cells. In the fuel cell stack, water is circulated through the cell stack to remove waste heat. The water is usually cooled by transferring the heat to ambient air that is then recirculated back to the fuel cell stack by the cooling system. However, the efficiency (%) of the cooling system decreases as the temperature rises (X. Zhang & Rahman, 2022).

Water cooling is also used in fuel cells in portable devices, such as portable computers, where water cooling may be sufficient. Alternatively, air cooling may be used in these devices. As the temperature increases, the air in the device becomes less dense and its ability to carry heat away is reduced. Therefore, it is difficult to transfer large amounts of heat away from the electronics using air cooling. These issues can be overcome by increasing the airflow rate. However, this increases the amount of power required to drive the air fans. Therefore, increasing the airflow rate is wasteful in terms of power consumption (Rashidi et al., 2022).

Alternatively, a 7/8ths efficiency gain can be achieved by halving the flow rate of the cooling fluid without reducing the operating temperature of the device. In order to achieve this gain, the cooling fluid must be pumped through a smaller path within the cooling system. However, this results in an increased pressure drop within the system. A reduction in pump power compensates for this increase in pressure drop (Kim et al., 2023).

Fuel cells require appropriate cooling, humidification, and pressure control. Fuel cells are usually used in stacks, where the gases from the individual cells are combined, and humidified, before being delivered to the electric generators. The ventilation fans and heat exchangers in the fuel-cell stack are responsible for removing heat and moisture from the gas stream and supplying dry gas and vapor to the generators (Rashidi et al., 2022)

Fuel cells must be surrounded by an air system, fuel system, stack cooling system, and humidification system for optimal performance. The flow of air and fuel must be kept separate from the coolant and the humidification system. The proper operation of each subsystem is critical to maintain optimal operating efficiency and extend the life of the fuel-cell stack (Rashidi et al., 2022).

Fuel cells can be controlled using an automatic water filling system, which automatically adds water to the humidifier tank when the fuel cell loses water due to evaporation or leakage. The system also monitors the pressure within the fuel cell to ensure that the hydrogen concentration is not too high and that the cell temperature does not exceed a predetermined level (B. Li et al., 2022). Fuel cell stacks can also be over-saturated with water, causing excessive humidity within the stack, so the system must monitor the moisture content of the gas being produced by the fuel cell to prevent this problem from occurring. The flow of air into the fuel cell must also be carefully controlled to ensure that the fans are generating enough air flow to provide adequate cooling for the system.

(Bao & Bessler, 2015) As temperatures increase, so does the rate of water vapor generation from the wetted surfaces of the fuel-cell stack. This increase in moisture in the air increases the relative humidity in the stack and causes other problems, such as corrosion, electro-oxidation, and ice formation on the wetted surfaces. To prevent these problems from developing, the stack must be properly humidified to prevent the water vapor from reaching the critical levels that would damage the components of the stack. The relative humidity (RH) of the fuel and air streams has a substantial impact on the performance and durability of fuel cells. Water vapour produced by the electrochemical reaction in the fuel cell must be evacuated from the cell to avoid the formation of water droplets, which can cause flooding and short-circuiting. Nevertheless, if the RH is too low, the fuel cell might dry up, resulting in performance decline and, in extreme cases, cell collapse (Bao & Bessler, 2015).

Fuel cells require a source of oxygen and a supply of hydrogen gas to be used to generate electricity. The hydrogen gas must be purified to 99.995% purity and must not contain any other gases or impurities that might impair the performance of the fuel cell or prevent it from operating at peak efficiency. In order to ensure that the hydrogen is pure and free of other gases, it must go through a process known as purification. This process removes all of the impurities and other gases that may be present inside the hydrogen gas tank before it can be used to generate the electricity that is needed to power the fuel cell (Du et al., 2021).

Wasted heat in fuel cells is often recirculated back into the fuel cell stack, but if the hydrogen is not pure, the fuel cell cannot recover as much energy as it could if the hydrogen were free from contaminants. As a result, more energy is wasted than is necessary to run the fuel cell, and this reduces the efficiency of the overall system (B. Li et al., 2022). The temperature of the fuel cell stack affects the energy output of the fuel cell, which in turn affects the hydrogen consumption. If the temperature is too high or too low, the performance of the fuel cell will be affected. If the temperature of the fuel cell stack rises too high, the operating temperatures of the system may become high enough to melt or distort the metal components in the system and cause significant damage (Qi et al., 2020a).

PEM fuel cells, such as those used in hybrid vehicles, suffer from various problems, including overheating and leakage of oxygen and moisture inside the cell. To prevent this problem from occurring, the fuel cell must be designed to operate within a certain temperature range to ensure that the fuel cell operates efficiently and does not overheat. However, if the fuel cell is operating outside of this range or if the environmental conditions are outside the recommended ranges for the system, the system may not operate at peak performance (Du et al., 2021).

The new polymer fuel cell developed by Los Alamos National Laboratory operates at higher temperatures than existing PEM fuel cells, which allows it to deliver more electricity and produce more fuel than other PEM fuel cells. While this technology has numerous advantages, it also has some drawbacks. For example, the higher operating temperature can cause certain components of the fuel cell to degrade over time and require replacement (Lim et al., 2022).

Additionally, a fuel cell operates more efficiently at higher temperatures, but operating the fuel cell at higher temperatures can result in increased power losses due to heat loss from the fuel cell to the air outside the cell. Modern PEM fuel cells operate between 80 and 120 degrees Celsius (176-248 degrees Fahrenheit) and produce electricity using hydrogen and oxygen. While this system is effective for a variety of applications, it has one significant drawback, it requires a significant amount of water in order to generate steam to drive the fuel cell reaction. In order to overcome this problem, researchers have developed a system that replaces the water with a liquid salt solution that requires less water to produce the same amount of steam and electricity as a traditional PEM fuel cell (B. Li et al., 2022).

The "liquid metal" PEM fuel cell developed by researchers at the University of Utah uses liquid sodium as the fuel, which is pumped into a membrane electrode assembly (MEA) where it reacts with oxygen to produce water. The water produced by the fuel cell is then used to drive a turbine that is connected to the generator to produce electricity. The sodium fuel that is used in the fuel cell is a non-toxic element that can be recycled after it has been used. Although this system eliminates the need for water and reduces the amount of waste that is produced by a traditional PEM fuel cell, it is not suitable for use in applications that require large amounts of hydrogen, such as automobiles (Ebrahimzadeh et al., 2018).

2.3 Pressure drop in bipolar plate related with behaviour in fuel-cell flooding

In general, the efficiency of the system is critical in the field of fuel cells since power losses in a system can lose energy. As a result, it is critical to guarantee that the established model helps to the achievement of the intended goal. When the pressure drop is minimal, the key changes are greater electrical output and improved electro-chemical reaction in the active area. The active area of a fuel cell is where the electrochemical reaction occurs. As a result, this research contributes to the development of a new model that is compatible with the parameters (Lebrouhi et al., 2022).

According to Barbir et al. (2005) The rise in pressure drop, particularly on the cathode side of a PEM fuel cell, indicates flooding of water, whilst an increase in cell resistance indicates drying. By measuring both pressure drop and cell resistance, it is possible to determine flooding or drying circumstances inside a fuel cell stack. These qualities can be used to make judgments on remedial action.

2.3.1 Pressure drop

Barbir et al. (2005) claim that friction inside the cell's channels or reactant gases cause the pressure to drop. Because product water is produced and must be removed from the cathode side, the cathode pressure drop is more essential. While some pressure drop is beneficial to fuel cell operation because it facilitates the elimination of excess liquid water from the cell, excessive pressure drop increases the parasitic power required for "pumping" air through the fuel cell.

However,Barbir et al. (2005) explain that “there are various variations from uniform pipe flow in a fuel cell channel:

- The roughness of the GDL differs from that of the channel walls.
- The reactant gas is involved in the chemical process, and the flow rate fluctuates along the channel.
- The temperature along the channel may not be uniform.
- The canal is usually not straight, but there are frequent abrupt twists (90 or 180), Liquid water may be present inside the channel in the form of small droplets or as a film, thereby lowering the channel cross sectional area in both circumstances” (Barbir et al., 2005) .

LAYOUT OF FUEL CELL

The figure represents the layout of fuel cell and this in multitude constitute to become a stack

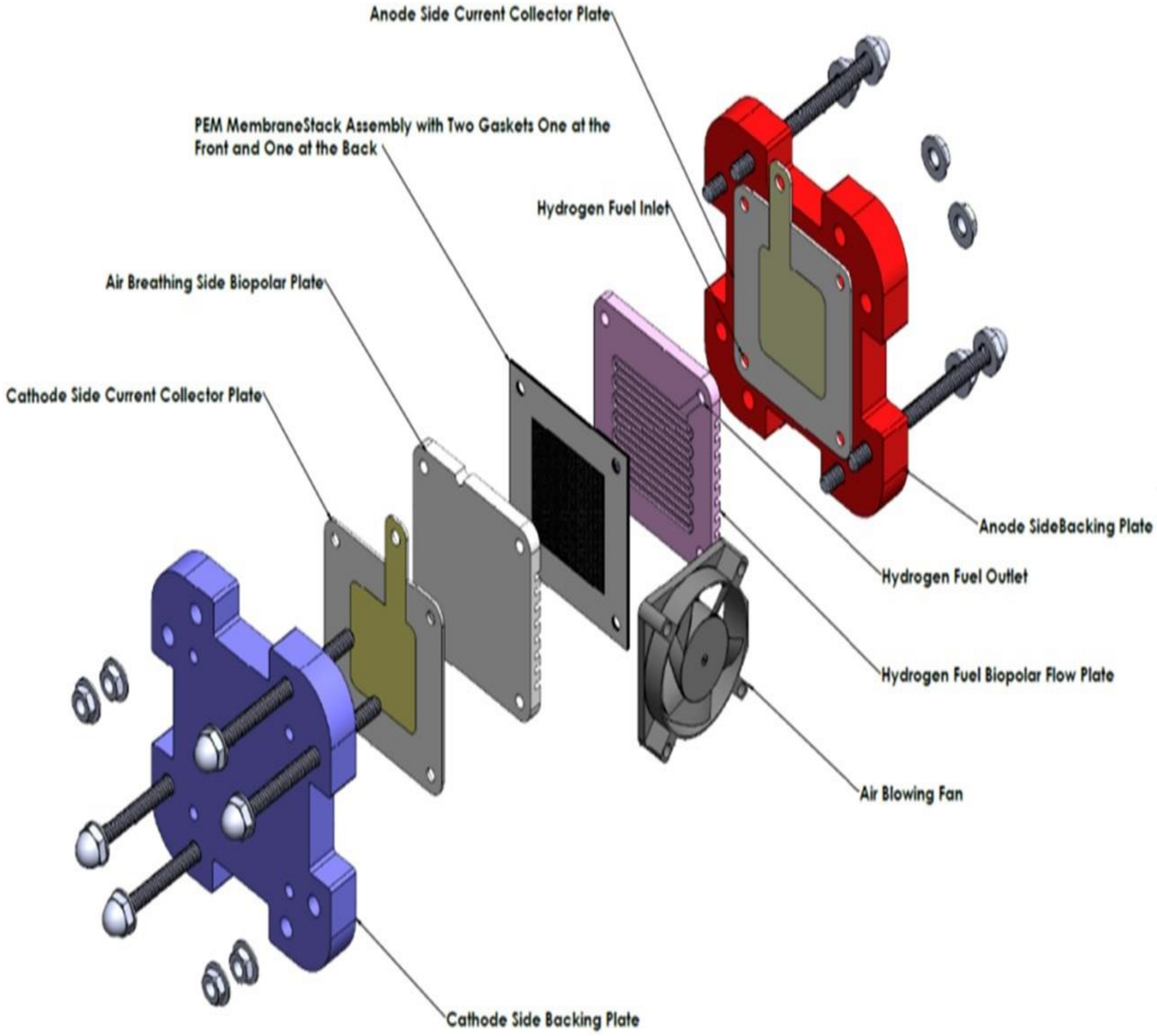


Figure 1: “Layout of Fuel-cell” (Wilberforce, et al., 2017)

Fuel-cell flooding

Water content on the cathode side of the fuel cell accumulates either near to the gas diffusion layer and the porous membrane, causing the system to dry up or become excessively sloppy, a phenomenon known as flooding in fuel cells (O'Rourke et al., 2009).

The operating pressure of the bipolar plate from the literature is 1bar (Velisala & Srinivasulu, 2018). "A certain amount of water is required for efficient fuel cell run, and the excess water must be removed from the cell otherwise flooding takes place which reduces the fuel cell performance" (Velisala & Srinivasulu, 2018)

Total pressure, static pressure, and absolute pressure control might lead to determining the rate of flow of the fluid or fuel inside the system, allowing substantial flooding to be avoided at all costs. Despite the geometry, most of the floods might be caused by poor geometry. As a result, existing bipolar plate models contain geometries in the form of serpentine groves and slotted groves with rectangular cross-sections. Another element that might cause a pressure drop and flooding is the diameter of the intake and exit, which allows the mass flow rate to be regulated variably, resulting in incompressible flow (F. Yang et al., 2023).

2.3.2 Bipolar plate geometry

The bipolar plate is a flow channel found in the fuel cell contributing the flow of either water, hydrogen, or Gas inside the system. It almost fills 71% of the fuel cell stack. To ensure the acting pressure the geometry could be one of the causes for change in pressure.

Wilberforce et al. (2019) explained that Bipolar plates that are poorly built result in unequal gas distribution across the fuel cell, localised hot patches in the electrolyte, and unstable current density. The bipolar plate geometry designs are responsible for the unequal velocity and pressure drop of the reactant through the fuel cell.

2.3.3 Flowrate and current-to-pressure drop relationships

According to (Xiong et al., 2021) the pressure loss is always proportional to flowrate, either linearly or squarely. There is frequently a correlation between hydrogen pressure drop and hydrogen mass flowrate. When the hydrogen stoichiometric ratio was held constant, the pressure loss became linear to flowrate. Qualitative and quantitative comparisons are required to compare the pressure loss between one cell and the other (Mortazavi et al., 2020).

2.4 Types of bipolar plate design and its impacts

The bipolar plate in fuel cells has been produced in a lot of different designs, each design has its own significant properties and various outcomes. The types of design are:

- Pin-type plate
- Parallel or straight plate
- Integrated plate
- Single serpentine plate
- Multi-serpentine plate

Pin-type plate

The most common type of bipolar plate in PEM fuel cells. Consists of a series of pins that are embedded in a polymer matrix. The pins provide a surface for the electrochemical reaction to take place. The polymer matrix provides electrical conductivity and helps to distribute the reactants and products evenly throughout the cell.

Parallel or straight plate

A newer type of bipolar plate that is becoming increasingly popular. Consists of a series of parallel channels that are etched into a metal sheet. The channels provide a surface for the electrochemical reaction to take place. The metal sheet provides electrical conductivity and helps to distribute the reactants and products evenly throughout the cell.

Integrated plate

A type of bipolar plate that combines the features of the pin-type plate and the parallel plate. Consists of a series of pins that are embedded in a metal sheet that has been etched with parallel channels. This type of plate offers the best of both worlds, as it provides a large surface area for the electrochemical reaction to take place, while also being electrically conductive and helping to distribute the reactants and products evenly throughout the cell.

Single serpentine plate

A type of bipolar plate that is characterized by a single serpentine channel that runs through the plate. This type of plate is relatively simple to manufacture and is often used in low-cost fuel cells. However, it can have a lower efficiency than other types of bipolar plates, as the reactants and products are not distributed as evenly throughout the cell.

Multi-serpentine plate

A type of bipolar plate that is characterized by multiple serpentine channels that run through the plate. This type of plate is more complex to manufacture than a single serpentine plate, but it can offer a higher efficiency. The multiple channels help to distribute the reactants and products more evenly throughout the cell, which can lead to a more efficient electrochemical reaction.

These are all the common types of designs used in a system(Squadrito et al., 2014).According to (Xiong et al., 2021), the total pressure drop may be accurately calculated using a frictional pressure loss formula in relation to mixture viscosity, stack temperature, operating pressure, stoichiometric ratio, and stack current. The pressure drop characteristics will be useful in anticipating liquid water flooding in fuel cell stacks before flow channels get clogged as a diagnostic tool in electric control systems. Pei et al. (2006b) claimed that using heavy factor by Sutherland equation for mixture viscosity, computed results reveal that when temperature exceeds 350 K, the hydrogen-vapor mixture viscosity will go outside the area of pure hydrogen viscosity and vapour viscosity.

Gas viscosity is computed using Sutherland's equation 2-1 (Crane, 1988)**:**

$$\mu = \mu_o \left(\frac{a}{b}\right) * \left(\frac{T}{T_o}\right)^{\frac{3}{2}}$$

with $a = 0.555T_o + C$ and $b = 0.555T + C$

where,

μ is the viscosity in centipoise at input temperature T,

μo is the reference viscosity in centipoise at reference temperature To,

T is the input temperature in degrees Rankine,

To is the reference temperature in degrees Rankine and

C is the Sutherland's constant, for hydrogen is 97

In the next section the determination of the pressure between inlet and outlet boundaries in a flow-channel is explained.

2.5 Pressure drop calculation

In order to Identify the mass flow rate and pressure losses in the fuel cell, it requires multiple mathematical equations to solve the problem, the factors that are mainly taken into account are area of the fuel cell, inlet and outlet diameter, operating temperature, and other parameters. Pressure loss is mainly occurred due to friction, so it is also taken into consideration.

In a fuel cell stack if the active area is not flooded then (O'Rourke et al., 2009)suggests using the following equation for single phase condition:

$$\Delta P = \int_0^L \frac{f\rho}{2d} V^2 \,\mathrm{d}x + \sum_1^i \xi \frac{\rho V^2}{2} + \int_0^L \rho g \cos\theta \,\mathrm{d}x + (\rho_{\mathrm{out}} V_{\mathrm{out}}^2 - \rho_{\mathrm{in}} V_{\mathrm{in}}^2)$$

Equation1: SINGLEPHASEFLOW IN A FLOW-CHANNEL 1

L is the Length of the gas flow channel,

D is the channel hydraulic diameter,

V_{out} is the Velocity at outlet boundary and

V_{in} is the Velocity at inlet boundary

ρ is the density of the fluid

ξ is the Turbulent Viscosity

Also Pei et al. (2006c) described that the hydrogen pressure loss at the anode side of fuel cells will undoubtedly increase if liquid water condenses in the flow channels. Because of the reduced pressure, the flooding problem may be recognised sooner.

However (Kim et al., 2023)confirms thatGas viscosity is computed using Sutherland's equation 2-1) which is used to calculate the dynamic viscosity using the heavy factor: The computed results for mixture viscosity show that when the temperature surpasses 350 K, the hydrogen-vapor mixture viscosity moves beyond the range of pure hydrogen viscosity and vapour viscosity.

2.6 Current density in a fuel cell

The current density in a fuel cell is a vector quantity and scalar magnitude that describes the flow of current throughout the flow field perpendicular to the other quantities.

Current density can be expressed as $J=I/A$,

Where,

I = electric current [A]

A = area [m2]

Higier & Liu (2009)Natarajan & Van Nguyen, (2004) Gerteisen et al. (2012) claimed that the concentration of anode water and the net water transport rate across the membrane are strongly intertwined. Natarajan & Van Nguyen, (2004)also claimed that segmenting the electrode as well as the current collector is advised for measuring current distribution with a segmented cell equipment. Among various channels of flow fields in the fuel cell the current density varies along the line, so this fluctuation tends to be diverging and does not help with forming an efficient system, thus Higier & Liu (2009) argued that “the current density distribution was fairly constant over the rib and land, though there were some fluctuations with increases at the rib channel interface. As the current density increased the current over the channel increased greatly and the current of the rib sections dropped almost to zero.” Therefore, the GDL- Gas Diffusion Layer reacting as a porous membrane not only deals with regulating the current field it also makes sure that the current density is perpendicular to the point in the flow field.

2.7 Impedance and its characteristics in the fuel cell

“Impedance describes the resistance that an electronic component, circuit, or system provides to alternating and/or direct electric current. Impedance is a two-dimensional vector variable made up of two distinct one-dimensional scalar phenomena: resistance and reactance” (TechTarget Contributor, 2021). To get the values for the impedance in a fuel cell, an analytical model of the proton exchange membrane cell must be examined first. The current, voltage, and oxygen concentration are also firmly bound because of the oxygen reduction process (Kulikovsky, 2021).

2.7.1 Evaluation of impedance in fuel cells

Okonkwo & Otor, 2021) According toHakenjos & Hebling (2005) “To establish the distribution of impedance across the system, numerical modelling and spatial resolved measurement are utilised in the evaluation of bipolar plates in fuel cells.” Therefore, further measures that are to be added with the existing parameters are introduction of current density into the bipolar plate. Proton exchange membrane fuel cells are complex systems with a lot of diffusion in the Gas Diffusion Layer, Ideal and free flow of gases and fuels, which makes it further complex, so it has to overcome by performing numerical simulation (Okonkwo & Otor, 2021).

2.7.2 Impedance spectroscopy in fuel cells

Rezaei Niya & Hoorfar (2013) The impedance spectroscopy or electro-chemical spectroscopy is used to diagnose the fuel cell to its core level that is by diagnosing the particle characterization and determining the metallic and electrical properties. This method also helps with assessing various electrochemical activities happening in the porous area. In contrast withRezaei Niya & Hoorfar (2013) “the nonlinear frequency response analyser (NFRA) has been used to assess membrane dehydration, fuel cell flooding, and anode CO poisoning all at the same time.” Another important factor affecting both the efficiency and durability of the fuel cell is the poisoning of the system, this will be explained in the upcoming sections.

2.8 Influence of air velocity in fuel cells

The air velocity in fuel cell stacks is a critical variable in the operation of these devices. Many factors, such as the flow rate of reactants and products through

the stack and changes in temperature, affect air velocity. Fuel cell stacks typically have a fuel supply and a coolant supply, and the flow rates of these streams must be regulated in order to ensure that the air velocities are maintained at acceptable levels. Optimal performance of a fuel cell stack requires the reactant gases to flow smoothly across the electrodes inside the stack without obstructions caused by impurities in the feed gas (Heidary et al., 2016).

This requirement is met by proper humidification of the feed gas streams. The high humidity of humidified gases results in very low viscosity, which allows the gas to be easily forced through very small openings or gaps in the stack. Efficient operation of the stack requires regulation of airflow rates and humidification rates in order to minimize turbulence, air stagnation, and air leaks(Kang et al., 2019).

Another type of humidifier is the humidifying stone, which is typically built into one end of the stack of a fuel cell power system. The humidifying stone works by injecting water droplets into the feed gas stream upstream of the oxidizer chamber of the stack. Both these types of humidifiers work well in dry climates, but they cannot be used in humid climates where water is in short supply. In humid climates, an electric desiccant dehumidifier is generally used to remove the excess moisture from the feed gas stream (Ramya et al., 2011). Desiccant dehumidifiers are more effective than household dehumidifiers, as they can remove moisture at a much higher rate and maintain a lower pressure drop across the dehumidifier than household models. Electric desiccant dehumidifiers are typically composed of two parallel rows of wicking material with space between them that allows air to pass between the rows. The wicking material absorbs the moisture from the feed gas stream and is periodically regenerated by passing a dry air stream through the dehumidifier (Xiao et al., 2022).

Fuel with an air velocity of 100 m/s, humidity of 2% RH, and a temperature of 25 °C contains about 2.7% moisture. This moisture must be removed to less than 0.05% RH to meet stack requirements for humidity. Most systems use a direct steam injection humidifier to supply supplemental water to the gas stream downstream of the reforming section (Xiong et al., 2021)

During operation of the system the water vapor produced at the cathode is partially absorbed by liquid water entering the cell as electrolyte and the remaining vapor exits the cell via the anode, which needs to be humidified. Also, the velocity plays a major role with the thermodynamic functions of a catalytic reactor by the amount of convective heat transfer developed which influences the reaction kinetics. The relative humidity and the volumetric flow rate ratio directly influence the mass transfer coefficient and thus the overall mass balance of the system (Pillai et al., 2019).

The equilibrium purge is a procedure where the relative humidity of the purge gas is adjusted to achieve thermodynamic equilibrium between the reactant gases and water in the air before they mix in the reaction zone of the fuel cell stack. If the reactor operates in cycles, the relative humidity should be constant or it will change with time (X. Yang et al., 2021). The boiler mode is used for reactors that operate under a continuous regime. If the humidity of the reactant gases is too high, the humidity of the air in the reactor will be higher. In this case, water will enter the system due to condensation inside the reactor (Janicka et al., 2021a). If the humidity of the reactant gases is too low, the water will leave the system in the form of water vapor and enter the atmosphere through the stack outlet. This will lead to reduced performance of the fuel cell stack. In order to avoid these issues, it is necessary to control the relative humidity of the reactant gases (Xiao et al., 2022).

The purpose of an endothermic dryer is to dry the exhaust air of a fuel reformer prior to entering the fuel cell stack. This will reduce the risk of corrosion inside the fuel cell stack and improve the performance of the fuel processor and fuelcell stack. Thus, it proves that the velocity of air in fuel cell also determines the corrosion (deterioration) of electrodes, due to humidity (Janicka et al., 2021a).

The fuel cell power plant from NGK is specially designed to deliver higher power density from its small footprint for energy intensive applications, including cogeneration, wastewater treatment and desalination systems, among others. NGK's fuel processor has been designed to include self-cleaning for the reforming stage using steam to reduce the sulphur content of the reformed gas before it enters the fuel cell system to maintain low humidity. The fuel cell power plant from NGK is designed to recover 50-60% of the energy consumed in the system, which reduces the need for external energy and makes it a carbon neutral solution. Additionally, the solution operates at high efficiency and therefore requires less maintenance compared to conventional power plants. The small size of the unit enables it to be easily installed in a wide range of environments, while the lack of noise ensures that there are no disturbances to the surrounding community (Tomida et al., 2021).

However, temperature increase has a positive effect on power production of the fuel cell (by increasing hydrogen production), and on heat production of the anode (by decreasing hydrogen consumption by product of water splitting reaction). It is important to keep the temperature levels stable to avoid any negative effects on the fuel cell performance (Novotný et al., 2022).

2.9 Poisoning of fuel cells

According to Shabani et al. (2019) the pollutants and impurities that might potentially reach the stack are one of the primary causes of fuel cell breakdown. The major impurities are created by the cathode side of the proton exchange membrane fuel cell stack, since the cathode side delivers air into the system, and air can contain a lot of pollutants and impurities.

2.9.1 Natural quick performance recovery from poisoning

As airborne contaminants create a lot of harm to the durability of a fuel cell, it needs to be resolved with correct signs that help it restore its prime power. The study by Shabani et al. (2019) claim that lower cathode potentials result in fast performance recovery when a PEM fuel cell is poisoned at a voltage of 0.5 V or less; cathode potentials greater than 0.69 V help in performance recovery when the voltage is greater than 0.5 V.

So, when the aforementioned study is taken into account, it shows that when an impurity is present, the potentials are supplied at a slower pace; thus, if the potential is discovered to be greater, it can lead to faster recovery from poisoning and avoid deterioration of the flow fields and the membrane exchange assembly.

2.9.2 Relationship between pressure drop, voltage loss, current density and poisoning

Poisoning happens in the platinum catalysts of proton exchange membrane fuel cells because of this, according to Q. Li et al. (2003) “ohmic contributions from electrodes, current collectors, and connections are included, the resulting conductivity values may be somewhat greater, whereas other ohmic contributions are ignored due to higher proton conductivity”. As a result of the preceding research, here it is confirmed by J.J. Baschuk (2003) that “it is possible to conclude that CO poisoning can be reduced by including oxygen into the fuel (oxygen bleeding)”. And there are several methods that are implemented by J.J. Baschuk (2003)and the “macro homogeneous technique was used to represent the catalyst layers, and the polymer electrolyte membrane was assumed to be completely hydrated”. Therefore, overcoming the potential impurities with added current density helps the system to stay more efficient.

2.10 Role of bipolar plate in fuel-cells

In fuel cells, the bipolar plate is the system integration route that joins all of the cells in a proton exchange membrane fuel cell stack. It allows gases to flow through, and the flow of these gases regulates several factors such as current density, mass flow rate, temperature, pressure, and many more. These plates have been in use for about two decades since the introduction of fuel cells. However, the challenges have never been resolved, therefore the development of these plates has continued since their commencement.

2.10.1 Pressure drop problem in bipolar plate

As discussed previously, earlier pressure drop caused by bipolar plate in proton exchange membrane fuel cells tends to be one of the major drawbacks that needs to be rectified, Belali-Owsia et al. (2015) suggested that in terms of temperature, reactant concentrations, humidity, and electrochemical reactivity, a compromise must be achieved over the active region.

In most cases of the design the numerical modelling comes out to be perfect but still it makes it harder to manufacture the plate, so a lot of designs are kept out of the equation. Belali-Owsia et al. (2015) claim that the pin type bipolar plates work well in high temperature operation without lowering the pressure and the efficiency.

According to Wilberforce, El-Hassan, Khatib, al Makky, et al. (2017) the serpentine flow channel in a fuel cell with five cells and a pressure of 101.325 Pa and a temperature of 288K did experience a very little amount of drop in pressure. Their study was carried out using the ABAQUS finite element software and MATLAB . When the flow fields constructed with the pin-type and the serpentine field are compared, the serpentine field appears to perform better than the other because the electrical output is significantly greater, the current density is higher, and the temperature is perfect to the needed level. In contrast, it performs marginally worse in pin-type. The pressure drop in the serpentine flow field is quite low.

2.11 Numerical modelling

Zafarparandeh & Lazoglu (2012) “A numerical model is a combination of a large number of mathematical equations that depends upon computers to find an approximate solution to the underlying physical problem.” In general, numerical modelling is used to perform finite element methods, by splitting a physical object into numerous finite objects or mesh to characterize the structural nature of the object.

2.11.1 Numerical modelling of fuel cells

The numerical modelling of fuel cells is carried out to assess and calculate the efficiency and performance of the stack. Because it is difficult to verify every model in real-time, numerical modelling is done with software such as ABAQUS, ANSYS Fluent, StarCCM+. Those software provide insight into the developed models and outcomes so that the best models may be investigated further.

According to Sarjuni et al., (2023) PEMFC modelling with Computational Fluid Dynamics (CFD), is generally recognised as a tough problem. Some of the most difficult issues encountered while working on CFD modelling for PEMFCs are related to the solution's quality, accuracy, and dependability. This is connected to issues like as mesh dependency, discretization errors, and convergence errors, among others, as well as the validity and reliability of the physical models used.

A mesh is required to solve for the flow within the fuel cell model, and for the fuel cells, an hexahedral mesh was chosen by (Sarjuni et al., n.d.) to give higher accuracy and precision with their findings.

According to the investigation undergone byWang et al. (2003) polarisation curve is taken into consideration throughout all numerical calculations so that when the temperature exceeds 353.15K, it may be designed to cool down so the system can stay hydrated. Various equations are involved in the CFD simulations are Nernst EquationEquation 2. CONTINUITY EQUATION , momentum, energy, and the species equations (L. Wang et al., 2003). Also, it proves that higher the pressure higher the performance of the fuel cell by solving using the equations mentioned above.

$$E_{cell} = E^0 - \left(\frac{RT}{nF}\right) \ln Q$$

Nernst Equation

Where:

E is the reduction potential,

E^0 is the standard potential in Volts,

R is the universal gas constant,

T is the temperature in Kelvin,

N is the ion charge (moles of electrons),

F is the Faraday constant and

Q is the reaction quotient

2.12 Modelling and preparation of membrane exchange assembly and gas diffusion layer

(Chaisena & Srimongkol, 2018) The mesh in fuel cells is a significant concern due to its detrimental effects on the cell performance. The mesh size and density are important parameters that can have a significant impact on the overall performance of the cell. In this work, the mathematical modelling of planar solid oxide fuel cell is investigated. The cell geometry and operating conditions were defined using the COMSOL Multiphysics software. The main objective of this work was to investigate the influence of three different operating points on the cell performance and identify the operating point which offers the best efficiency (Chaisena & Srimongkol, 2018).

Fuel Cell Energy (FCE) has recently developed an advanced Direct Fuel CellTM (DFCTM) technology that offers higher efficiency and lower operating temperature compared to other fuel cell types on the market. The DFCTM consists of a membrane electrode assembly (MEA) that consists of an anode, a cathode, and a separator. It is a flexible structure that can support three-dimensional configurations such as stacks or modules for use in portable electronics applications (Pasupathi et al., 2016).

(Alp & Arthur, 2011)The fuel cell stack configuration and MEA configuration are proprietary to FCE. However, it has been reported that each cell in the stack consists of 16 ceramic layers with a thickness of approximately 5 microns (1 mm). The total thickness of the entire stack is approximately 180 microns (6 mm). There are a total of 8 ceramic layers on each side of the stack (Alp & Arthur, 2011). The fuel cell membrane electrode assembly (MEA) is prepared by chemical vapor deposition (CVD) of zirconia-stabilized yttria-stabilized tetragonal zirconia polycrystals (YSZ–TSZ–PZT) from two different precursors: YSZ and PZT. The structure is composed of a cell substrate, a gas diffusion layer (GDL), electrolyte layers, and catalyst layers. The two MEAs are stacked together to form a stack and then sandwiched between two end plates (Roy et al., 2017).

The electrodes for FCE consist of transparent electrodes made by chemical vapor deposition (CVD) of thin layers of strontium-dopedlanthanumzirconate-titanate supported by a glassy carbon binder. A chromium-based thermosetting conductive ink is applied to the surface of the electrodes prior to the coating process in order to reduce the parasitic series resistance that may be present between the electrodes (Woo, 2019). The conductive ink is applied by screen printing. The cell assembly is then encapsulated in a sandwiched arrangement of glass and carbon fibre composite end plates to create a gas-tight package. The DFC power system contains one hydrogen tank, which contains compressed hydrogen at a pressure of about 700 bar (10,000 psi). During operation, hydrogen from the hydrogen tank is released into the fuel cell stack where it reacts with oxygen from the air to produce electricity (Woo, 2019). The oxygen is consumed, and the hydrogen is replenished from the hydrogen tank. A coolant, glycol, is circulated through the fuel cell stack and removed from the stack via a radiator. This circulating loop maintains a stable temperature within the fuel cell stack and promotes more efficient operation of the fuel cell stack. The power generated by each FCE can be used to operate equipment directly or can be converted to direct current electricity by an inverter (Jörissen, 2009).

2.13 Study on PEM fuel cell performances

As discussed earlier the performance of the fuel cell is based on various factors such as temperature, pressure, and the prevention of poisoning, also it is proven that higher the pressure higher the performance.

According to the study undergone by Sun et al. (2005a) other than pressure, temperature also has a major role in the performance, “Temperature and other transport parameters, such as membrane proton resistance, gas diffusivities, and so on, reduce activation energy. It all depends on the temperature” (Sun et al., 2005).

The ionic resistance is lowered when the porous membrane of the fuel cell is finely hydrated as per study by X. Li et al., (2020), and this is a good sign because, if the system is more hydrated the flow of protons inside the system can be spontaneous and makes it more efficient.

So, the Cathode side has a platinum catalyst that make way for the oxygen reduction reaction to happen, Pillai et al., (2019)claimed that “Hydrogen kinetics are further orders slower than the platinum catalysts”. MEAs operating with H2/air, anode Pt loadings may be lowered to 0.05 mgPt/cm2 without significant voltage losses, but cathode Pt loadings can be reduced to 0.20 mgPt/cm2 with a voltage loss of just 20 mV up to 1.0 A/cm2”.(Pillai et al., 2019). In the next chapter the methods for modelling a fuel cell are described in detail.

2.14 General methods of fuel-cell modelling

Wu & Chiou (2021)To numerically model the bipolar plate in PEM fuel cells to analyse the pressure drop in various channels and to select the most suitable channel design Wu & Chiou (2021) a three-dimensional finite-element model of the bipolar plate using COMSOL Multiphysics software. The model in this study by Wu & Chiou (2021) was validated by comparing its results with those of previously published numerical models. It was then used to study the pressure drop in various channels to select the most suitable channel design. The Wu & Chiou (2021) model shows that the pressure drop increases as current density increases. This shows that the current density is an important factor to consider when designing a fuel cell stack, and that the flow rate in the upstream channel should be at least equal to that in the downstream channel to prevent the pressure drop from increasing when the current density is increased (Y. Wang et al., 2022).

The Wu & Chiou (2021) model was used to study the pressure drop in various channels in order to select the most suitable channel design. The results show that the pressure drop is lower when the cross-sectional area of the plates is the same for both upstream and downstream channels than when they are different. This is consistent with the results of previous studies. The model shows that the pressure drop increases as current density increases (Mortazavi, 2021a).

The pressure drop curve of a PEM fuel cell studied by Kang et al., (2019) shows the pressure drop as a function of current density for the different designs studied. The current through both channels is equal; the current through the upstream channel is equal to the current through the downstream channel; the current through the upstream channel is greater than the current through the downstream channel; the current through the upstream channel is less than the current through the downstream channel.

The pressure drop calculated by Lu et al., (2023)for the design where the current through both channels is equal is 0.06 Pa at 500 mA/cm2 and 1.07 Pa at 2000 mA/cm2. This suggests that increasing the current density will slightly increase the pressure drop. However, it can be reduced by decreasing the size of the plates in the channels and by increasing the flow rates in both channels.

Pressure drop curves were investigated by Singhal& Ansari (2016) for the case where the flow rate through the upstream channel is equal to that through the downstream channel are 0.04 Pa at 500 mA/cm2 and 0.07 Pa at 2000 mA/cm2. The author showed that if the current density is kept constant, the pressure drop will be lower when the flow rates are the same.

Singhal & Ansari, 2016)The pressure drop curves for the case where the flow rate through the upstream channel was greater than that through the downstream channel are 0.05 Pa at 500 mA/cm2 and 0.09 Pa at 2000 mA/cm2 (Singhal & Ansari, 2016). This shows that increasing the volume of the active area will reduce the pressure drop even when the flow rate is the same.

As highlighted above, the pressure drop is an important parameter to study for this sort of studies. In the next chapter methodologies to determine the pressure drop in proton exchange membrane fuel cells are explained in detail and all the methods used to approach the results are explained.

Thus, the methods involved are described in this chapter and in further discussion in this study the other methodologies to determine the pressure drop and its disadvantages are discussed.

3 CHAPTER: METHODOLOGIES TO DETERMINE THE PRESSURE DROP IN PROTON EXCHANGE MEMBRANE FUEL CELLS

There are various methods to measure the pressure drop in proton exchange membrane fuel cells (PEMFCs). The most common are the wet test method and the dry test method.

The wet test method investigated by Mortazavi (2021b), is primarily used in laboratory settings, and it involves adding water to the fuel cell and measuring the pressure drop across the cell while the current is being measured. This method is highly accurate but can only be used in laboratories because of the large amount of time and resources required. It is also not practical for field tests because it is difficult to add water directly to the fuel cell without damaging it.

For such methods, the water is then allowed to escape through the exhaust manifold of the fuel cell at a controlled rate until the pressure drop across the cell can be measured. During the experiment, a small voltage is usually applied to the cathode of the fuel cell to help facilitate water transfer from the injection chamber into the exhaust manifold of the fuel cell. BIPOLAR plate flow field design is important as it affects the performance of the fuel cell because of improper gas distributions over the catalyst layer. In this method, the gas distribution is determined by the length and diameter of the flow channels connecting the inlet and outlet to the electrodes. It is important to keep the channel lengths as short as possible to minimize pressure drops in the channels and to prevent mixing of gases across the catalyst layer (Pillai et al., 2019).

The wet test method also involves simulating the electrochemical reaction of the fuel cell as a constant mass sink/source of water under the electrode reactants. As the water flows out of the cell, the hydrogen and oxygen are consumed, resulting in the generation of electrons and protons at the anode. These ions are then transported to the cathode where they react with the oxygen in the water to produce water that is released back into the inlet circuit. The total amount of water flowing through the cell is equal to the amount of water released by the cell.

Therefore, the total mass of water supplied to the cell is equal to the mass of the water produced by the cell (Reimer et al., 2021).

The dry test method, however is commonly used in field tests, involves measuring the pressure drop across the fuel cell while the electrical current is zero (Ruan 2014a). This method requires less equipment and time than the wet test method, but it is less accurate than the latter because it cannot measure actual current generation in the fuel cell. In conclusion, the wet test method is the most accurate method for measuring the pressure drop in a PEMFC.

The pressure drop across a PEMFC can be used to detect the performance degradation during transient conditions. A decrease in pressure drop indicates that the fuel cell is not working as well as it should and therefore should be repaired or replaced. This knowledge can also be used to optimize the design of the PEMFC to maximize its performance and durability (Kang et al., 2019).

Some fuel cell test systems use humidification of the reactant gas streams. Humidified air increases the effectiveness of the heat transfer between the air and the water within the fuel cell and the cooling water surrounding the fuel cell stack. When the humidified air exits the fuel cell stack, it enters the conditioned space as dry compressed air that is ready for use by the facility's system operators. The humidification system also removes water vapor from the exhaust air exiting the fuel cell stack. This helps to maintain proper air quality in the room where the fuel cell test system is operating (Xiao et al., 2022).

3.1 CFD analysis

The potential of Computational Fluid Dynamics (CFD) for predicting fuel cell behaviour under various pressure drop conditions is discussed. The research conducted has shown that CFD is a very accurate tool for predicting the behaviour of fuel cells under pressure drop conditions (Pandi et al., 2023). This paper consists of three parts. In the first part, it represents some background information on fuel cells and pressure drop characteristics. The second part discussed some of the modelling assumptions used throughout the study. Finally, in the third part, the results of the simulation were discussed.

3.1.1 Introduction to finite viscous compression and manifold energy resistance in fuel cells

Pressure drop characterization in PEMFCs is difficult due to complex flow patterns at the inlet and outlet of a PEMFC flow channel. The predicted pressure drop may not be the same as the measured one due to the imperfections in the fabrication of the components of the system. However, many studies have analysed the pressure drop of various configurations of PEMFCs. In this study, a new model was developed by Mortazavi (2021b) to predict the pressure drop of a PEMFC flow channel with finite viscous compressibility and a porous matrix at the inlet and outlet of the flow channel. This model was used to investigate the effects of parameters like thickness, porosity, and permeability on the pressure drop characteristics of a PEMFC flow channel (Mortazavi, 2021b Banerjee et al., 2013a).

Maharudrayya et al. (2016) and Esfeh et al. (2017) investigated the pressure loss and the flow pattern of a PEMFC flow channel containing 20 percent Nafion solution under steady and dynamic conditions using a finite volume method solver called COMSOL Multiphysics®. The pressure loss for various flow rates was determined for both the static and dynamic cases. It is found that the pressure drop increases with an increase in flow rate. This is mainly due to the resistance offered by the porous media to the fluid flow. The increase in flow rate also increases the backpressure on the membrane which can increase the pressure loss of the system. Similar results were obtained for the dynamic case where the decrease in the pressure drop is more significant as the flow rate increases (Esfeh et al., 2017).

The pressure drop decreases with an increase in flow rate for the dynamic case as due to the decrease in the pressure drop due to the increase in the flow rate. This trend is reversed for the case of a static condition (Singhal & Ansari, 2016).

The pressure loss of the reactor was lower for a flow rate of 0.1 L/min than for a higher flow rate of 2.0 L/min. This decrease in pressure loss is more significant for the case where the flow rate decreases. This is due to the fact that the pressure drop is directly proportional to the flow rate of the fluid in the system (Maharudrayya et al., 2016). Higher mass flow rate of the fluid will result in higher resistance to the flow and hence, higher pressure drop for the system (Singhal & Ansari, 2016).

The pressure drop across a control valve can be calculated by using the following formula: $P = Q^* \rho^*A^*V/L$ where Q is the flow rate of the fluid through the valve, ρ is the density of the fluid, A is the area of the flow channel, V is the volume of the flow channel and L is the length of the flow channel (Rabert T, 2022).

3.1.2 Testing using various FEM software

Numerical modelling of fuel cells is undergone using various software such as, ABAQUS, ANSYS Fluent, COMSOL, StarCCM+ and various CAE methods. In 2015, CFD simulations of the gas flow channels in bipolar plates for PEM fuel cells were developed using Ansys CFX software and results were compared with experimental results using laser Doppler anemometry and particle image velocimetry techniques. The results obtained were further validated using a high-fidelity model of the same fuel cell stack. Simulations revealed that the fluid flows in the channel were more turbulent than expected due to the presence of a non-homogeneous distribution of graphite particles in the electrode material (Balasubramani et al., 2020).

Numerical simulations of flow channels in bipolar plates using porous anode and cathode layers for PEM fuel cells was carried out using the finite element method (FEM) combined with computational fluid dynamics (CFD). Following previous work by Y. Wang et al., (2022) composite layer model of the bipolar plate was developed consisting of three layers (porous carbon-coated paper, solid carbon, and stainless steel) (Ramya et al., 2011).

The polar plate geometry and flow channel design was optimised using a genetic algorithm, with the effect of pressure drop across the flow channels taken into account during the optimisation process. An Ansys CFX-based model was then developed based on the optimised geometry of the flow channels and the results of tests performed on a small-scale prototype device (Wu & Chiou, 2021).

The polar plate geometry and flow channel design was then simulated using CFD. The simulation results were then compared with experimental data obtained using a laser Doppler anemometer and a particle image velocimeter for a device like that used in the simulation study (Iranzo et al., 2022). The simulation results indicated that the volume-averaged Reynolds numbers within the flow channels were higher than those predicted by the empirical correlation developed by Brown and Othman(n.d.), and that the CFD model accurately predicted the flow field within the flow channels (Reimer et al., 2021).

3.2 Impedance spectroscopy for fuel cells

Electrochemical impedance spectroscopy is one of the promising methods to test fuel cells. The technique has many advantages, such as the non-destructive character of the test, its high resolution and sensitivity, and its capability for characterizing dynamic processes in fuel cells (Raychaudhuri et al., 2022a). Therefore, many researchers use this technique to study the properties of different fuel cell materials or electrodes. One of these studies focused on the effect of the Nafion® electrolyte solution on the impedance characteristics of a polymer electrolyte membrane fuel cell (PEMFC). In this study, the impedance spectrum of a PEMFC was measured after it had run for about 2 hours and then after it stopped operating for 24 hours. The impedance spectra showed a decrease in conductivity after 24 hours, which was attributed to the Nafion® electrolyte solution. The conductivity of the Nafion® electrolyte solution decreased as the water in the electrolyte solution evaporated.

Nafion®, developed by DuPont, is a polymer electrolyte membrane that is widely used in PEMFCs. Nafion® is (EIS Diagnosis for PEM Fuel Cell Performance, 2010) commonly used for membrane electrode assemblies (MEAs), the components of the fuel cell that are sandwiched between the two electrodes. Nafion® has a high permeability to protons so that the flow of protons from the cathode to the anode. It is also hydrophilic and ionically conductive, which makes it suitable for PEMFCs. However, Nafion® is also toxic and flammable, and its flammability limits its operating temperature to below 100 °C. In order to increase the performance and lifetime of a PEMFC, it is essential to understand the role that the Nafion® electrolyte solution plays in the performance of the fuel cell. To do this, the researchers measured the impedance of a PEMFC that had run continuously for more than 2 hours and then after they shut down the fuel cell and stopped supplying the electrolyte solution, they measured the impedance of the fuel cell again. They found that the impedance of the fuel cell increased when the electrolyte solution was removed, meaning that Nafion® is degrading over time (Cha et al., 2022).

The PEMFC durability test conducted by Basco et al. (2013) consists of subjecting a fuel cell stack to a continuous repetition of the required charge/discharge cycles from a full state of charge to full state of discharge or vice versa, without any maintenance process in between cycles. In the continuous durability test, the power output of the fuel cell gradually decreases as the cycle number increases. The humidity level inside the fuel cell stack also changes, which affects the power output of the fuel cell. The researchers also found that the degradation of Nafion® increases the resistance of the fuel cell's current path, which causes a decrease in current density and therefore a drop in power output. This decrease in the power output of the fuel cell is most likely caused by the decomposition of some of the components in Nafion® as it continues to degrade over time (Cong Tinh & Kim, 2020).

3.3 Methods to determine electrical output in fuel cells

Electrical output in PEM fuel cells is a critical parameter to consider when studying these devices. There are a variety of methods to calculate electrical output in PEM fuel cells, and each has its own advantages and disadvantages (Derbeli et al., 2020).

The "one-dimensional steady state model" developed by Zong and Yue in 2012 was a further development of the "two-dimensional steady-state model" developed by Menon et al. in 2010. Both models assume that the cell operates as a closed system and that the oxygen reduction reaction in the cathode and the oxidation reaction in the anode. It is the simplest of all the models used to estimate electrical output in PEM fuel cells (Pandi et al., 2023).

A three-dimensional steady state model was developed by Pu and Li in 2011. It assumes that the cell is an open system consisting of the anode, the cathode, a Nafion® membrane, gas diffusion layers, and gas channels. This model allows for a more realistic depiction of the internal processes occurring in the cells, but it requires significantly more computational power than the other models (Cong Tinh & Kim, 2020)

A three-dimensional unsteady state model (Reimer et al., 2021) was developed by Zong and Yue in 2014. It uses particle-based methods to model the flow of gas through the porous electrodes. The particles are released or removed from the electrode based on changes in electrochemical potential. This model takes into account time-varying conditions such as temperature and pressure that can affect the flow of gases within the cells.

Katopodes (2019)developed models for estimating electric output of fuel cells based on the chemical kinetics of the reactions taking place in them. Although these models are more accurate and precise than either of the two-dimensional models described above, they are computationally expensive and are not suitable for real-time applications.

Fuel Cell Energy (FCE) has developed a more advanced Direct Fuel CellTM (DFCTM) that uses a novel anode/cathode structure. In order to accurately calculate power output from the DFCTM, it is necessary to take into account the non-uniform electric field distribution caused by the embedded current collectors in the external surface of the electrodes. Solving the Poisson equation for the complex structure of this fuel cell is very complex and requires additional modelling and simulation software which is not currently available to the researchers at the FCE, but still the results were obtained using the above-mentioned methods (Singh, 2016).

3.4 Discussion of fuel cell poisoning prevention methods

PEM fuel cells are a type of clean energy technology that generate electricity by converting chemical energy from fuels into electrical energy. In order to minimize the potential for fuel cell poisoning, it is important to understand the methods used to prevent this type of poisoning (Levitan et al., 2021).

PEM fuel cells, also referred to as polymer electrolyte membrane fuel cells, operate at relatively low temperatures (approximately 90 degrees Celsius) and produce only small quantities of toxic by-products during operation. Unlike other types of power generation technology, a PEM fuel cell does not require the use of an incinerator in order to dispose of the waste material created during energy production, reducing the overall environmental burden of the technology (Xiong et al., 2021).

PEM fuel cells use a proton exchange membrane to conduct electricity from the anode to the cathode, producing only water as a by-product of operation. During the manufacturing process of a PEM fuel cell, there are a number of factors that have the potential to contribute to cell poisoning (Raychaudhuri et al., 2022).

One of the key factors in cell poisoning is the presence of metallic impurities in the fuel, particularly precious metals such as platinum and palladium. As these precious metals are expensive, reducing their use can reduce the overall manufacturing cost of the fuel cell. To ensure that these precious metals are not used in the generation of hydrogen gas, the fuel should be filtered using a metal-ion separator to remove any metal ions from the fuel before it is delivered to the fuel cell. If the fuel is not filtered in this way, the metal ions can build up at the electrodes of the fuel cell, resulting in corrosion and damage to the electrode material and a drop in the efficiency of the fuel cell (Schonvogel et al., 2021).

The KIT-1 Hydrogen Production Demonstration Kit contains a metal-ion separator, which is used to filter the fuel and remove any potential metal impurities that may be present in the fuel. Once the fuel has been filtered, it is then sent to the fuel cell stack where it is converted into electricity and heat before being discharged from the cell. Although the filtering process is relatively slow, it ensures that only the cleanest fuel is sent to the fuel cell stack to ensure that it runs efficiently (Khabazipour & Anbia, 2019).

PEM fuel cells need to be purged with dry air to remove any liquid water, as liquid water can freeze in the fuel cell stack and cause damage. If the cell is not properly purged, the water in the cells may build up and freeze, damaging the electrode plates and reducing the efficiency of the entire cell (Nguyen et al., 2021).

PEM fuel cells use water as a coolant, which needs to be constantly removed and filtered from the fuel cell stack to keep the operating temperature low and prevent the cell from overheating. As the coolant leaves the fuel cell stack, it needs to be pumped back through the system, as the electrons created at the cathode cannot be used to power the pump that removes the water from the fuel cell stack (Singh, 2016).

A humidifier system is used to keep the fuel cell stack dry. This system uses air from the surrounding atmosphere to humidify the air inside the fuel cell stack, allowing the water molecules in the air to be converted into steam as they pass through the fuel cell stack. The water vapour is then removed from the fuel cell stack and sent back to the humidifier where it is heated and returned to the atmosphere (Janicka et al., 2021b).

During the electrolysis of water to produce hydrogen and oxygen, a significant amount of heat is generated which can heat up the electrolyte solution and other components in the cell. To control the temperature, the hydrogen gas produced by the fuel cell is humidified and recycled through a humidifier system. The humidifier system uses a fuel cell stack to humidify the recycled hydrogen gas. The humidity of the hydrogen gas is increased by adding water vapor from the air into the fuel cell stack and then removing the moisture using a heat exchanger (Xiao et al., 2022).

3.5 Characterization and setup to determine current density fluctuation in PEM fuel cell

There are a number of different software programs that can be used to model fuel cells and their behaviour. Some of these programs are ANSYS, MATLAB and LabVIEW. MATLAB is a powerful computer programming language that has been used in many scientific and engineering settings. ANSYS is a computer software program that engineers use to simulate and analyse engineering problems (Iranzo et al., 2022). LabVIEW is a program used for designing electronic systems and for prototyping. All these programs can be used to model fuel cells and their behaviour. Below I will discuss how each of these programs can be used to help analyse fuel cell behaviour.

ANSYS is a computer program that engineers use to simulate and analyse engineering problems. ANSYS was used to simulate the transient behaviour of the PEM fuel cell (Heidary et al., 2016). The simulation showed that the temperature was not uniform throughout the cell. The temperature increased near the cathode and decreased near the anode. The heater voltage was also not constant throughout the cell but increased as time passed. This was because the heaters were not evenly distributed in the cell. The fuel cell start-up and shut-down behaviour was simulated in MATLAB. The start voltage for the start-up phase decreased as the power output increased. After the start-up phase was completed, the voltage reached a steady value and stayed that way for the rest of the simulation. During the shut-down phase the voltage increased until the cell ran out of fuel and then remained at that level for the duration of the simulation (Nguyen et al., 2021a).

4 CHAPTER: FINDINGS AND COMPARISION OF PRESSURE DROP IN PEMFC

4.1 Serpentine channel in PEMFC

A serpentine flow channel is a common configuration for conduits in chemical and mechanical engineering. It has many advantages, such as reduced pressure drop and increased heat transfer.

Serpentine flow channels are also commonly used in proton exchange membrane fuel cells (PEMFCs) because of their design simplicity, ease of manufacture and flexibility of use. Furthermore, the serpentine geometry allows the design of a single fuel-oxidant inlet for both fuel and oxidant; only one fuel crossover is required in the hydrogen/air or hydrogen/methane flows. Additionally, this approach reduces the complexity of the system and the size of the hardware required (Velisala & Srinivasulu, 2018).

The serpentine flow channel was selected as a reference for comparison of the new geometries. The goal of the study was to investigate the effect of geometry on the performance of the fuel cell under various operating conditions (Zamora-Antuñano et al., 2019).

Two-dimensional simulations of the serpentine flow channel were performed using a commercial software ANSYS CFX by (Zamora-Antuñano et al., 2019). The dimensionless analysis was performed using the cell performance function based on electrochemical reaction and transport of reactants and products within the porous medium and the ionic current flowing through the separator. Three different bipolar plate geometries were analysed: a single channel, a serpentine channel, and a double channel structure. The single-channel structure represented the original design of the research prototype and tested in this study. The other structures were simulated to increase the manifold area to improve overall performance. Detailed analysis of pressure and velocity was performed for each case in order to assess the impact of geometry on the airflow patterns within the conduit (Zamora-Antuñano et al., 2019).

The double-channel structure investigated by (Lan et al., 2023) showed the highest performance, with 21.3% higher maximum power density and 19.2% lower pressure drop compared with the single-channel structure. This improved performance was due to the increase in manifold area and better distribution of the fuel and air streams across the bipolar plates. The pressure drop for the double-channel case was also lower than the one predicted by existing analytical models.

In the fuel cell they investigated, Pandi et al.,(2023) observed that, water was also observed to form in the cathode flow field at high current density. This led to the formation of water bubbles near the membrane. These particles eventually accumulated at the membrane surface and reduced its conductivity. In conclusion, the simulation results demonstrated the potential of incorporating the double-channel geometry into the design of portable fuel cells for mobile applications.

Experiments were also conducted with proton exchange membrane fuel cells incorporating two different anode and cathode flow field designs to carry the reactants and products within the porous matrix. For the experiments, the corrosion tests were performed using acidic aqueous solutions in acid-resistant stainless-steel containers. An electrochemical analyser was used to measure the polarization resistance and Tafel slopes of the electrodes to determine the performance of the fuel cells (Khabazipour & Anbia, 2019).

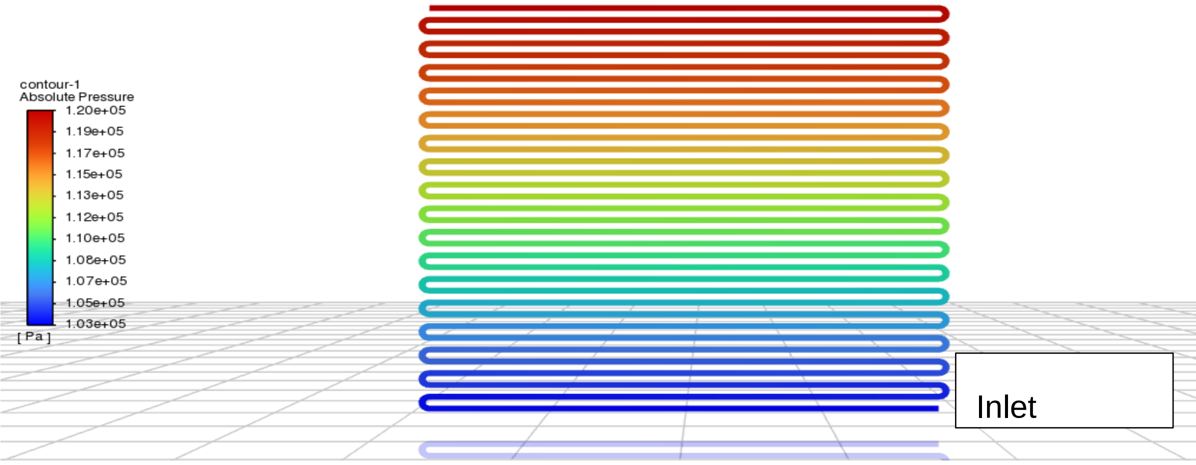
The double-channel design allowed Randrianarizafy et al. (2020) to simulate the start-up and shutdown of the fuel cell. During start-up, the fuel gas was supplied to the cell using a peristaltic pump and the oxygen was delivered via an air inlet tube connected to the atmosphere. After pumping was stopped, the gas flow fields were allowed to stabilize and the reactions within the cells were monitored over 5 minutes while the voltage measurements were taken for every process.

4.2 Synopsis for the findings

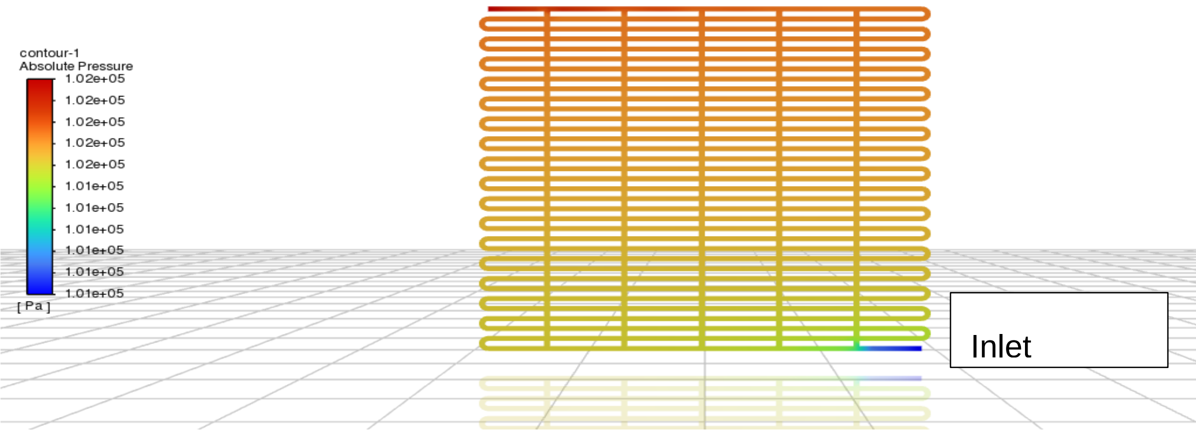
In the following discussion the findings of pressure from various designs studied are explained. The following results demonstrate the pressure involved with the same parameters found in the literature. And the same values are applied to the newly developed models from this research. The models from the literature and the research are designed using Solid works Software and the mesh was made using the ANSYS mesh, the type of mesh used was hexahedral for better accuracy in the results. Before meshing the component using ANSYS space claim the volume were extracted to describe the boundary conditions of the bipolar plate. After that the mesh was simulated using ANSYS Fluent. The model used in the software was Laminar. The PISO algorithm was used for all the models and second order upwind is used across all the models to provide subtle results. The inlet and outlet conditions were set as per the literature. The inlet pressure in the literature is slightly higher than the models designed in this research. It was intentionally reduced in the new models to prove that the newly designed models perform better than the model in the literature even at a lower pressure. The fluid used in the flow channel is Liquid Hydrogen. The absolute pressure is shown to describe the performance of the fuel cell at vacuum state with the same boundary conditions. The dynamic pressure is shown to describe the performance of the fuel cell when the pressure on a surface when a flowing fluid is brought to rest that is greater than the pressure on the surface when the fluid is not moving. The static pressure is shown to describe the performance of the fuel cell when the amount of pressure exerted by a fluid that is not moving. The total pressure is shown to describe the performance of the fuel cell when the static pressure and the velocity pressure sums up. All the numerical findings are discussed in the upcoming sections.

4.3 Results from the literature vs models from this study

4.3.1 Absolute pressure literature vs model 1



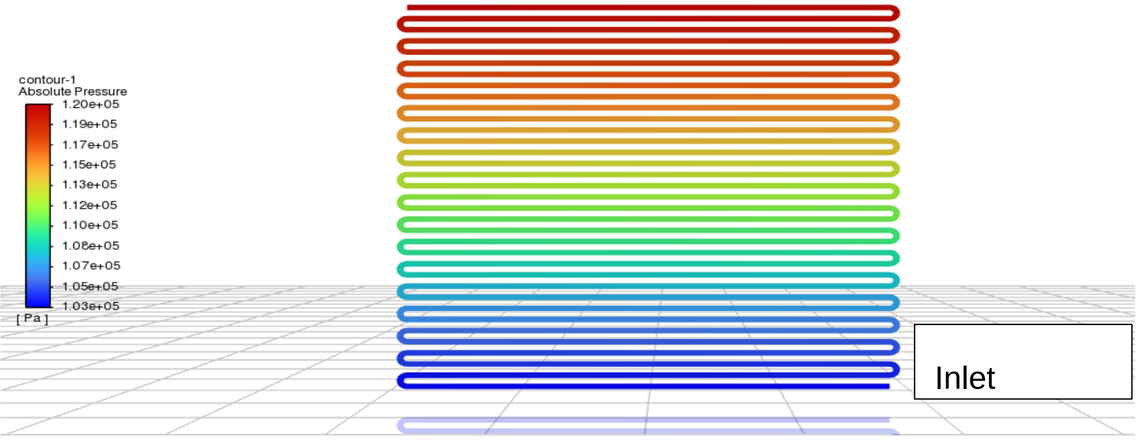
Absolute pressure 4.3-1 from literature (velisala & srinivasulu, 2018)



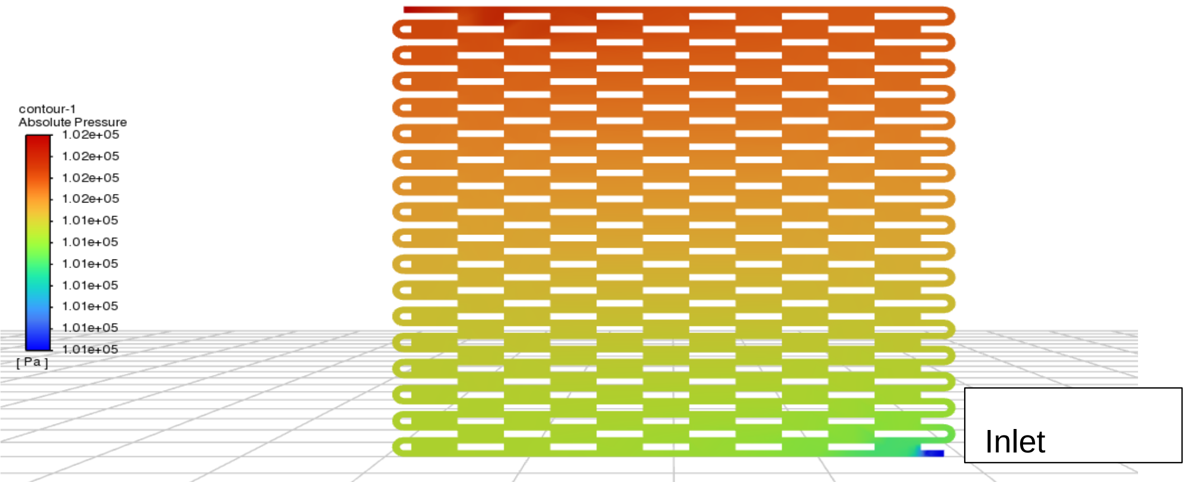
Absolute pressure 4.3-2 from validated model-1 (jayvassanth j, 2022)

The figure (Absolute pressure 4.3-1) and figure Absolute pressure 4.3-2 represent the absolute pressure of the bipolar plate in a pem fuel cell. The outlet pressure of the (Absolute pressure 4.3-1) is 120000pa and the outlet pressure of Absolute pressure 4.3-2 is 102000pa. Both the models are operated with a current density of 0.5v.

4.3.2 Absolute pressure literature vs model 2



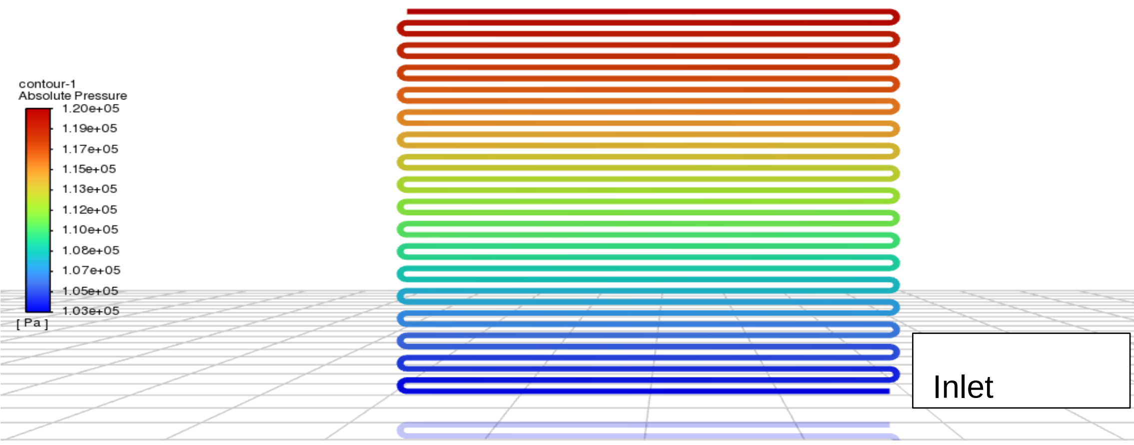
Absolute pressure 4.3-3 from literature (velisala & srinivasulu, 2018)



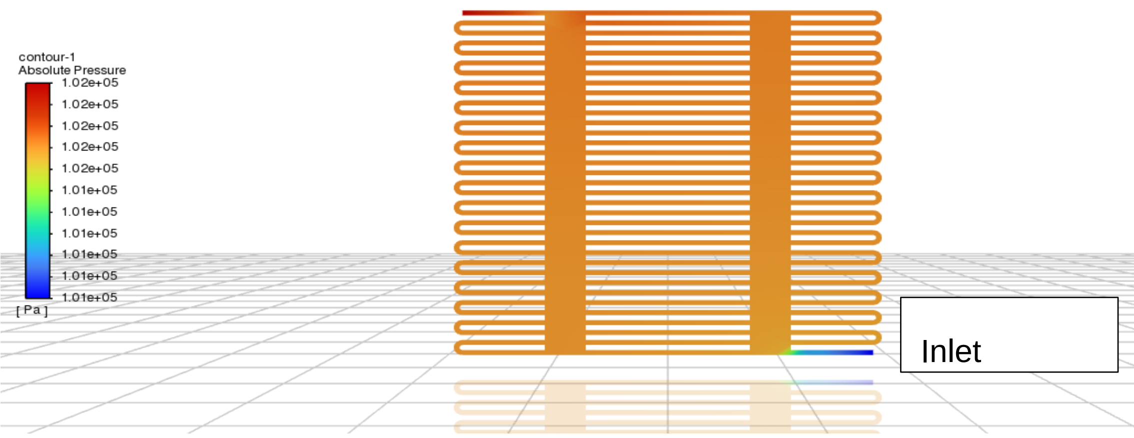
Absolute pressure 4.3-4 from model 2 (jayvassanth j, 2022)

The figure (Absolute pressure 4.3-3) and figure (Absolute pressure 4.3-4) represent the absolute pressure of the bipolar plate in a PEM fuel cell. The outlet pressure of the (Absolute pressure 4.3-3) is 120000pa and the outlet pressure of Absolute pressure 4.3-4 is 102000pa. Both the models are operated with a current density of 0.5V.

4.3.3 Absolute pressure literature vs model 3



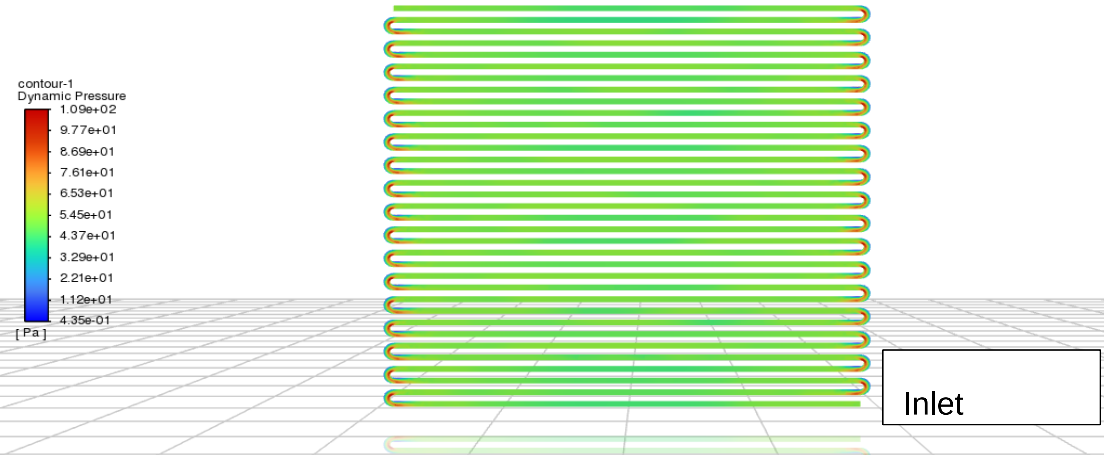
Absolute pressure 4.3-5 from literature (velisala & srinivasulu, 2018)



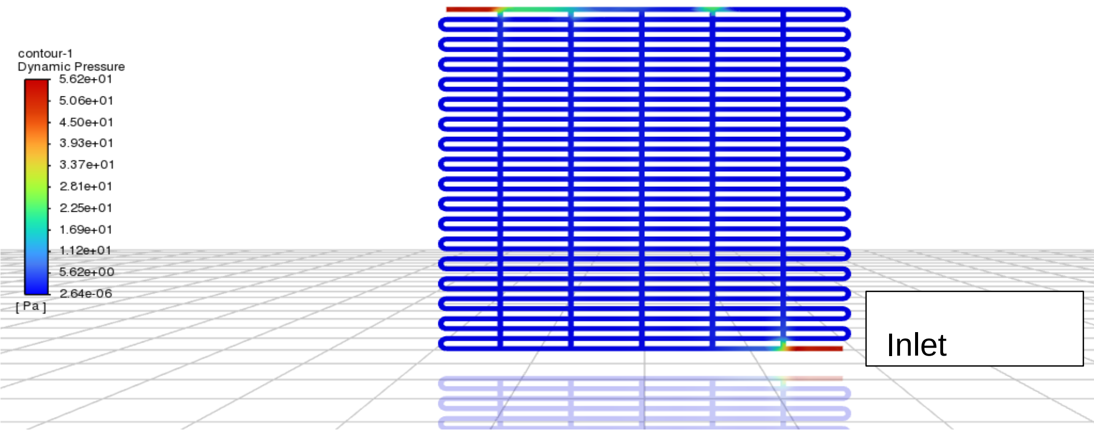
Absolute pressure 4.3-6 from model 3 (jayvassanth j, 2022)

The figure Absolute pressure 4.3-5 and figure Absolute pressure 4.3-6 represent the absolute pressure of the bipolar plate in a PEM fuel cell. The outlet pressure of the (Absolute pressure 4.3-5) is 120000pa and the outlet pressure of (Absolute pressure 4.3-6) is 102000pa. Both the models are operated with a current density of 0.5V.

4.3.4 Dynamic pressure literature vs model 1



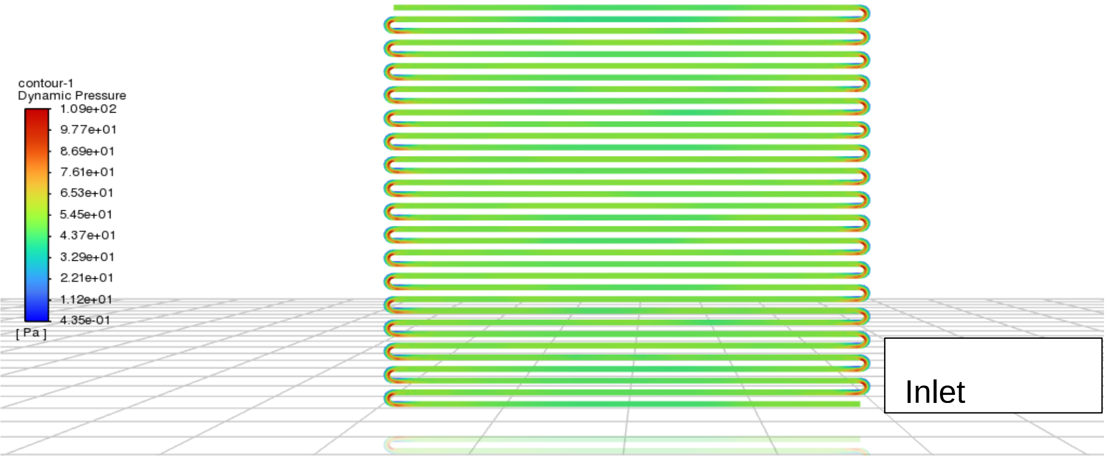
Dynamic pressure 4.3-1 from literature (velisala & srinivasulu, 2018)



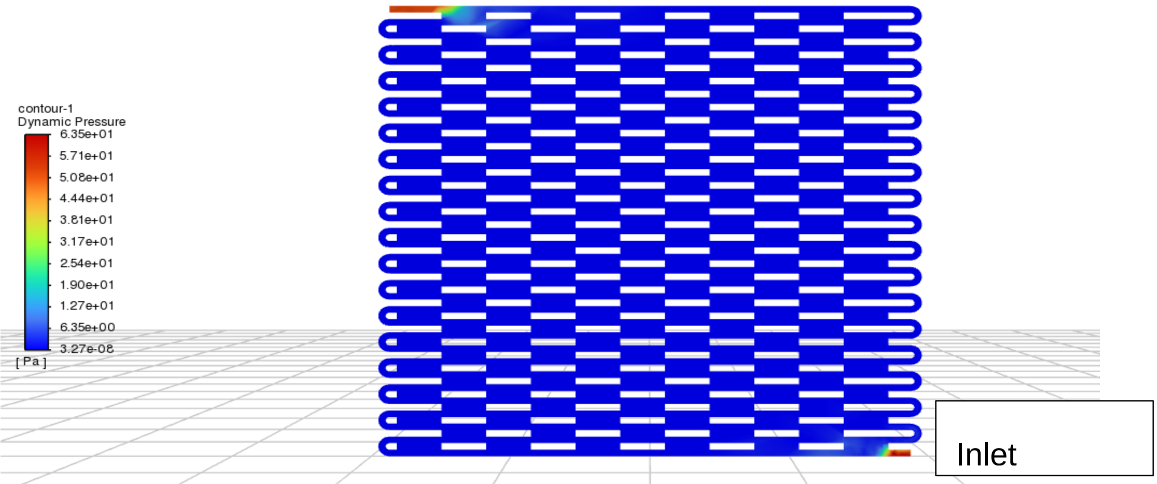
Dynamic pressure 4.3-2 from model 1 (jayvassanth j, 2022)

The figure (Dynamic pressure 4.3-1) and figure Dynamic pressure 4.3-2 represent the dynamic pressure of the bipolar plate in a PEM fuel cell. The outlet pressure of the (Dynamic pressure 4.3-1) is 190pa and the outlet pressure of (Dynamic pressure 4.3-2) is 562pa. Both the models are operated with a current density of 0.5V.

4.3.5 Dynamic pressure literature vs model 2



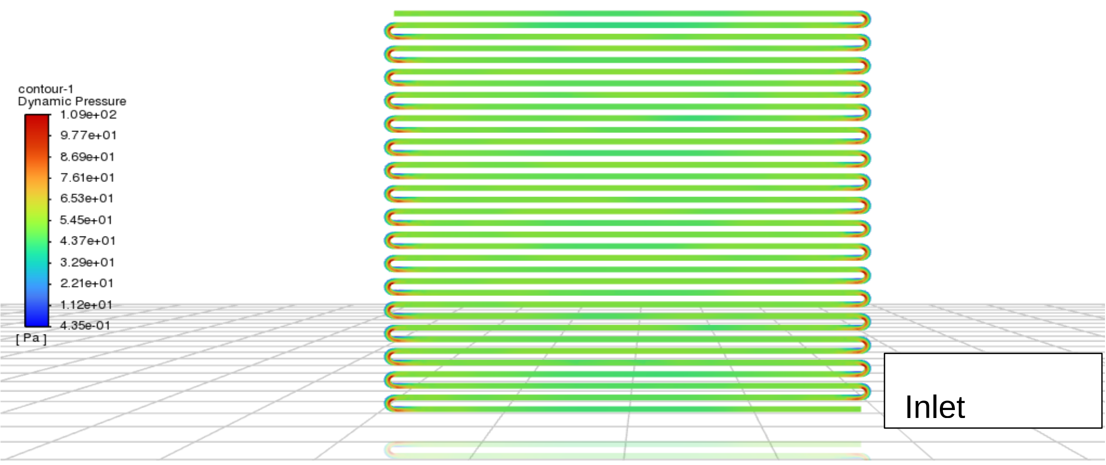
Dynamic pressure 4.3- DYNAMIC_PRESSURE (velisala & srinivasulu, 2018)



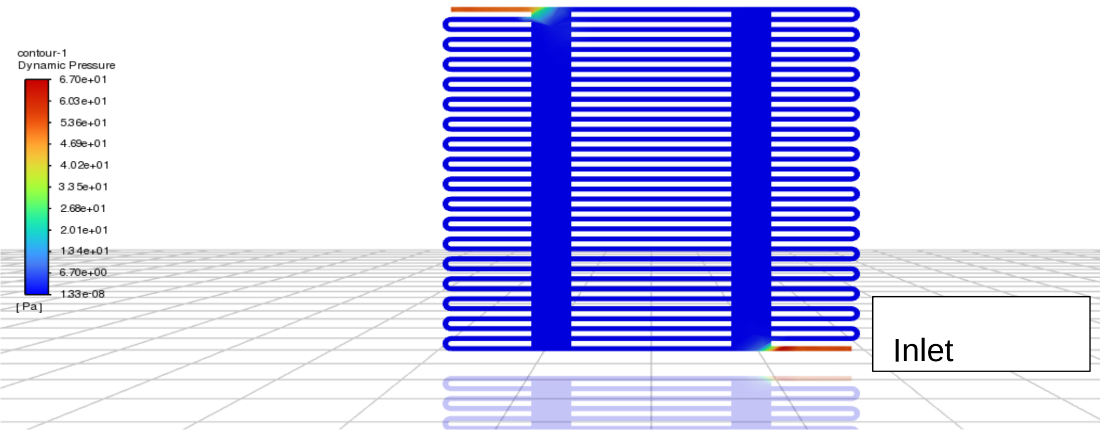
Dynamic pressure 4.3-3 from model 2 (jayvassanth j, 2022)

The figure (Dynamic pressure 4.3- DYNAMIC_PRESSURE) and figure (Dynamic pressure 4.3-3) represent the dynamic pressure of the bipolar plate in a PEM fuel cell. The outlet pressure of the (Dynamic pressure 4.3- DYNAMIC_PRESSURE) is 190pa and the outlet pressure of (Dynamic pressure 4.3-3) is 635pa. Both the models are operated with a current density of 0.5V.

4.3.6 Dynamic pressure literature vs model 3



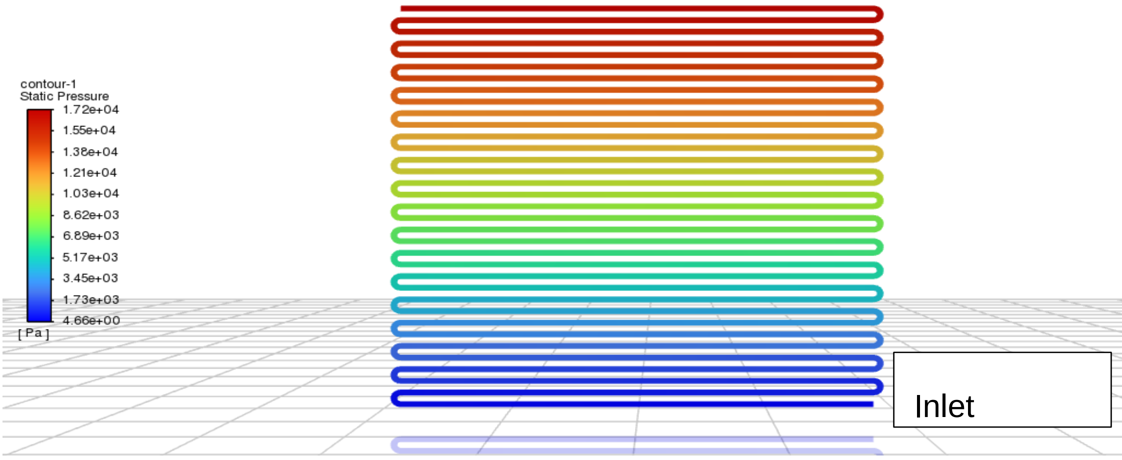
Dynamic pressure 4.3-4 from literature (velisala & srinivasulu, 2018)



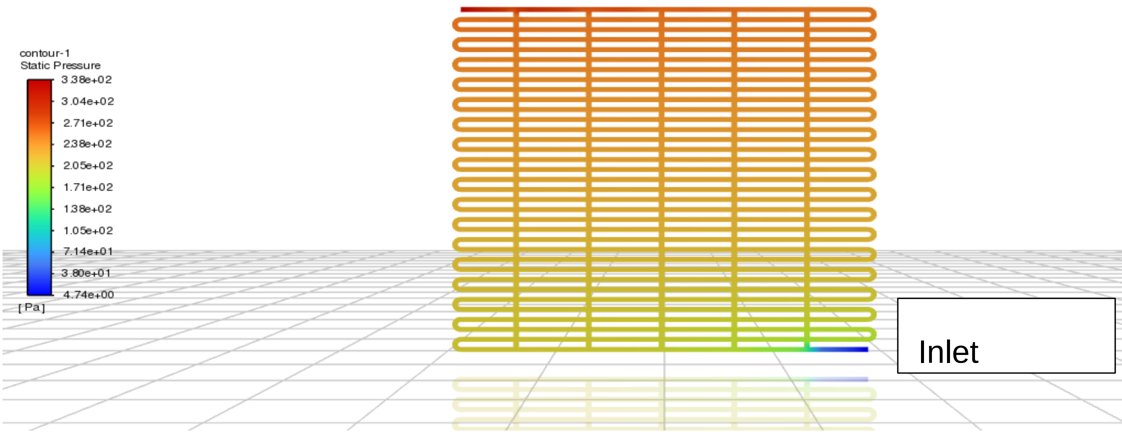
Dynamic pressure 4.3-5 from model 3 (jayvassanth j, 2022)

The figure (Dynamic pressure 4.3-4) and figure (Dynamic pressure 4.3-5) represent the dynamic pressure of the bipolar plate in a PEM fuel cell. The outlet pressure of the (Dynamic pressure 4.3-4) is 190pa and the outlet pressure of (Dynamic pressure 4.3-5) is 670pa. Both the models are operated with a current density of 0.5V.

4.3.7 Static pressure literature vs model 1



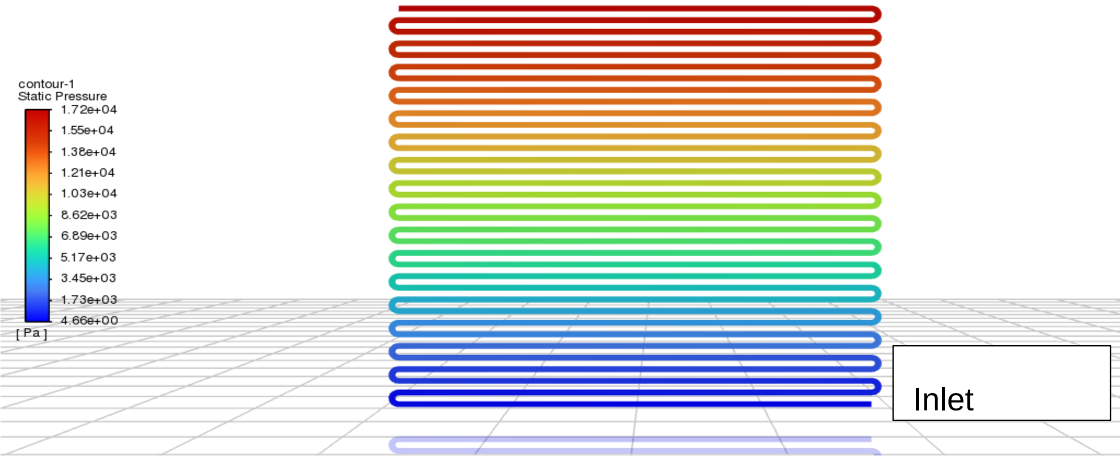
Static pressure 4.3-1 from literature (Velisala & Srinivasulu, 2018)



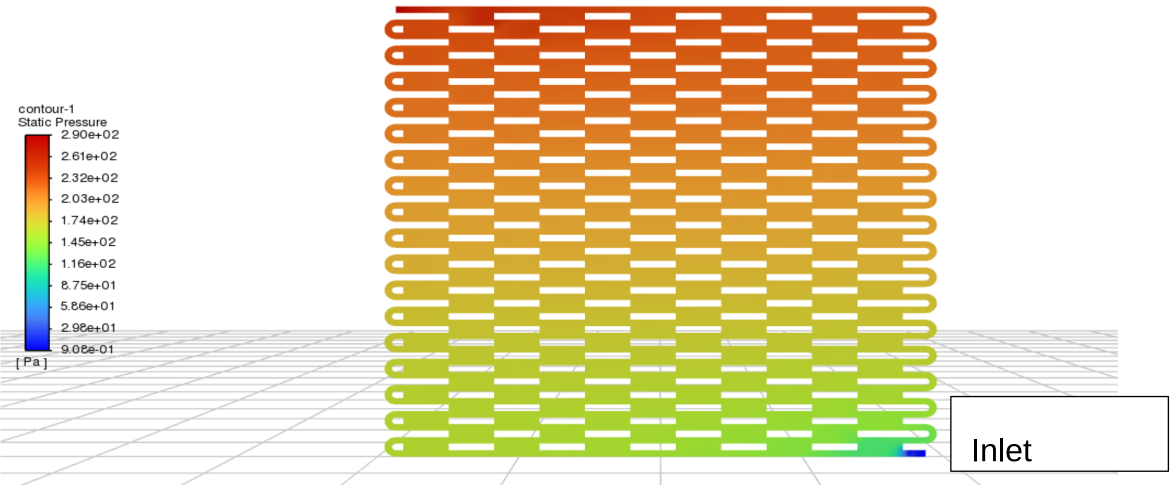
Static pressure 4.3-2 from model 1 (jayvassanth j, 2022)

The figure (Static pressure 4.3-1) and figure (Static pressure 4.3-2) represent the static pressure of the bipolar plate in a PEM fuel cell. The outlet pressure of the (Static pressure 4.3-1) is 17200pa and the outlet pressure of (Static pressure 4.3-2) is 33800pa. Both the models are operated with a current density of 0.5V.

4.3.8 Static pressure literature vs model 2



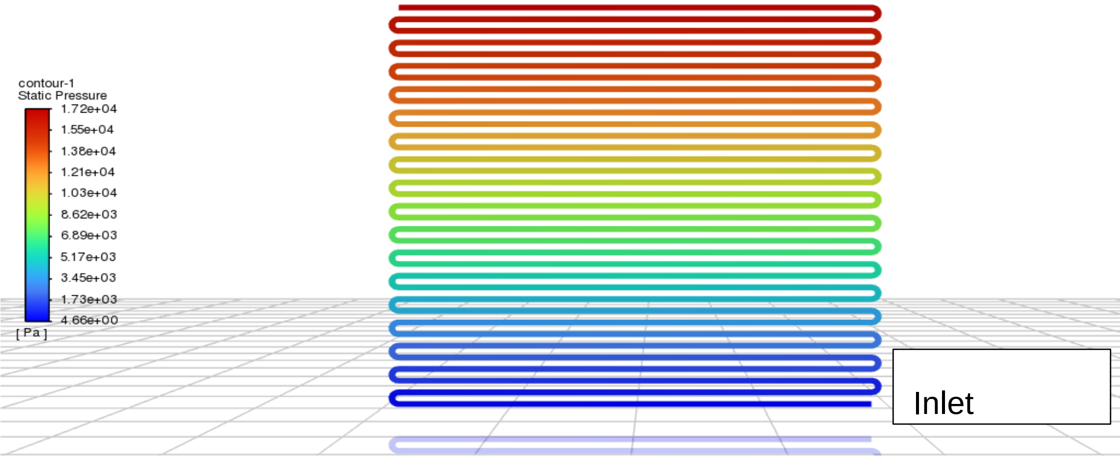
Static pressure 4.3-3 from literature (velisala & srinivasulu, 2018)



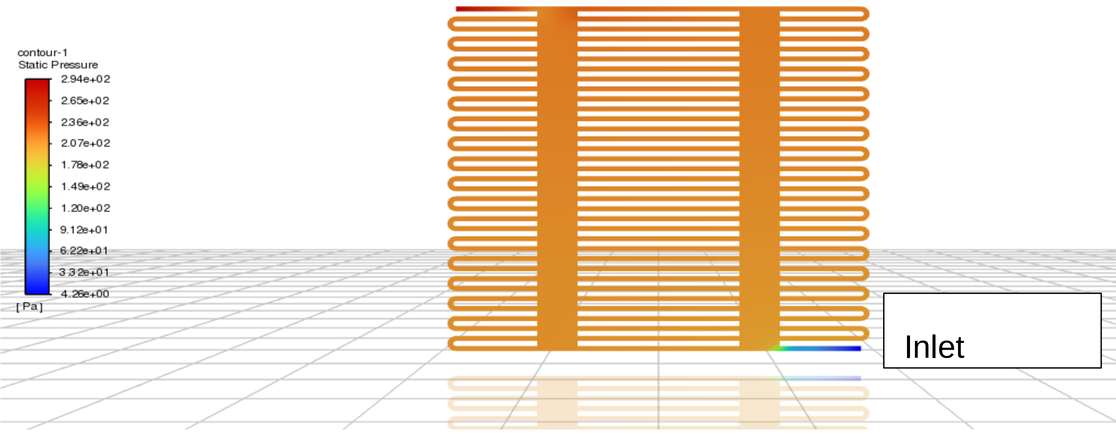
Static pressure 4.3-4 from model 2 (jayvassanth j, 2022)

The figure (Static pressure 4.3-3) and figure (Static pressure 4.3-4) represent the static pressure of the bipolar plate in a PEM fuel cell. The outlet pressure of the (Static pressure 4.3-3) is 17200pa and the outlet pressure of (Static pressure 4.3-4) is 29000pa. Both the models are operated with a current density of 0.5V.

4.3.9 Static pressure literature vs model 3



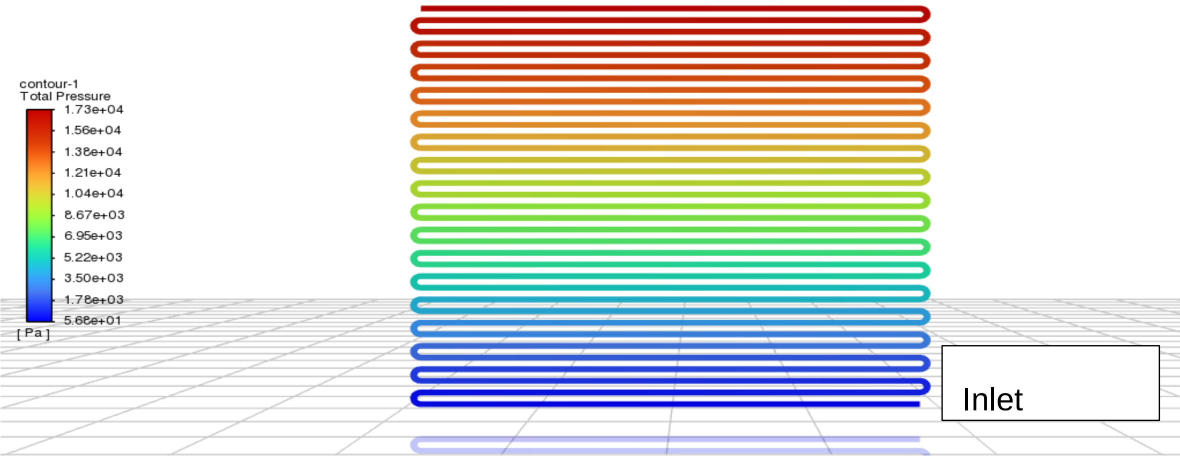
Static pressure 4.3-5 from literature (velisala & srinivasulu, 2018)



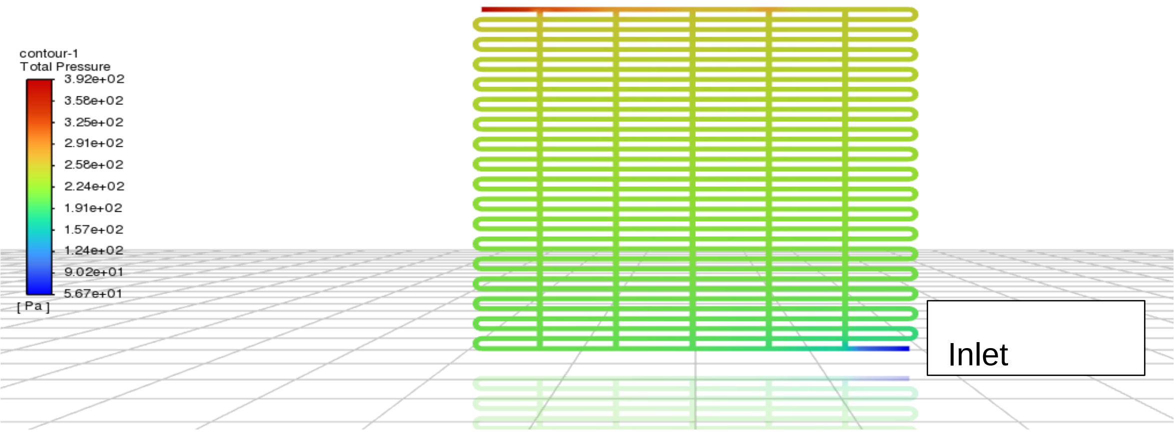
Static pressure 4.3-6 from model 3 (jayvassanth j, 2022)

The figure (Static pressure 4.3-5) and figure (Static pressure 4.3-6) represent the static pressure of the bipolar plate in a PEM fuel cell. The outlet pressure of the (Static pressure 4.3-5) is 17200pa and the outlet pressure of (Static pressure 4.3-6) is 29400pa. Both the models are operated with a current density of 0.5V.

4.3.10 Total pressure literature vs model 1



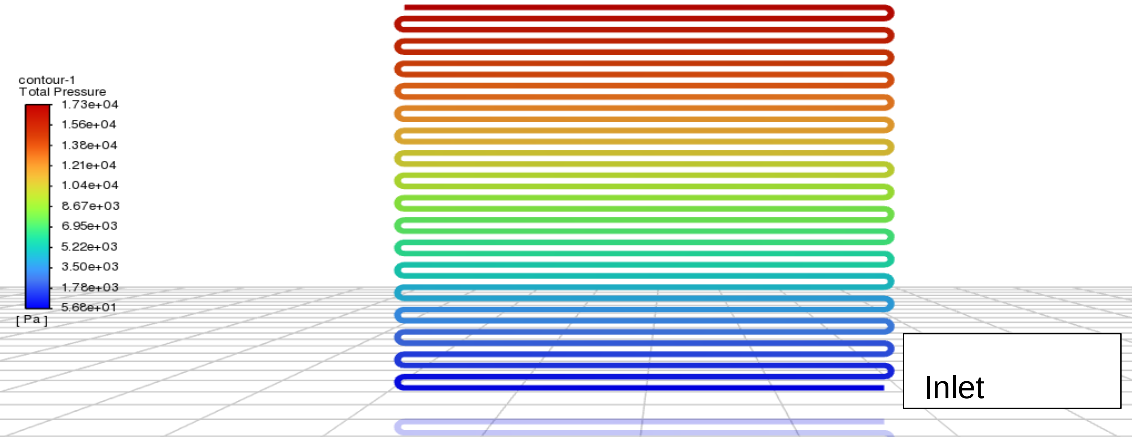
Total pressure 4.3-1 from literature (Velisala & Srinivasulu, 2018)



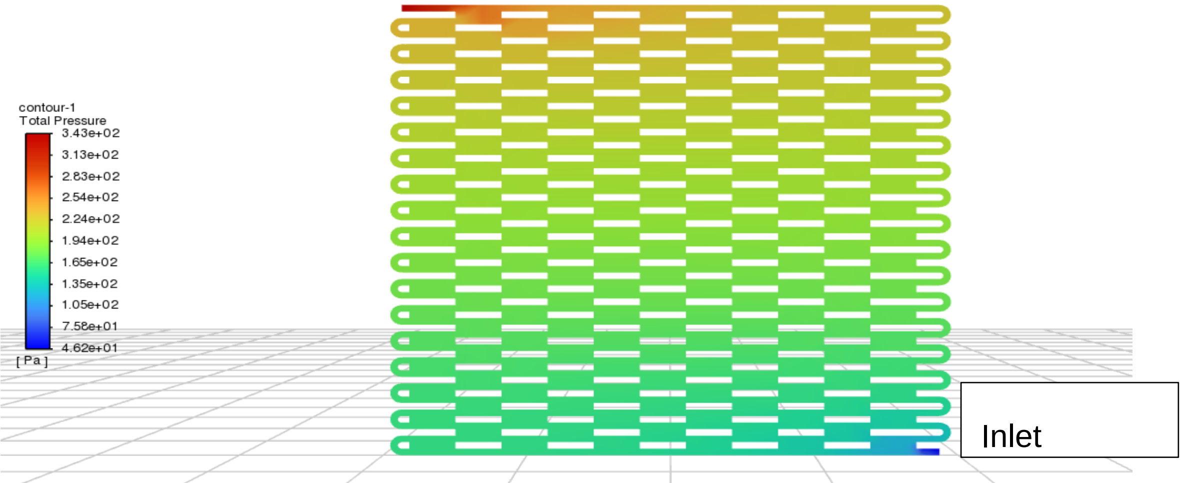
Total pressure 4.3-2 from model 1 (jayvassanth j, 2022)

The figure (Total pressure 4.3-1) and figure (Total pressure 4.3-2) represent the total pressure of the bipolar plate in a PEM fuel cell. The outlet pressure of the (Total pressure 4.3-1) is 17300pa and the outlet pressure of (Total pressure 4.3-2) is 39200pa. Both the models are operated with a current density of 0.5V.

4.3.11 Total pressure literature vs model 2



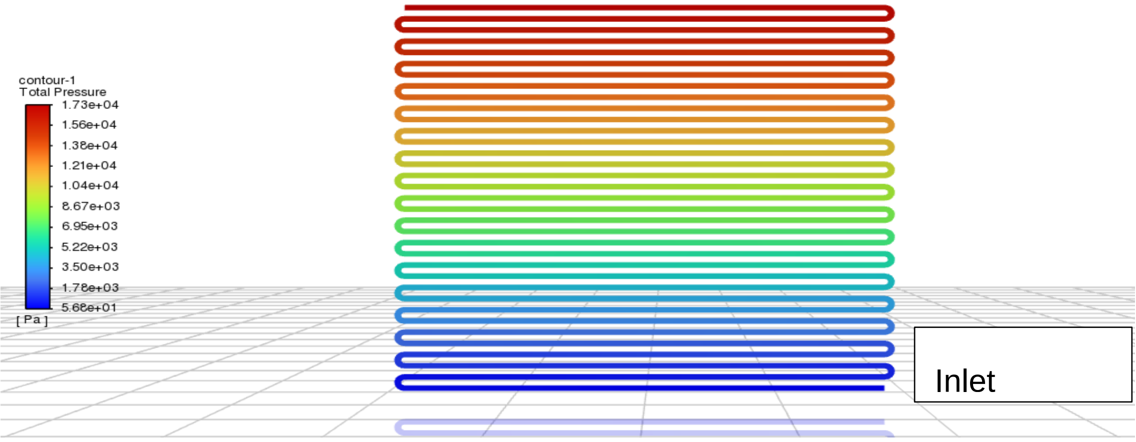
Total pressure 4.3-3 from literature (velisala & srinivasulu, 2018)



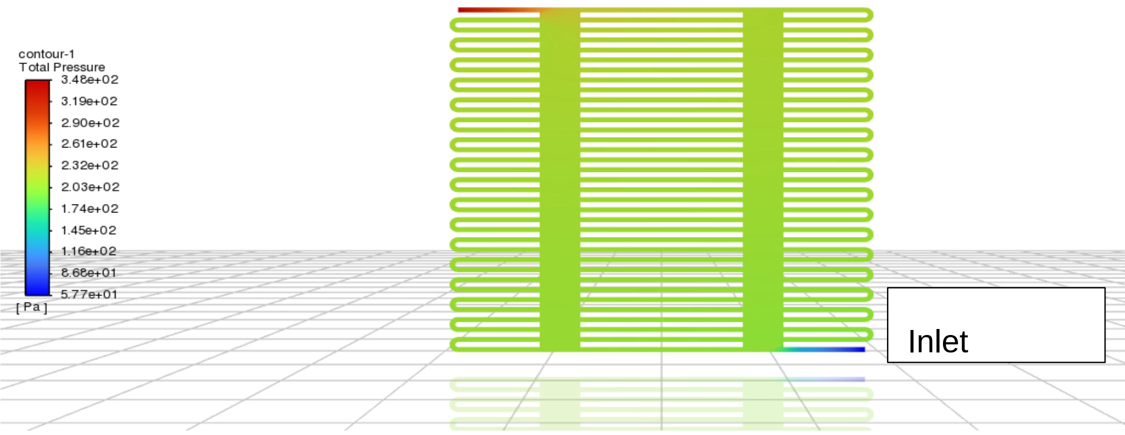
Total pressure 4.3-4 from model 2 (jayvassanth j, 2022)

The figure (Total pressure 4.3-3) and figure (Total pressure 4.3-4) represent the total pressure of the bipolar plate in a PEM fuel cell. The outlet pressure of the (Total pressure 4.3-3) is 17300pa and the outlet pressure of (Total pressure 4.3-4) is 34300pa. Both the models are operated with a current density of 0.5V.

4.3.12 Total pressure literature vs model 3



Total pressure 4.3- TOTAL_PRESSURE (velisala & srinivasulu, 2018)



Total pressure 4.3-5 from model 3 (jayvassanth j, 2022)

The figure (Total pressure 4.3- TOTAL_PRESSURE) and figure (Total pressure 4.3-5) represent the total pressure of the bipolar plate in a PEM fuel cell. The outlet pressure of the (Total pressure 4.3- TOTAL_PRESSURE) is 17300pa and the outlet pressure of (Total pressure 4.3-5) is 34800pa. Both the models are operated with a current density of 0.5V.

4.4 Discussion on results from the study and the literature

From the evaluation of results from the study and the literature on fuel cell pressure drop, it is clear that significant pressure drop can occur in a fuel cell system when the flow rate of reactant into the cell decreases. This is especially true for fuel cells operating at low flow rates. Furthermore, the results indicate that the maximum allowable pressure drop is a function of both flow rate and temperature of the cell. It is generally believed that as the operating temperature of a fuel cell increases, the overall resistance of the cell decreases, thereby reducing the pressure drop across the cell (Mortazavi, 2021).

In the tests conducted by DLR Aerospace, fuel cell pressure drop was observed to increase significantly as the flow rate of reactant gas into the cell decreased. The data obtained showed a maximum allowable pressure drop of about 4 atm at an operating flow rate of 1 SCCM for a test cell operating at a temperature of 120C. At this flow rate and at this temperature, there were significant decreases in the power density and efficiency that resulted from these pressure drops (Wilk & Węcel, 2019).

However, when operating the fuel cell at an operating pressure of 1.5 atm, a maximum allowable pressure drop of only 2 atm was observed at the same operating flow rate and temperature as the previous case. This indicates that operating a fuel cell at a higher pressure than necessary can improve the system performance by reducing the maximum allowable pressure drop that is experienced in the cell (Liu et al., 2015).

A fuel cell operating at 1.5 atm and 120C demonstrated a power density of 0.7 W/cm2 while one operating at 1.05 atm and 120C had a power density of 0.9 W/cm2. This indicates that a higher operating pressure can reduce the maximum allowable pressure drop, leading to increased efficiency and power production in the cell (Ramalingam & Indulkar, 2017).

A fuel cell operating at 1.05 atm and 90% relative humidity demonstrated a maximum allowable pressure drop of only 1 atm. This illustrates the importance of carefully controlling humidity levels in fuel cell systems in order to reduce the maximum allowable pressure drop and improve overall system performance (Solomon et al., 2023).

The maximum allowable pressure drop observed in the fuel cell tests is a function of both temperature and flow rate. However, the humidity of the membrane was found to be a more significant factor in determining the maximum allowable pressure drop in the fuel cell system. Therefore, efforts should be made to ensure that the temperature and humidity levels in the fuel cell environment are tightly controlled in order to improve the overall system performance (Qi et al., 2020).

Power density and max allowed pressure drop will decrease if the flow rates decrease or the temperature increases. Therefore, reducing the relative humidity of the fuel cell environment will increase the power density of the fuel cell system. This will help to overcome the lower power densities observed when the flow rates or temperatures were reduced in the experiments (Nguyen et al., 2021).

The reduction of the thermal losses, power density and efficiency by the higher pressure of the fuel cell was attributed to the reduction in the maximum allowable pressure drop that was experienced in the fuel cell tests. The ASCI flow field was found to be the most efficient flow field among the four flow field combinations tested. This is due to the small size of the channels and the narrowness of the channels which allowed for high velocity and low resistance flow through the channel walls. This resulted in the lowest maximum allowable pressure drop among the flow field configurations tested (Ruan, 2014b).

The PEM fuel cells with metal foam flow field also operated at a safe temperature range (55°C-90°C) while the conventional flow field is likely to exceed this temperature range. This suggests that metal foam flow field can be used as a reliable design platform for compact, high temperature operation in PEM fuel cells(Heidary et al., 2016).

Max allowable pressure drop is the pressure difference between the inlet and outlet of a system. Pressure drop calculations are dependent on the flow rate of the system and temperature differences between inlet and outlet of the system.

The metal foam flow field was found to have the lowest maximum allowable pressure drop among the flow field configurations tested, which indicates that it was the most reliable flow field configuration for PEM fuel cells under high pressure conditions (Mortazavi, 2021).

4.4.1 Pressure in bipolar plate of the novel model

The results from the literature were checked using Ansys Fluent, and the software configuration was PISO, with first order outwind favoured owing to the geometry. The Laminar model is used for validation since the Reynold's number is smaller than the requirement for a turbulence model. According to the literature, hexahedral mesh has been used.

To determine the flow in a channel, continuity equation is used,

$$\rho (u \cdot \nabla) u + \nabla p - \nabla \cdot \eta \nabla u + (\nabla u) T = 0$$

$$\nabla \cdot (\rho . u) = 0$$

Equation 2. CONTINUITY EQUATION

Where,

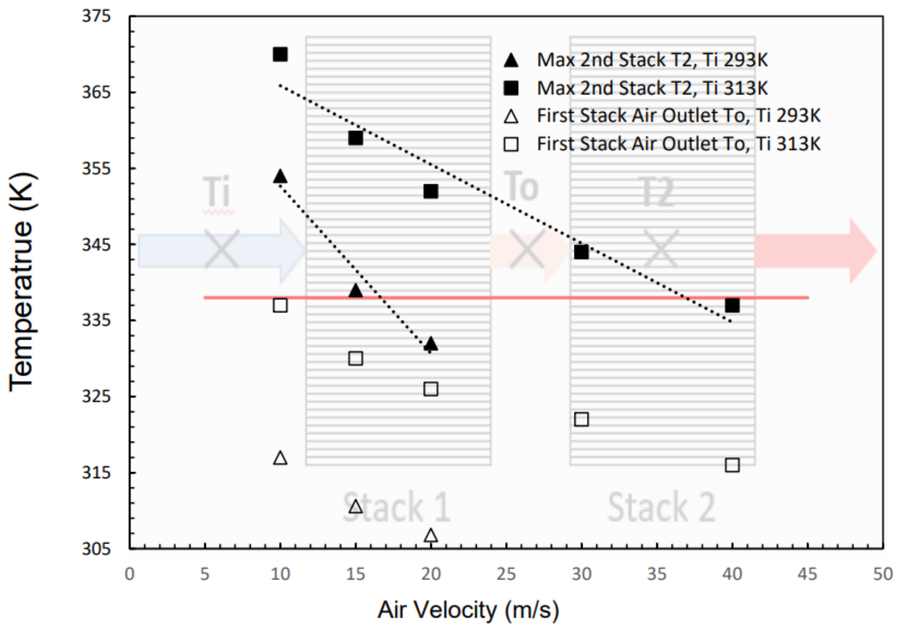
ρ is the Density of the Gas,

T is the Temperature of the fluid/gas,

U is the velocity at inlet and

V is the velocity at outlet

4.4.1.1 Relationship between air velocity and temperature



AIR VELOCITY VS TEMPERATURE (Miller, 2017)

The above figure represents the relationship between the velocity of air and temperature and from that it is understood that higher the velocity the temperature gets lower and lower.

4.4.2 Prime problem in the literature paper model

The geometries described in the literature perform well in all parts of design terminology and meshing with the hexahedral structure is usually efficient into getting accurate numerical results However, when it comes to the porosity in the bi-polar plate, the material utilised creates a lot of frictional loss, which causes clogging inside the flow channels. This does not stop with obstructing the flow; as a consequence of the clog, the velocity decreases; as a result of the decrease in velocity, the optimal temperature necessary for the system lowers completely, preventing the system to work as intended. The considerable pressure loss has been discovered using the ANSYS Fluent proton exchange membrane fuel cell model, which includes all of the fictitious fuel cell setup. The mass flow rate is the next major issue affecting the system's efficiency. When the velocity is disturbed, the flow of gases and air slows down, dehydrating the entire system fast, which might potentially be the main reason of etching of the walls of the cell (Velisala & Srinivasulu, 2018).

4.4.3 Pressure in models developed by the study

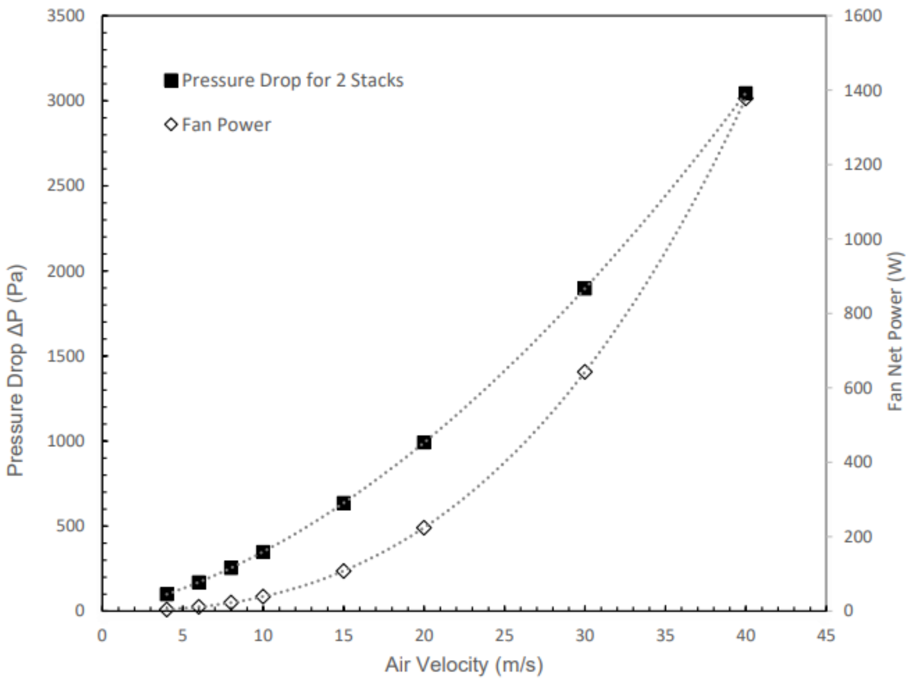
The pressure in the model developed in this research varies far more than the pressure described in the literature, owing to the poor porosity of the material used in the bipolar plate and the addition of a metal foam, which causes a complete variation in flow. As a result, it not only fills the blank region as needed/intended, it also naturally hydrates itself due to the way it is created.

The Static pressure 4.3-2 from model 1 bipolar plate features a single serpentine channel with a rectangular junction flow channel across it. This brings the pressure to a condition of equilibrium and compressing the gas in the centre of the channel adds pressure, ensuring that the flow is never blocked and continues to flow with a laminar flow.

The Static pressure 4.3-4 from model 2 bipolar plate is a one-of-a-kind combination of a pin slot and a serpentine flow channel. When compared to the literature, this model is found to be the best because the flow is not disrupted as the gas goes through the inlet and engages with the pin slot channel as it touches the slot the flow is deviated towards the serpentine so what happens is a lot of deviation resulting in a smooth laminar flow towards the outlet causing no hinderance and no drop in pressure.

The validated Static pressure 4.3-6 from model 3 bipolar plate design also features a unique shape with a single serpentine channel and two huge groves with rectangular cross-section. Because the design favours the optimal state for the fuel cell, it solves the pressure drop problem. Because of the narrowness of the serpentine channel, the gas enters the inlet at a compressed pressure and flows for some distance before meeting the rectangular grove, which acts like an overflowing well, accumulating some pressure inside the grove and releasing whenever a situation arises to initiate a pressure drop, the external pressure enters and fixes the required pressure instantaneously.

4.4.3.1 Relationship between pressure drop, fan power, air velocity



RELATIONSHIP BETWEEN PRESSURE DROP, FAN POWER, AIR VELOCITY (Miller, 2017)

The progression of the stack system's pressure drop (2 stacks in series) and the net fan power needed, with the latter stated as the relationship provided by (Miller, 2017).

4.5 Various pressure across different models

Quantity	Literature Model	Model 1	Model 2	Model 3
Absolute Pressure (Pa)	120000	102000	102000	102000
Dynamic Pressure (Pa)	190	562	635	670
Pressure Co-Efficient (Pa)	28100	55100	47300	48000
Static Pressure (Pa)	17200	33800	29000	29400
Total Pressure (Pa)	17300	39200	34300	34800

TABLE 4.1: pressure comparison of models

Various quantities of pressure varying between all the models of both in the literature and three different models designed in this research. Even though the absolute pressure in the literature paper is slightly higher the other models developed here overcome in every other quantity. The dynamic pressure in the literature model is much lower even with a very good absolute pressure, it failed mainly because of the frictional losses that happened inside the walls of the bipolar plate. When looking into the pressure coefficient the Static pressure 4.3-6 from model 3 displays a drastic difference which is very good for the development stage, it indeed has a very good electrical output.

The static pressure is calculated when there is no movement of particles inside the flow channel, even at stationary state the other three models displays a very good progress because the design is designed in order to retain the fluid for some time so that the dehydration never happens inside the flow channel. And finally comes the total pressure this is the main criteria to decide he best model that can be used in the real-time applications. As the pressure is much higher in the other models it shows that the models designed in this research shows better output rather than one described in the literature.

5 CHAPTER: CONCLUSION

The primary purpose of this research was to examine the pressure drop of a certain bipolar plate design from the literature and uncover any defects in that model. In addition, the study attempted to create three new types of bipolar plates with low pressure drop.

The results of the three unique bipolar plate designs produced throughout the investigation were provided earlier in the discussion. When compared to the model from the literature, these designs demonstrated considerable improvements in minimising pressure drop issues. As a result, fuel cells outfitted with the new bipolar plate designs demonstrated increased electrical output and current density.

The novel bipolar plate geometries provided a more efficient channel layout and enhanced flow distribution, which contributed to a lower pressure drop. This, in turn, allowed for more efficient and uniform reactant dispersion, reducing localised effects that cause pressure losses. As a consequence, the fuel cells produced more electrical output and current density, resulting in improved performance and overall efficiency.

The comparison of the three novel bipolar plate designs' results with the literature model highlighted the importance of improved bipolar plate design in fuel cell efficiency. The proposed designs demonstrated their potential to pave the way for more efficient and reliable PEM fuel cells by addressing the pressure drop challenges observed in the existing model, making them suitable for a wide range of applications, including on-road transportation, stationary power generation, and backup power systems.

These innovative bipolar plate designs' success has far-reaching ramifications for the future of PEM fuel cells. The enhanced bipolar plate designs might possibly serve as a basis for subsequent breakthroughs in fuel cell technology as research and development in this sector continues. Continuous innovation will surely boost fuel cell commercial viability and speed their incorporation into many sectors and energy systems, contributing to a greener and more sustainable energy environment.

Finally, the in-depth investigation has offered useful insights into the numerical modelling and optimisation of bipolar plates in proton exchange membrane (PEM) fuel cells. The investigation of different elements of PEM fuel cells, such as their history, relevance, advantages, problems, and prospective solutions, as well as the emphasis on bipolar plate design, has given insight on crucial parameters impacting fuel cell efficiency.

Going ahead, the prospective uses of PEM fuel cells remain extensive, ranging from on-road vehicles and stationary power generation to emergency backup power. Furthermore, the combination of fuel cells with renewable energy sources and battery storage technologies is a possible route for long-term energy solutions.

Fuel cell technology, with its numerous uses and ongoing improvements, is at the forefront of crafting a more efficient and environmentally friendly energy landscape as the search for greener and more sustainable energy solutions continues. The entire potential of PEM fuel cells may be realised via continued research and development, propelling humanity towards a brighter and more sustainable future(Tomida et al., 2021).

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