

Technical review notice

Educational PEM Fuel Cell Performance

Abdul Barek | 8 October 2026

Please read this notice before the original academic material.

The following pages preserve the original dissertation extract or presentation. This notice supersedes their experimental efficiency interpretations and direct simulation-validation claims. It does not alter the original measurements or establish corrected experimental results.

Experimental efficiency

The percentages labelled as efficiency in dissertation Table 4.7 and the related presentation do not substantiate hydrogen-to-electricity conversion efficiency. Power-percentage pairs imply a reference near 1.24-1.25 W, but its physical meaning is undocumented. Values above 100% cannot be explained as demonstrated fuel-energy conversion exceeding the energy input. These percentages and their causal explanations must not be treated as verified efficiency results.

Power, timing and measurement boundaries

Several reported powers differ from the products of the tabulated voltage and current. Original logs are needed to confirm simultaneous readings, units and the electrical measurement boundary. Entries such as 3.40 in the runtime table cannot yet be resolved as decimal minutes or minutes-and-seconds. Missing readings must remain missing rather than being assumed to be measured zeros.

Scope of the supported conclusions

The educational bench experiments and automotive-scale Simscape analysis are separate studies. The model was not directly validated against the educational stack. The records support a descriptive discussion of operating behaviour; they do not establish experimental efficiency, durability or the causes of performance variation.

Before journal submission

Recover the original logs, reconcile voltage-current-power calculations, confirm timing notation and cell/stack boundaries, and measure hydrogen consumption matched to electrical energy output. Specify HHV or LHV consistently. No replacement efficiency is claimed until these inputs are verified. The manuscript remains in preparation.

MSc Project Report
School of Physics, Engineering and Computer Science
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**Performance Analysis of an Educational Proton Exchange
Membrane Fuel Cell Stack.**

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Date
27/04/2026

ABSTRACT

This dissertation is concerned with the design and analysis of a Reversible Educational Proton Exchange Membrane (PEM) Fuel Cell to implement in education application. This research started with the investigation of various fuel cell technologies, and then three early design concepts were developed. The most appropriate design was chosen and developed after consideration. The PEM fuel cell was developed as a 3D CAD model to assist in the design and visualize before real implementation. The prototype was then assembled and tested experimentally to test voltage, current, power output, hydrogen production and efficiency. Findings revealed an average hydrogen filling time of 2.30 minutes and a discharge run time of 3.28 minutes. Also, a MATLAB/Simulink model was constructed to model system performance, displaying similar trends to experimentation. In general, the system was effective in illustrating the concepts of hydrogen energy.

Keywords: Proton Exchange Membrane, 3D Cad Model, Fuel Cell, Voltage, Experimental test.

1. INTRODUCTION

Global energy demand has been rising at an unprecedented rate on account of population growth, industrial growth and technological evolution. This increasing demand has been predominantly satisfied by burning of fossil fuels, which has led to increased emissions of greenhouse gas to the environment and accelerated global warming(Gao *et al.*, 2009). These challenges have led to an increased demand for cleaner and more efficient and environmentally sustainable energy conversion technologies.

In response, large efforts have been made to research on alternative and renewable energy sources (wind, solar, hydrogen-based systems). Despite the great progress, aspects relating to the performance, efficiency and dynamic behaviour of these technologies are not yet sufficiently understood(Aljaidi *et al.*, 2025). This is especially true for complex energy conversion systems with strong coupling between electrochemical, thermal and fluid dynamic processes. The weak availability of detailed modelling approaches - in particular, in areas of thermal and fluid behaviour, and system-level control - identifies the need for further investigation(Moreira and Da Silva, 2009).

Fuel cells are a promising solution in the array of clean energy technologies. Unlike traditional combustion-based power systems, fuel cells can convert the chemical energy to electrical energy directly by electrochemical reaction processes, and they have high efficiency and low emission(Menesy *et al.*, 2019). Among the different types of fuel cells, Proton Exchange Membrane Fuel Cells (PEMFCs) have attracted great attention as they have a low operating temperature, fast startup capability, high power density, and suitability for use in transportation applications(Redhwi, Almalki and Radhwi, 2026).

Although the conceptual design of PEM fuel cells is relatively simple, the actual function of these fuel cells is highly complex, multidisciplinary. The system consists of coupled phenomena such as mass transport due to diffusion and convection, electrochemical reactions, heat transfer, thermodynamics and electrical conduction(Outeiro *et al.*, 2007). These interactions lead to various losses that impact the efficiency and performance and thus accurate modelling and analysis is essential. Consequently, this thesis is focused on the development and performance analysis of a PEM fuel cell stack model which is dynamic in nature, with special focus on the case of automotive-scale applications(Yalcinoz and Alam, 2008).

1.1 Project background

Fuel cells are electrochemical devices for conversion of energy to electricity because of the reaction of a fuel, most commonly hydrogen, with an oxidant such as oxygen from the air and without direct combustion. If the reactants are continuously fed into the cell, a fuel cell can produce electrical power, which is basically different from batteries, which are limited by the stored energy capacity(Martoccia *et al.*, 2025). This continuous operation principle is shown conceptually in Figure 1.1 where fuel and oxidant are seen as part of an input, while electricity and heat are produced as part of an output(Martoccia *et al.*, 2025).

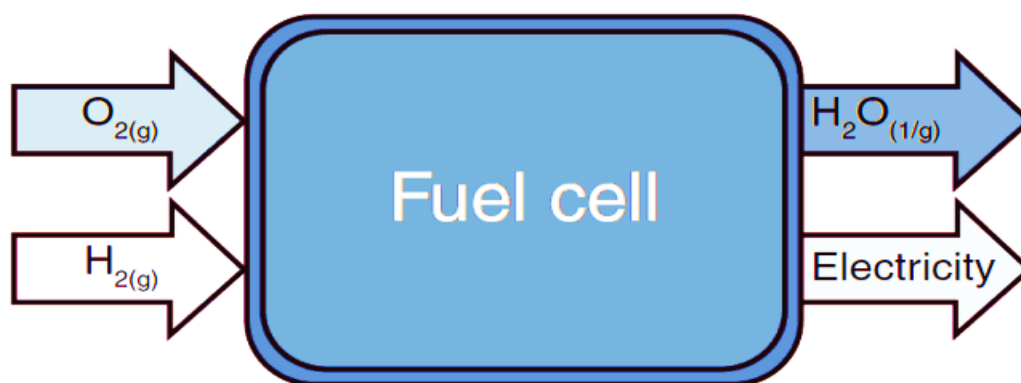


Figure 1. 1 Fuel Cell Source: Martoccia *et al.*, 2025

Fuel cell systems have found wide applications across industries such as stationary power generation, residential energy generation, transportation, aerospace applications and power generation for remote and/or military installations. Among the various fuel cell technologies, PEM fuel cells have proven to be one of the most commercially feasible fuel cell technologies(Haghighi and Sharifhassan, 2016). For example, on their practical relevance, there are real-world implementations of them in the automotive industry, with the Toyota Mirai in commercial production since 2014 with an output power of around 114 kW. This vehicle has been known for its high fuel efficiency and low environmental impact, which strengthens the possibility of PEMFCs for use in light duty vehicles(Kanouni and Laib, 2024).

A typical PEM fuel cell has some major components, as shown in Figure 1.2, which is largely constituted by the proton exchange membrane, the catalyst layers, the gas diffusion layers, the bipolar plates, and the gaskets. Many of these elements together constitute the Membrane Electrode Assembly (MEA) which is the heart of the fuel cell system. The MEA offers the required environment for electrochemical reactions through the conduction of protons, electron transport and reactant diffusion. According

to the arrangement, MEAs can be fabricated in three-layer, five-layer or seven-layer structure as illustrated in Figure 1.3(Kazmi, 2011).

The proton exchange membrane-commonly manufactured from materials like Nafion-allows only positively charged protons through (and no electrons), so that the electrons will be forced to flow through an external circuit to produce useful electrical power. Adjacent the membrane are the gas diffusion layers, which serve many functions; to transport the reactants to the catalyst layers, remove the water product, provide mechanical support, and provide electron conduction. These layers are normally made of porous carbon-based materials(Aroge, 2018).

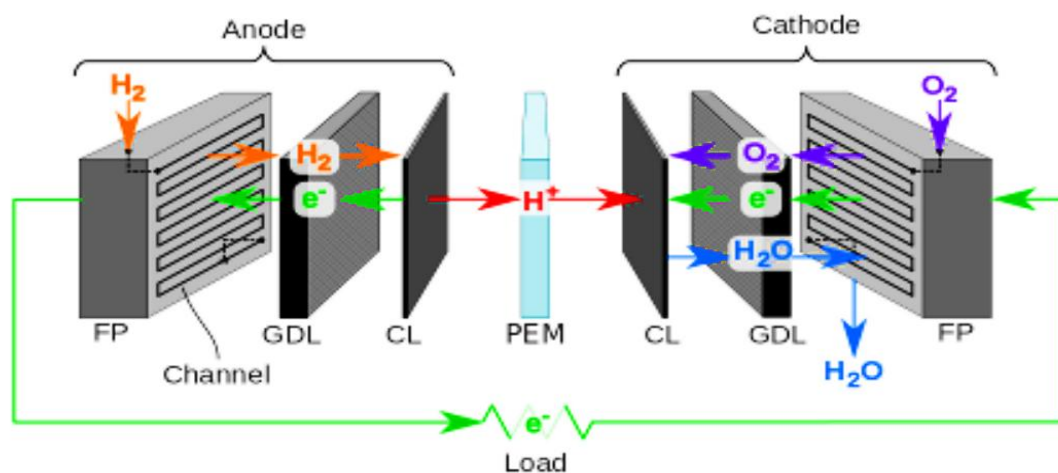


Figure 1. 2 Major Components of Fuel cell Source: Aroge, 2018

Bipolar plates, which are located between the individual cells in a stack, are important for the current collection, distribution of reactants, heat removal, and structural integrity. They also avoid the leakage of the reactants and enable the connection of multiple cells in series to create the desired voltage and power output, as shown in Figure 1.4. The last essential part is the gasket which ensures proper sealing and maintains compression throughout the stack and prevents crossover and short-circuiting of gas(Berg *et al.*, 2004).

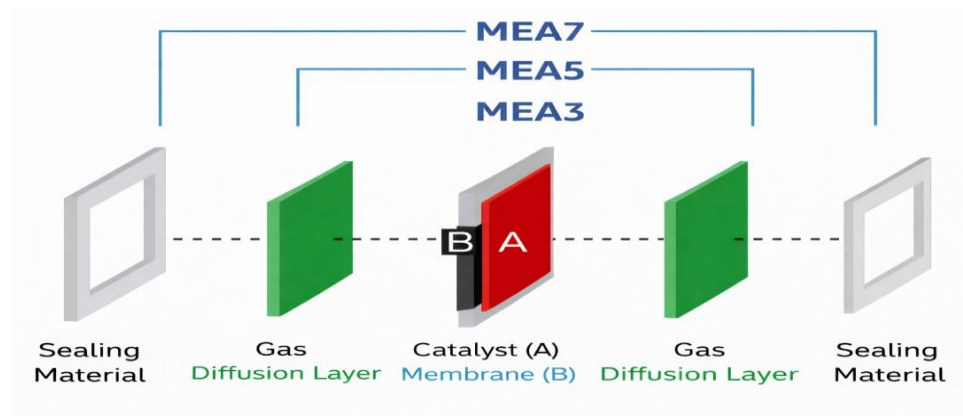


Figure 1. 3 MEA Types Source: Berg *et al.*, 2004

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During operation hydrogen is introduced to the anode and oxygen to the cathode where electrochemical reactions take place as explained in Equations (1.1) - (1.3) and shown in Figure 1.4. Although the theoretical open-circuit voltage of a single PEM fuel cell is about 1.2 V, the actual operating voltage is much smaller - usually about 0.7 V, due to activation, ohmic and concentration losses. To have voltage and power levels like what I would have in automotive applications, many cells are connected in series to form a fuel cell stack (Fly, 2015).

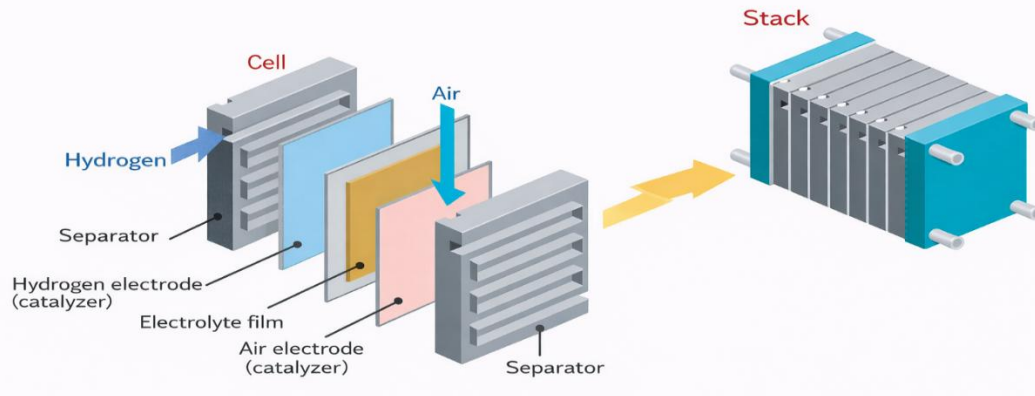


Figure 1. 4 Stack of Fuel cell Source: Fly, 2015

Given these complexities and factors that affect system performance, dynamic modelling is of prime importance to understand the system behaviour under varying operating conditions (Alrewq and Albarbar, 2016). This project is therefore inspired by the necessity to build a detailed, physics-based PEM fuel cell stack model with the capability to include electrochemical, thermal and fluid dynamics effects and which can be used to analyse its performance and enable design optimization for automotive applications (Giacoppo, Hovland and Barbera, 2019):

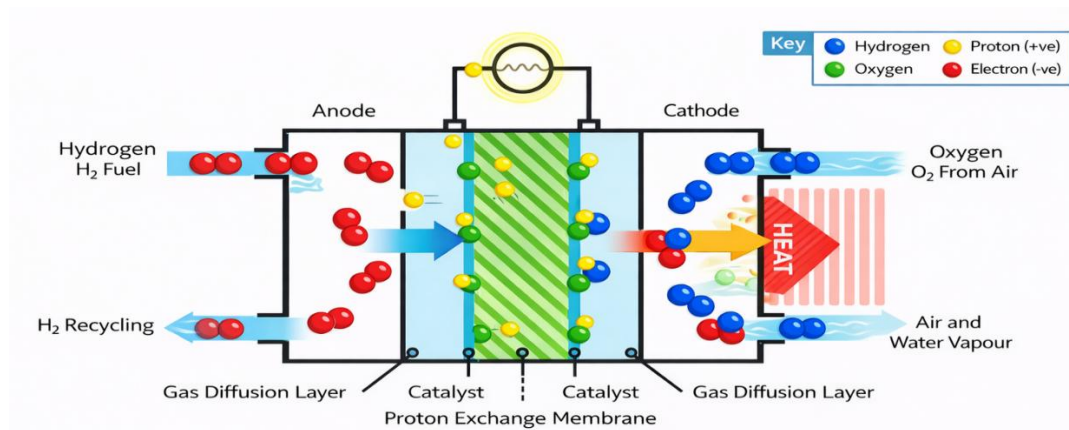


Figure 1: Fuel Cell Electrochemical Reaction

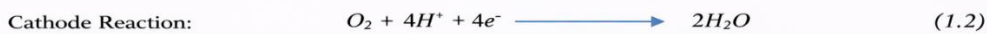


Figure 1. 5 Electrochemical Process of Fuel cell Source: Albarbar, 2016

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1.2 *Research Problem*

Despite significant progress in Proton Exchange Membrane (PEM) fuel cell technology, performance prediction and optimization at the automotive stack level is challenging because of the strong coupling between electrochemical, thermal and reactant flow phenomena. Many existing PEM fuel cell models are based mainly on steady-state electrical behaviour and often simplify or ignore thermal dynamics and transient effects in the power cell which are critical to the efficiency, durability and power production under realistic driving conditions. In automotive-scale applications, fast-changing load and non-uniform temperature distribution and variants of operating parameters, like pressure and humidity, can severely degrade the performance of the system if not handled properly. Furthermore, there is a lack of availability of validated, scalable and physics-based dynamic models that can represent high-power PEM fuel cell stacks and still be suitable to be used at system level for simulation and control design. This research addresses these gaps by creating a dynamic PEM fuel cell stack model in the environment used for modelling the stack, namely in the MATLAB Simscape software, through a combination of electrochemical, thermal and flow sub-models, which will allow for a thorough performance analysis and validation for automotive applications.

1.3 *Aim and objectives*

The goal of the dissertation is to design, develop and to analyse a Reversible Educational kit of Proton Exchange Membrane (PEM) Fuel Cell system and to test the performance of this system both by experimental testing and MATLAB to test performance in educational and laboratory scale applications. The research concentrates on the operational behaviour, efficiency as well as performance features of the fuel cell under both the electrolyser and fuel cell operation.

Specific objectives of this research are to:

1. Design and create a 3D CAD model of the PEM fuel cell, fabricate and assemble a working reversible educational prototype.
2. Experimentally assess the performance of the fuel cell by measuring the important parameters like voltage, current, power output, hydrogen production, and efficiency under varying operating conditions.
3. Determine the steady-state behaviour of the system, such as power output, efficiency trends, and hydrogen utilisation.
4. Create a MATLAB/Simulink model which will simulate the behaviour of the fuel cell and model the experimental conditions.

5. Compare and confirm the simulation results with experimental data to evaluate the accuracy and determine variations in performance.

1.4 *Significance of Study*

This experiment is a contribution to the study and creation of a Reversible Educational Proton Exchange Membrane (PEM) Fuel Cell, with the aim of using it as a teaching and experimental aid. Contrary to the automotive scale systems, the present research focuses on a low power and small-scale prototype that illustrates the basic principles of hydrogen production, storage and energy conversion. Combining experimental testing with MATLAB modelling offers a holistic method in the study of the system behaviour both in real and simulated conditions. The paper identifies how operational issues like hydrogen supply, load changes, and system architecture impact performance, efficiency, and stability. This work can provide useful information to students, researchers, and educators by helping them fill the gap between theoretical modelling and practical implementation. Also, the created prototype and simulation model can be used as a baseline of further improvements and facilitate the development of sustainable and clean energy technologies at educational institutions.

1.5 *Ethical considerations*

This study has been carried out in compliance with established ethics in academic and engineering research. The project entails the design, modelling and testing of a small size Reversible Educational PEM Fuel Cell, and subject to no human, animal, or secret industrial information. All information, even theoretical concepts, models and reference materials have been credited to prevent occurrence of plagiarism to maintain academic integrity. The safety of the experimental procedures was ensured using an educational fuel cell kit, where handling of both hydrogen and electrical elements was done carefully. To encourage transparency and reproducibility, all the modelling assumptions, limitations and results have been presented. Also, this study can contribute to the implementation of ethical engineering because it will advance clean and sustainable energy technologies, which will enhance the impact on the environment and the understanding of hydrogen-energy systems.

2. LITERATURE REVIEW

This chapter presents a comprehensive review of the existing research in respect of Proton Exchange Membrane (PEM) fuel cell modelling, performance analysis, and system-level simulation with a particular emphasis on the automotive scale applications. The present review explores analytical, empirical and physics-based modelling approaches published in the literature in terms of their capabilities and limitations to capture electrochemical, thermal and mass transport phenomena. Special attention is paid to dynamic and transient models to deal with the real-world operating conditions (variations in the load and issues related to thermal management). Studies using numerical tools like MATLAB and Simscape are discussed to determine the relevance of system level simulation framework. In addition, published experimental data and manufacturer specifications are examined as benchmarks for the validation of the model. By identifying the gaps of current modelling practices especially the lack of interaction between thermal-fluid dynamics and dynamic behaviour, this chapter provides both the motivation and groundwork for the modelling approach taken in this thesis.

2.1 PEM Fuel Cell Systems- Reversible Educational

This dissertation is based on the critical foundation of literature review which offers a thorough and critical insight into the hydrogen fuel cell technologies, specifically reversible educational Proton Exchange Membrane (PEM) fuel cells. It combines the results of academic research, technical research and experimentation to aid in the modelling, design, and testing involved in this project. The review is concerned with the electrochemical behaviour, system configuration, optimisation of efficiency, and operational issues in small-scale educational fuel cell systems (Barbier, 2013; O'Hayre et al., 2016).

PEM fuel cells have been widely researched as a sustainable energy source, as one of the most appropriate technologies because of their low operating temperature, fast start-up, and high efficiency. Basic research papers by Barbier (2013) and Hayre et al. (2016) are clear descriptions of how electrochemical reactions take place, how proton exchange works, and how the system thermodynamics works. Other essential issues mentioned in these works include water management, thermal control, and current density optimisation that directly impact fuel cell workings and longevity (Barbier, 2013; O'Hayre et al., 2016).

PEM fuel cells that can be used in both electrolysis and fuel cell mode are known as reversible, which can be of great benefit in storage and utilisation of energy. Zhou et al. (2018) revealed that dual-mode operation enhances the overall system efficiency and flexibility. Most research available is however restricted to single stack configurations with little emphasis on multi-stack systems particularly in the field of education. This is where a research gap exists that this dissertation will fill with the help of experimental validation and performance analysis of a small-scale reversible PEM system (Zhou et al., 2018).

Multi-stack configurations of PEM fuel cells have been investigated to increase the output performance. Back-to-back systems in series give higher voltage output, whereas in parallel, current stability is better. According to Sundaresan et al. (2020), series arrangements are better in use where the voltage needed is high, and parallel systems are more reliable in delivering the current. On the same note, Chen et al. (2019) examined multi-stack PEM systems and found out inefficiencies between electrolysis and discharge modes, especially with a lack of water balance and unable to save energy. These results underline the importance of controlled experimental research, which is conducted in this project (Sundaresan et al., 2020; Chen et al., 2019).



Figure 2. 1 Multi Reversible Fuel Cell Stack. (Sundaresan et al. (2020))

The electrolysis of hydrogen is subject to the Faraday laws according to which the production of hydrogen depends directly on the input of electricity. Liu et al. (2021) highlighted the importance of having an accurate current control to maximise the

efficiency of hydrogen production. However, most experimental systems do not satisfy appropriate water balance, which results in either dehydration or flooding of the membrane which significantly affects the performance of the systems. Most fuel cell education kits do not have sophisticated control systems, which restrict the effectiveness and reliability of these kits (Liu et al., 2021).

One of the most important issues with reversible PEM systems is water management. Mok et al. (2020) have discovered that the main reasons of efficiency loss include membrane dehydration and flooding. The presence of a dehydrated membrane diminishes the conductivity of protons and excess water prevents the passage of gases by closing diffusion channels, raising internal resistance. To overcome these problems, the past research has suggested better membrane material like Nafion, controlled hydration, and water recirculation systems. Regardless of these achievements, most of the educational systems fail to control water well, which is the focus of this project because it is carefully monitored and regulated by the water input (Mok et al., 2020).

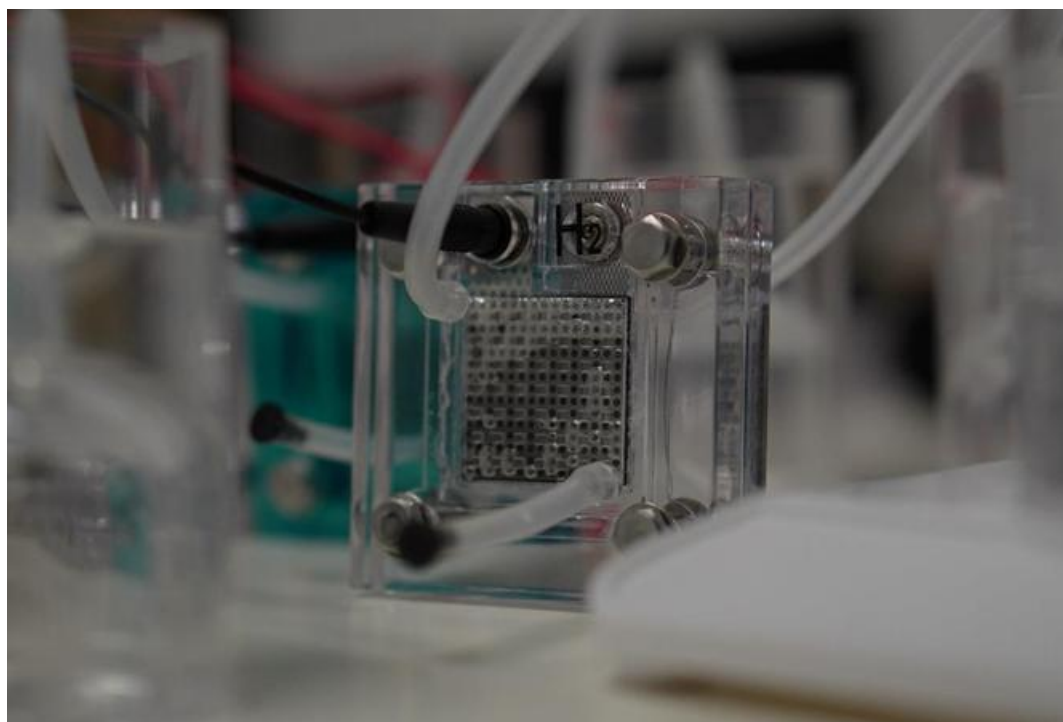


Figure 2. 2 Reversible PEM System Water Management. (Mok et al., 2020)

PEM fuel cells are commonly evaluated by measuring their performance in terms of voltage, current, power output and efficiency. Singh et al. (2022) have shown that the electrical parameters optimisation can greatly enhance hydrogen use and the efficiency of the system in general. Also, graphical analysis techniques like voltage-time and efficiency-time curves can be used to give useful information about the behaviour and degradation of a system. In educational systems, stable operating environments are crucial in the proper data collection and analysis (Singh et al., 2022).

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To achieve stability of experimental measurements, Chen et al. (2020) emphasized the need to employ resistive loads to avoid voltage spikes and current variations. In this project, a 3 ohm, 0.5W resistor (Model 236A) is used in series with the load to serve as a current limiter and, a voltage stabiliser. This enhances the accuracy of measurements because it eliminates noise and ensures the operating conditions during testing remain the same (Chen et al., 2020).

The literature analysis has indicated the following gaps in research: few studies have been done on multi-stack reversible PEM fuel cells in educational institute, a lack of energy balance analysis in small scale design, and the lack of water management method to support extended operation. Moreover, the theoretical models and experimental validation are not integrated, which restricts the practical applicability of research (Chen et al., 2019; Mok et al., 2020).

2.2 Machine Learning- Enhanced Performance Modelling of Proton Exchange Membrane Fuel Cells

Wilberforce and Olabi (2020) explore predicting performance of Proton Exchange Membrane Fuel Cell (PEMFC) under different ambient and operating conditions using Adaptive Neuro-Fuzzy Inference System (ANFIS). As shown in the schematic of the experimental setup in Figure 2.1, the supply of hydrogen, humidification control, air flow control, and a potentiostat are incorporated to produce polarization data.

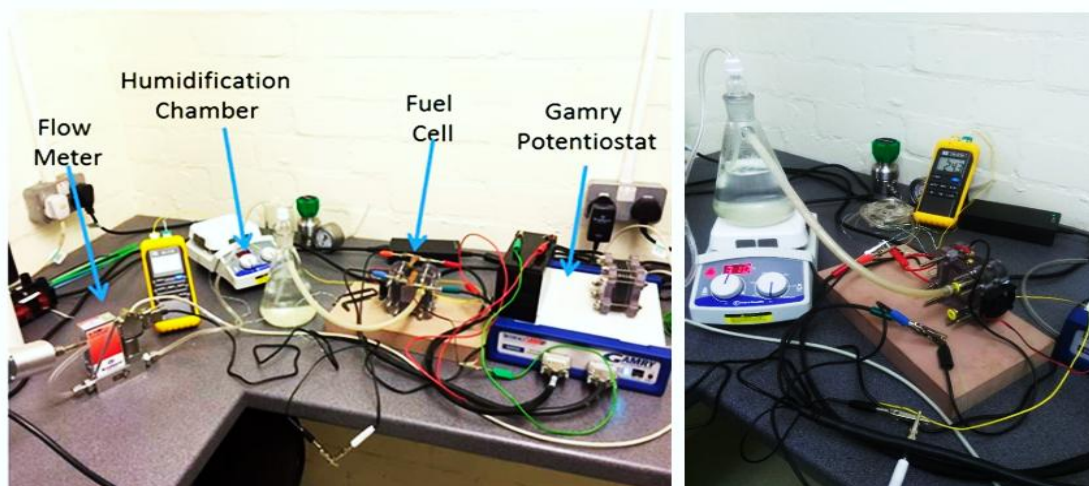


Figure 2. 3 Experimental setup of PEMFC

Source: Olabi (2020)

The following figure clearly shows the coupling between the hydrogen flow rate, oxygen supply, and the humidity conditioning, highlighting the fact that the performance of PEMFC is very sensitive to the operating variables(Aroge, 2018). The study places itself within an overall sustainability research context by addressing the

need for good, cost-effective predictive models to cut down the need for extensive experimental testing(White, 2025).

The theoretical basis for the research is based on the architecture of ANFIS, which is a combination of neural networks and fuzzy logic. The five-layer ANFIS structure is shown in Figure 2.2 along with the fuzzification, rule generation, normalization, defuzzification and output summation layers. Wilberforce and Olabi (2020) explains how membership functions (especially generalized bell functions) are used to convert input parameters (pressure and flow rate) into fuzzy sets. The adaptive nodes and rule-based inference mechanism shown in the figure help to understand how the behaviour of nonlinear PEMFC is captured. This hybrid learning approach corrects limitations in the classical regression models, and particularly the electrochemical non-linearities.(Han, Park and Chung, 2016)

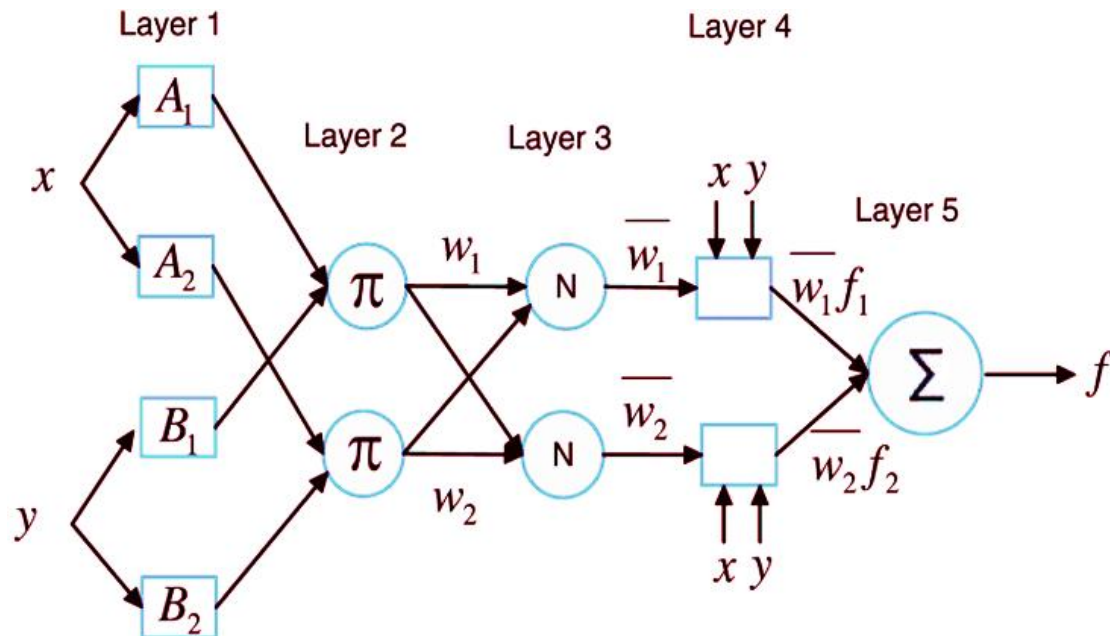


Figure 2. 4 five-layer ANFIS structure

Source: Chung, 2016

Experimentally, the authors look at hydrogen and oxygen pressure and flow rates as independent variables. Tables and corresponding discussions make operational ranges (1-2.5 bar for H₂ and 0.8-2.3 bar for O₂) highlighted(Spiegel, 2011). The polarization curves produced by the potentiostat are graphically interpreted in the subsequent graphical results, where the predicted values and the experimental values overlap almost perfectly. The high correlation coefficients and low value of Root Mean Square Error (RMSE) prove the predictive ability of ANFIS. The graphical comparison of the predicted and measured voltage outputs shows the strength of the training-testing separation of the dataset methodology(Regmi *et al.*, 2020).

Comparative modelling constitutes one more significant contributor. Wilberforce and Olabi (2020) compare ANFIS with Multiple Linear Regression (MLR) and feed forward Performance Analysis of an Educational Proton Exchange Membrane Fuel Cell Stack.

back propagation neural networks. The performance plots indicate that although MLR has some problems with non-linear polarization behaviour, ANFIS has a better accuracy. The correlation plots are a visual way of reinforcing this conclusion, showing ANFIS predictions lying close together around experiment data points. These graphical analyses confirm the argument that adaptive neuro-fuzzy systems are more suitable for PEMFC dynamic modelling than purely statistical methods(Mohiuddin, Basran and Khan, 2018).

Overall, the study is a significant contribution to the sustainable modelling of energy since it has been shown that ANFIS can determine the voltage-current characteristics of PEMFC in the presence of variable ambient conditions with considerable reliability. The combination of experimental validation and algorithmic structure visualization of the research enhances the methodological transparency. Wilberforce and Olabi (2020) conclude that the use of machine learning-based hybrid systems has the potential to reduce the computational complexity and ensure high predictive accuracy, yielding the practical benefits for fuel cell optimization and the development of control systems.

2.3 Degradation-Aware Modelling and Simulation of the PEMFC Systems for Fuel Cell Electric Vehicles

Ahmadi Sarbast (2021) studies on the PEMFC performance deterioration and operational life prediction using semi-empirical modelling framework. The thesis starts by setting degradation mechanisms into the context of vehicular applications(Natarajan *et al.*, 2019). Figure 2.3 categorizes the prognostic approaches into model-free, model-based and hybrid approaches to lay out the methodology base to select a semi-empirical approach(Wagner and Hoffmann, 2015). This figure highlights the trade-off between an easily understood model and a simplified model that is computationally simple and justifies the choice between a model that is mechanistic and simple(Yang *et al.*, 2024).

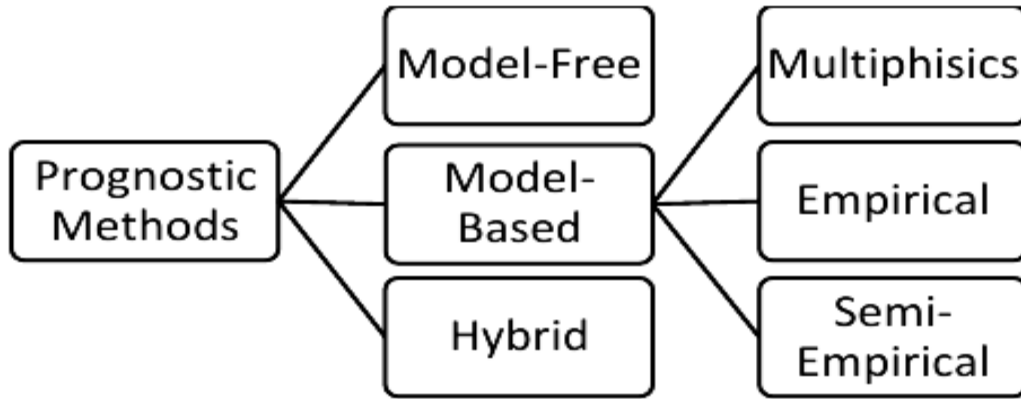


Figure 2. 5 prognostic approaches Source: Sarbast, 2021

Vehicular load condition is the focus of the degradation analysis. Figure 2.4 shows four modes of operation of load (startup/shutdown, idling, dynamic load, and high power). Ahmadi Sarbast (2021) highlights the fact that the rate of degradation is considerably different between these modes, with dynamic load and start-up/shutdown being the most harmful to voltage decay. The graphical representation helps to understand the role of fluctuating current densities in accelerating the degradation of the catalysts and the stress in the membrane, especially during automotive duty cycles (Kar, Chanda and Banerjee, 2024).

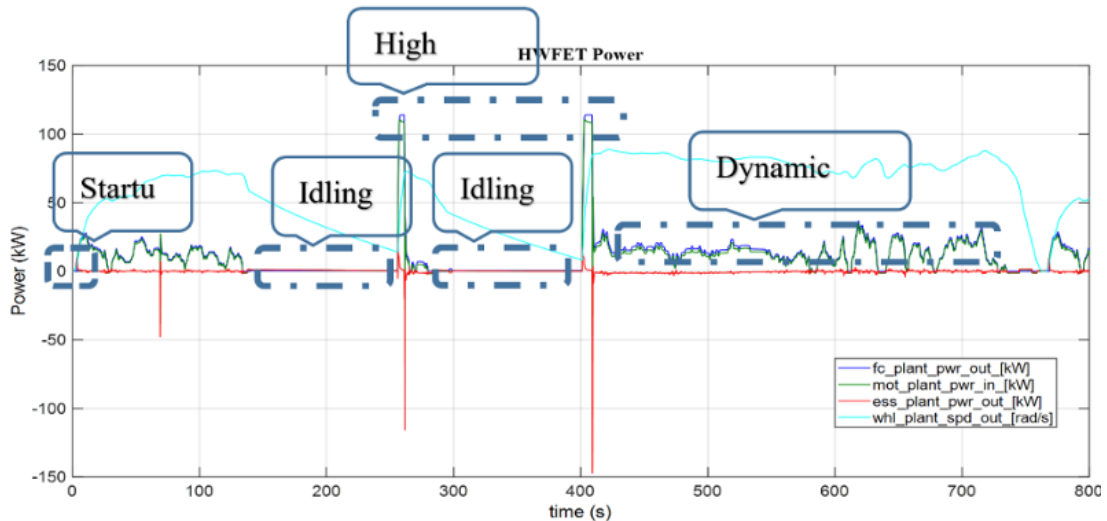


Figure 2. 6 four modes operation of load Source: Banerjee, 2024

The thesis enhances further the polarization behaviour and degradation trends through experimental validation (Wilberforce, Biswas and Omran, 2022). The voltage and power vs. current density curve is shown in Figure 2.5, showing the classical activation, ohmic and concentration loss regions (Wu *et al.*, 2008). Following figures 2.6 and 2.7 voltage degradation at constant and rippled current conditions versus time. These figures show progressive voltage decay thus proving that it is necessary to consider

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time-dependent degradation parameters in performance models(Han, Park and Chung, 2016).

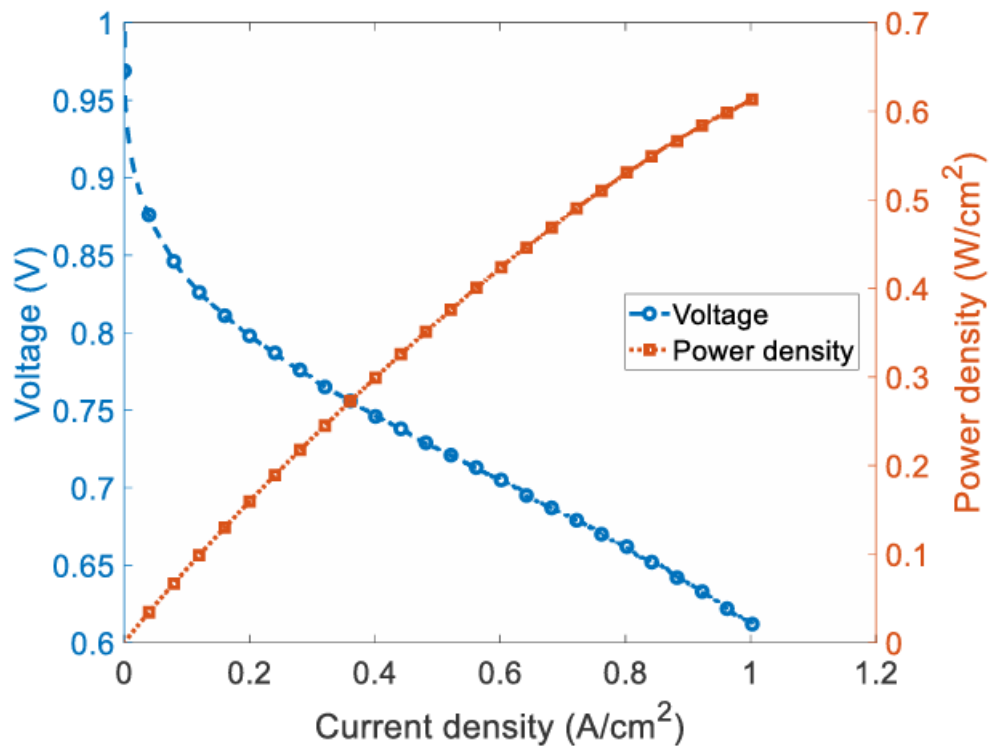


Figure 2. 7 Density curve Source: Chung, 2016

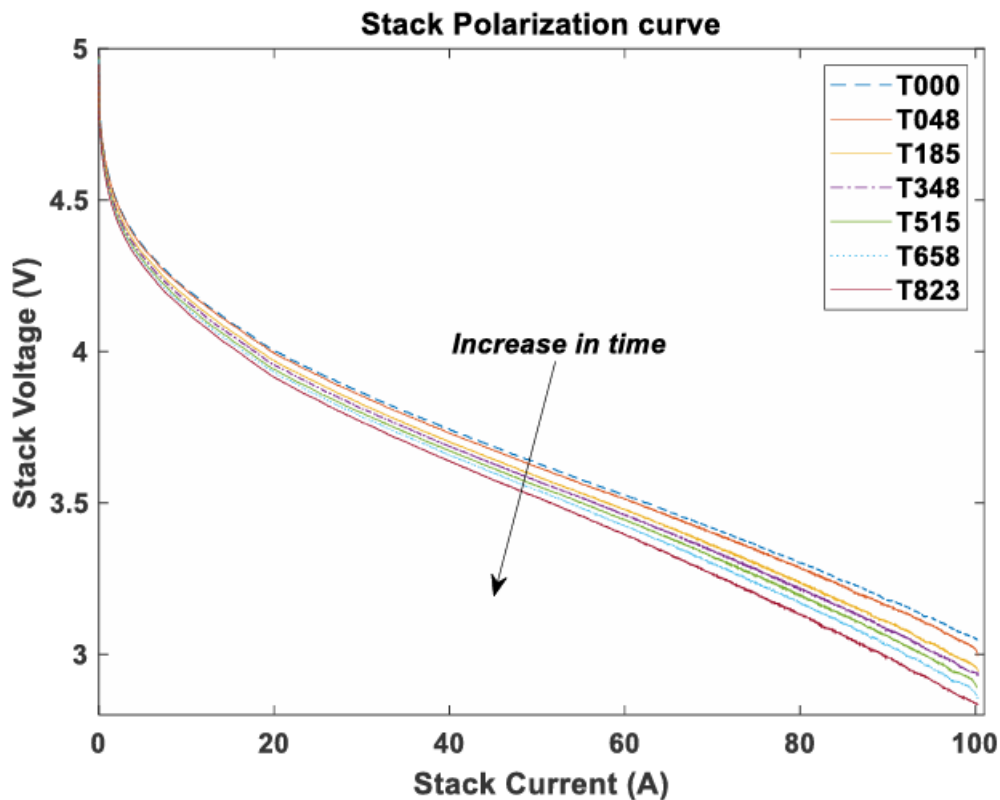


Figure 2. 8 voltage degradation Source: Park, 2016

Performance Analysis of an Educational Proton Exchange Membrane Fuel Cell Stack.

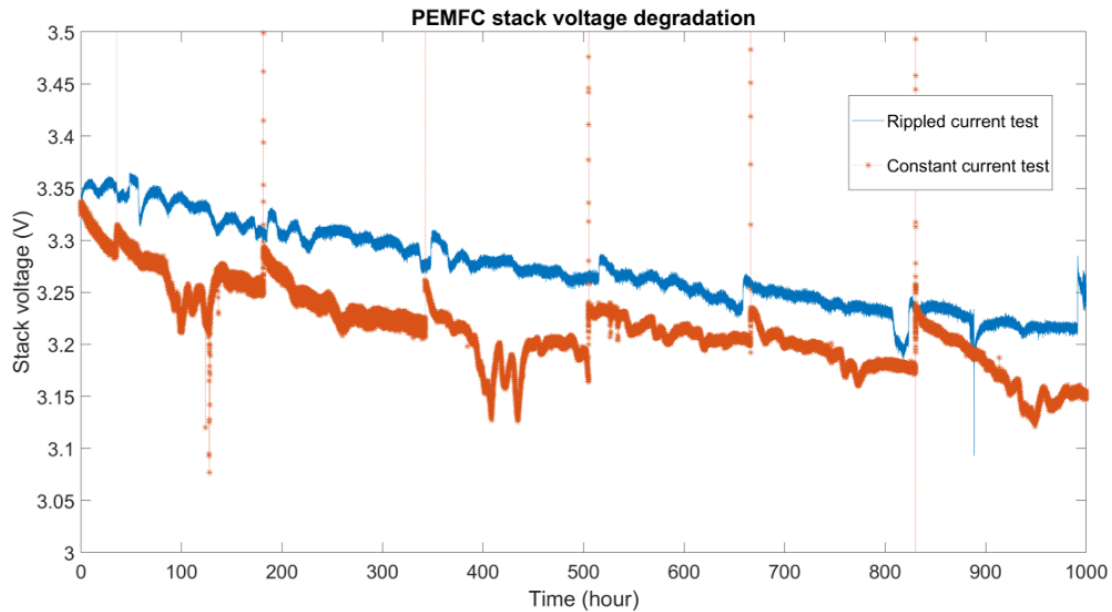


Figure 2. 9 voltage degradation at constant and rippled current conditions versus time

A great contribution of Ahmadi Sarbast (2021) is the creation of a unified semi-empirical degradation model that takes platinum oxidation, active surface area loss and ohmic resistance increase in consideration (Wagner and Hoffmann, 2015). Results of model fitting are shown in figure 2.8 where the closeness in agreement between simulation results and experimental data is noted. The deterioration of activation, ohmic, and concentration loss terms are further explained where the evolution of the various voltage loss parameters over long periods of operation is shown (Belyaev *et al.*, 2016).

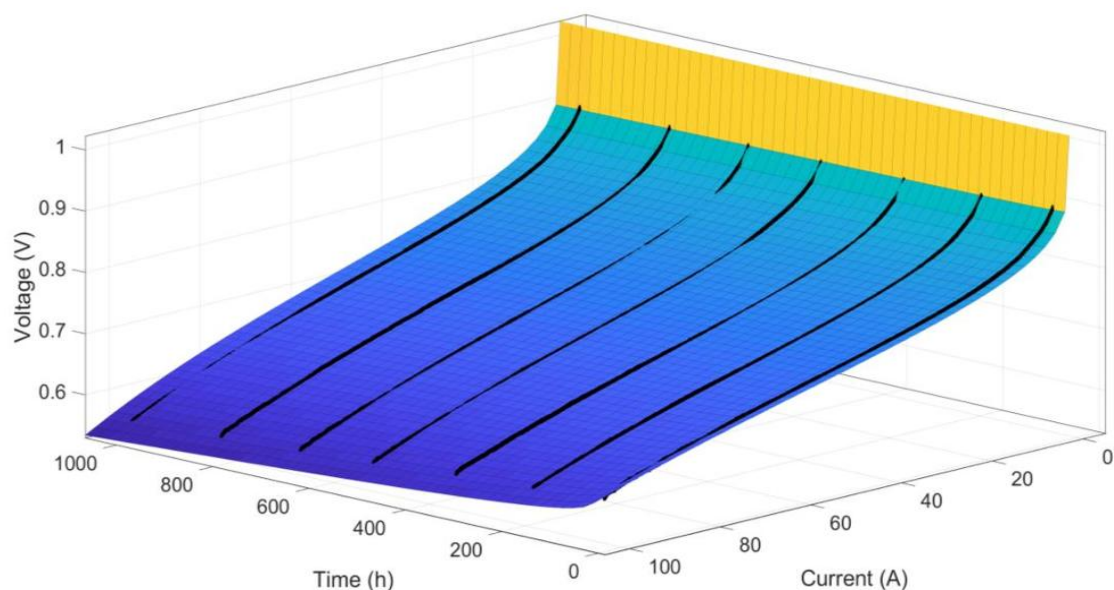


Figure 2. 10 model fitting Curve plot Source: Belyaev *et al.*, 2016

The practical implementation of the model is illustrated by vehicle level simulation based on the UDDS driving cycle. UDDS speed profile is shown in Figure 2.9 and Performance Analysis of an Educational Proton Exchange Membrane Fuel Cell Stack.

voltage degradation in various powertrains under different conditions is shown in Figure 2.10. These simulations confirm that hybridization with an energy storage system has the effect of reducing the severity of degradation. Ahmadi Sarbast (2021) concludes that accounting for degradation in degradation-aware modelling of the vehicle design allows for optimization of the sizing and strategies of the PEMFCs ultimately increasing the fuel cell lifespan and reducing the lifecycle costs(Belyaev *et al.*, 2016).

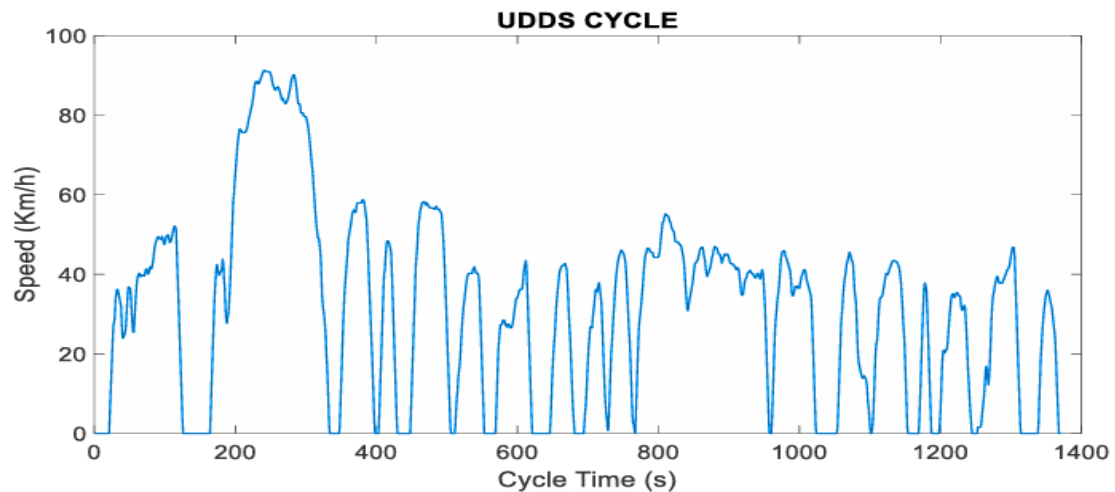


Figure 2. 11 UDDS speed profile Source: Belyaev *et al.*, 2016

In summary, in this thesis a comprehensive degradation modelling framework is given, which was validated using experimental data and vehicle simulation. Through systematic approaches to the use of diagnostic figures and mechanistic parameter tracking, Ahmadi Sarbast (2021) develops predictive modelling for PEMFC durability applications for transportation purposes(Abdelnasir *et al.*, 2019).

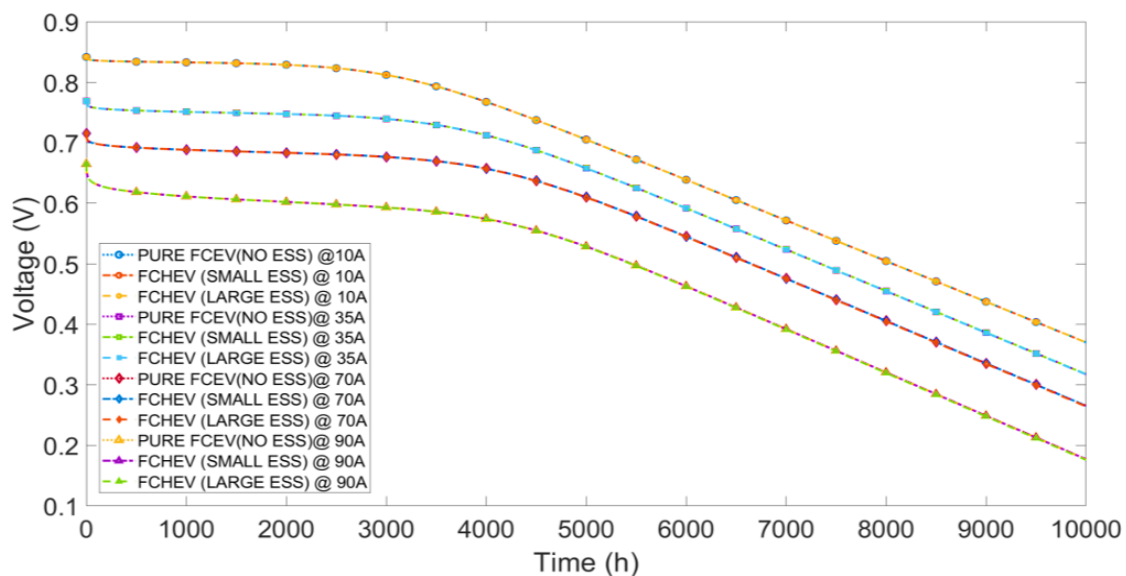


Figure 2. 12 voltage degradation in various powertrains under different condition

Source: Abdelnasir *et al.*, 201

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2.4 Control-Oriented Dynamic modelling and Embedded Implementation of Hybrid PEMFC System

Zhang (2010) investigated the dynamic modelling and control of a PEM fuel cell - battery hybrid system with an emphasis on simulation and experimental validations. The basic principle of electrochemistry is shown in Figure 2.11, which shows the oxidation of hydrogen at the anode and reduction of oxygen at the cathode (Hwang, Wang and Kuo, 2012). This figure lays down the theoretical background for the energy conversion in fuel cells with the conduction of protons through the electrolyte and the conduction of electrons through the external circuit. Zhang (2010) uses this electrochemical basis to support the development of mathematical model that captures the mass conservation and the energy balance in the stack. The figure supports the argument that fuel cells are continuous energy conversion devices and not storage units leading to the need for system level modelling (Puranik, Keyhani and Khorrami, 2010).

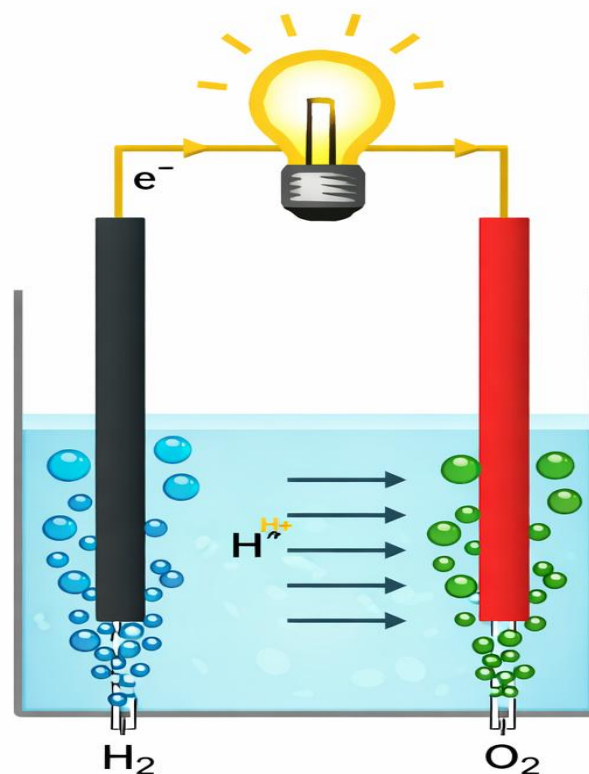


Figure 2. 13 Fuel Cell Mechanism Source: Zhang 2010

Zhang (2010) further explains PEM fuel cell behaviour as polarization characteristics as illustrated in Figure 2.12. This figure illustrates the three major voltage losses: activation losses, ohmic losses and concentration losses (Rabih *et al.*, 2008). The activation region exhibits high speed voltage drop at low current levels because of

electrochemical kinetics whereas the linear ohmic region is related to membrane resistance and contact losses. At high current density, losses from mass transport of the concentrations are the dominant ones (Rabih *et al.*, 2008). The author incorporates these voltage loss mechanisms into the electrochemical model to accurately predict stack voltage under different load conditions. This polarization analysis becomes important when designing controllers which can be used to stabilize output voltage (Fam *et al.*, 2021).

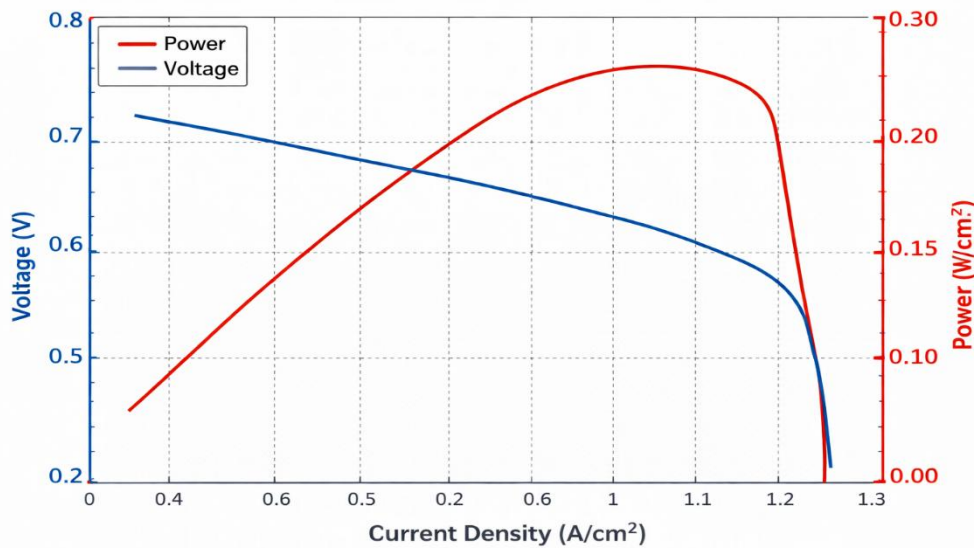


Figure 2. 14 PEMFC polarization between Power vs Voltage Source: Fam *et al.*, 2021

Dynamic response of the modelled system is shown in Figure 2.13 (Voltage Response to Step Input) Zhang (2010) tests the transient performance with step changes in load showing the voltage dips and recovery behaviour. The figure confirms the need to introduce reactant flow dynamics and membrane hydration in the model. Without proper control it is possible that sudden load increases will lead to temporary fuel starvation and voltage instability (Qin *et al.*, 2016). The simulation results show that the proposed control-oriented model can capture the transient behaviour successfully, which makes it suitable for controller design and system optimization (Hwang, Wang and Kuo, 2012).

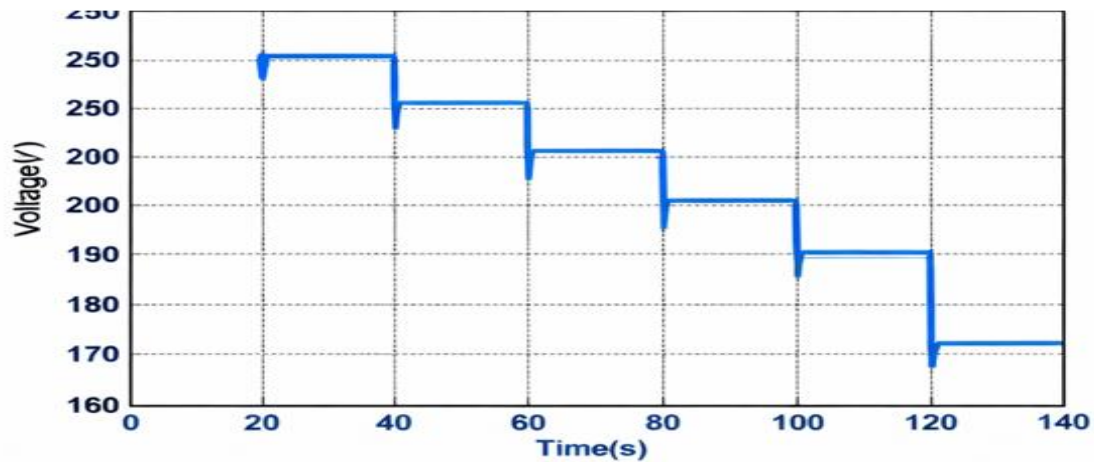


Figure 2. 15 Voltage Behaviour Response Source: Kuo, 2012

Water management control is validated with the aid of Figure 2.14 (Polarization Curve with and without Humidifier Control). This figure is a comparison of stack performance with controlled and uncontrolled humidification (Arias *et al.*, 2017). The results show that keeping the membrane in appropriate hydration condition can improve the voltage output significantly and to lower the performance degradation. Zhang (2010) emphasizes on improper humidification which causes membrane drying or membrane flooding, both of which decrease efficiency. The addition of a humidification controller helps to increase system stability and prolongs the life of the membranes (Dematteis *et al.*, 2021).

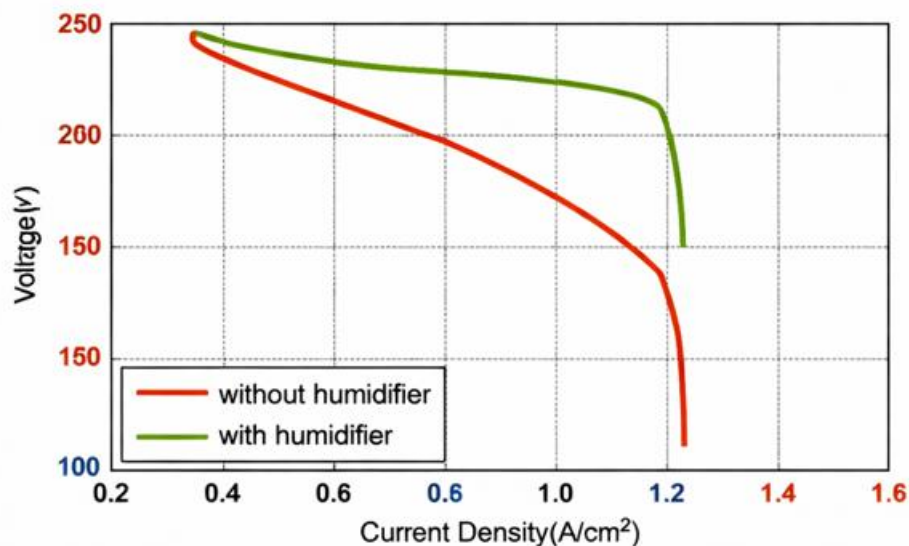


Figure 2. 16 Polarization Plot between Voltage and Current Source: Dematteis *et al.*, 2021

Finally, an example of system-level hybridization is shown in Figure 2.15. This figure introduces the combination of the PEM fuel cell stack, lithium-ion battery and DC/DC boost converter. Battery is used as the fuel cell's transient response is slow while converter is used to control voltage for variable loads. Zhang (2010) validate the 100 Performance Analysis of an Educational Proton Exchange Membrane Fuel Cell Stack.

W prototype system experimentally and show that the simulation results agree with the practical results(Andrews and Mohammadi, 2014). The contribution of this study can be seen from the figure that includes modelling, control design and hardware implementation into validated hybrid power system(Belyaev *et al.*, 2016).

2.5 Thermodynamic and Electrochemical Modelling of a Serpentine flow PEM Fuel Cell

Awotwe et al. (2017) performed the modelling and experimental validation of PEM fuel cell using serpentine bipolar plate design using MATLAB simulation(Berg *et al.*, 2004). The structural configuration is presented in Figure 2.16. This figure points out this serpentine flow channel geometry which is designed to improve the distribution of reactants and water removal(Page *et al.*, 2007). The authors state that flow field design has a significant impact on mass transport and overall efficiency. The serpentine configuration results in uniform gas diffusion across the membrane electrode assembly (MEA) which reduces the concentration losses and enhances the performance consistency(Al-Dabbagh, Lu and Mazza, 2010).

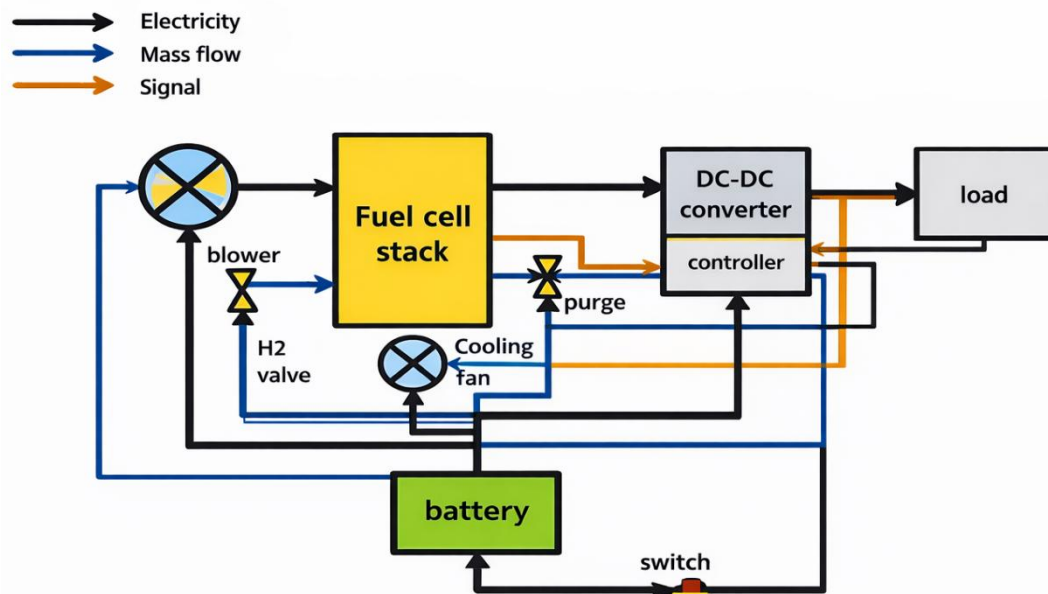


Figure 2. 17 PEMFC Battery system Mechanism Source: Mazza, 2010

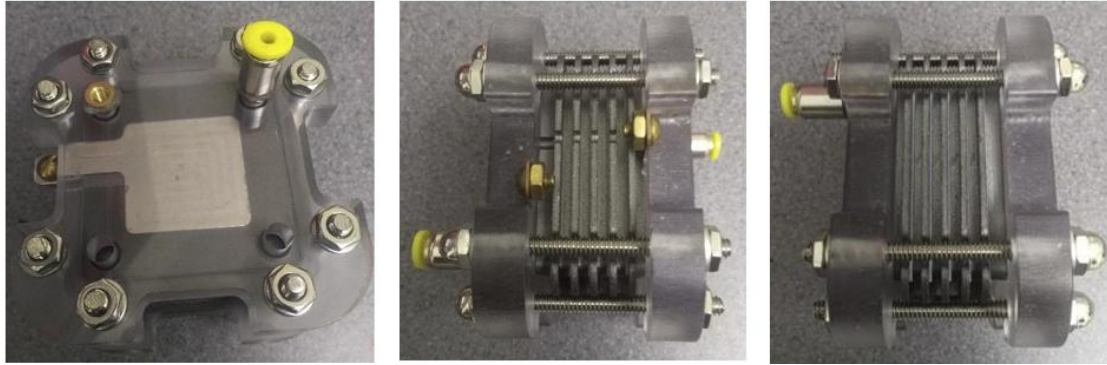


Figure 2. 18 PEMFC Serpentine with active field Source: Mazza, 2010

Electrochemical losses in the fuel cell can be explained from Figure 2.17 (Various Losses Experienced in a Fuel Cell). The figure dissects activation, ohmic, and concentration overpotentials and is why the measured open circuit voltage is less than the theoretical 1.229 V. Awotwe et al. (2017) use an integration of Gibbs free energy and thermodynamic relations into models in MATLAB to estimate the theoretical cell potential. However, irreversible losses cause the decrease of practical voltage output. This graphical representation is used to help build a mathematical model that could be used to predict realistic polarization behaviour(Basha *et al.*, 2022).

The polarization performance of the five-cell stack is presented in Figure 2.18. The curve shows voltage drop with increased current density and agrees with the theory. The maximum stack voltage measured was 4.49 V for low current with the voltage decreasing with increasing load(Page *et al.*, 2007). The authors suggest voltage drop is caused by ohmic resistance/ reactant diffusion limitation. MATLAB-generated polarization curves were shown to be in good agreement with experimental measurements, and the simulation approach was validated(Yang *et al.*, 2024).

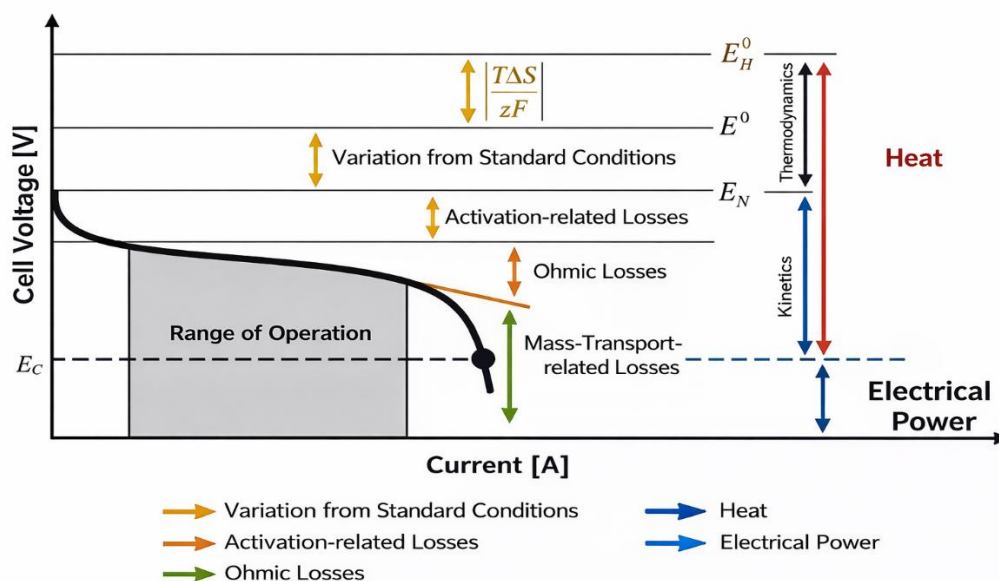


Figure 2. 19 Electrochemical losses in fuel cell Source: Yang *et al.*, 2024

Performance Analysis of an Educational Proton Exchange Membrane Fuel Cell Stack.

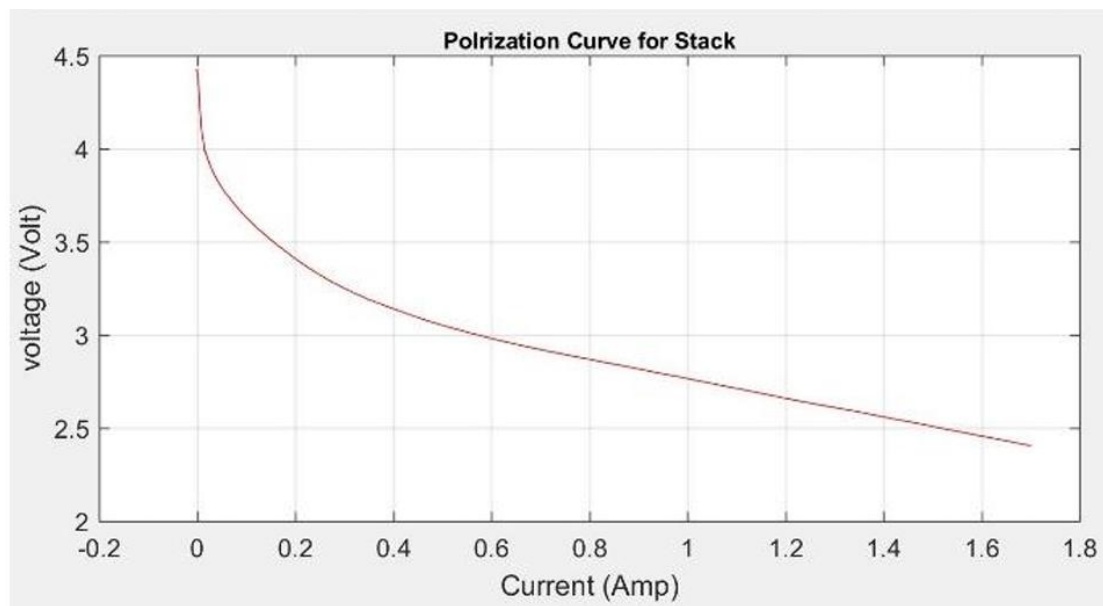


Figure 2. 20 Polarization plot Source: Yang *et al.*, 2024

Further analysis of a single cell performance is in Figure 2.19 where scaled polarization curves show an open-circuit voltage of ~ 0.9 V lower than theoretical expectations. The open circuit voltage of about 0.9 V was detected, which was less than expected theoretically (Hwang, Wang and Kuo, 2012). The deviation has been attributed to activation polarization and internal resistance (De Bruijn, Dam and Janssen, 2008). The figure confirms the fact that an increase in the current density significantly reduces the voltage, which makes it important to optimize the operational conditions such as temperature and humidification (Nasef *et al.*, 2018).

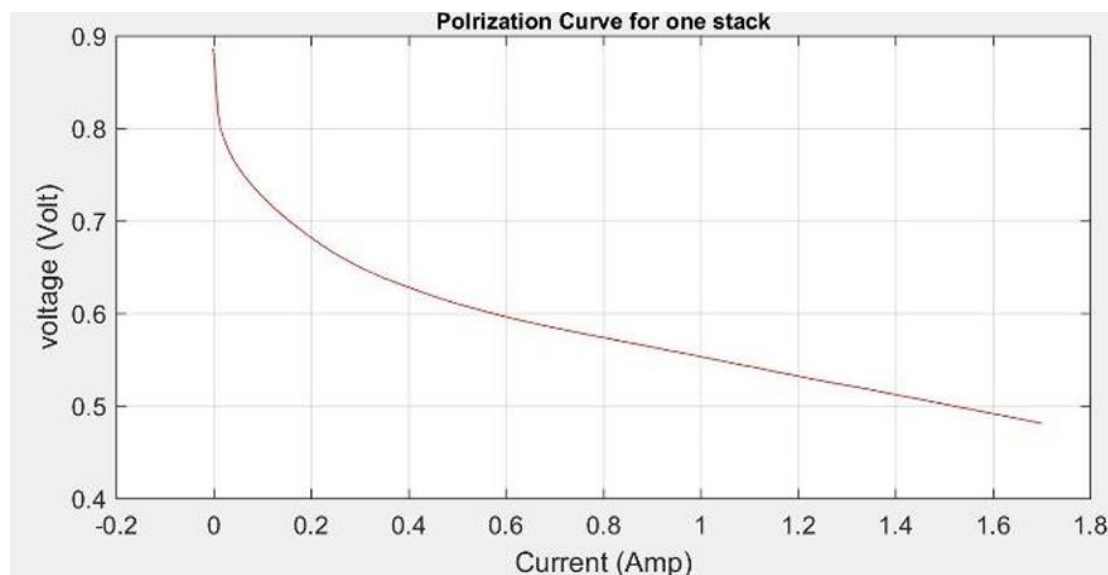


Figure 2. 21 polarization plot of open circuit Source: Nasef *et al.*, 2018

Effects of water management are examined using Figure 2.20. The figure shows that the water production rises with current density proportional to it. Too much water and it floods; too little water and the proton conductivity is reduced. Awotwe *et al.* (2017)

Performance Analysis of an Educational Proton Exchange Membrane Fuel Cell Stack.

conclude that the efficient humidification and serpentine flow channel design increase water removal efficiency and enhance overall system performance (De Bruijn, Dam and Janssen, 2008). The research manages to combine the use of thermodynamic modelling, MATLAB simulation and experimental verification to come up with a full understanding of how PEM fuel cells behave (Fam *et al.*, 2021).

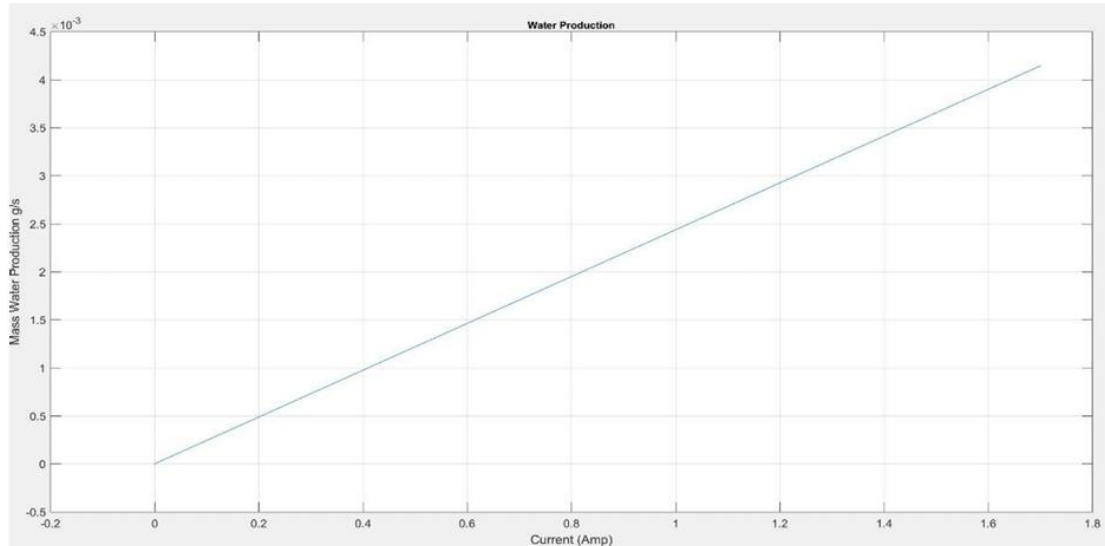


Figure 2. 22 water production process with current density Source: Fam *et al.*, 2021

2.6 Integrated Computational Framework for Improving the Efficiency and Power Density of Proton Exchange Membrane Fuel Cells

The research conducted by Obayopo *et al.* (2012) examines the performance improvement of Proton Exchange Membrane (PEM) fuel cells using numerical modelling and optimisation techniques. The basic operating principle of PEM fuel cells is shown in Figure 2.21 which is a schematic diagram of a single PEM fuel cell. The figure clearly shows the membrane, catalyst layers, gas diffusion layers (GDL) and bipolar plates which reveal how the hydrogen oxidation and oxygen reduction reactions happen across the membrane (Mitlitsky *et al.*, 1999). This structural representation lays the electrochemical foundation of the research by identifying transport of species and conduction of protons, which is important to performance modelling (Albarbar and Alrweq, 2017).

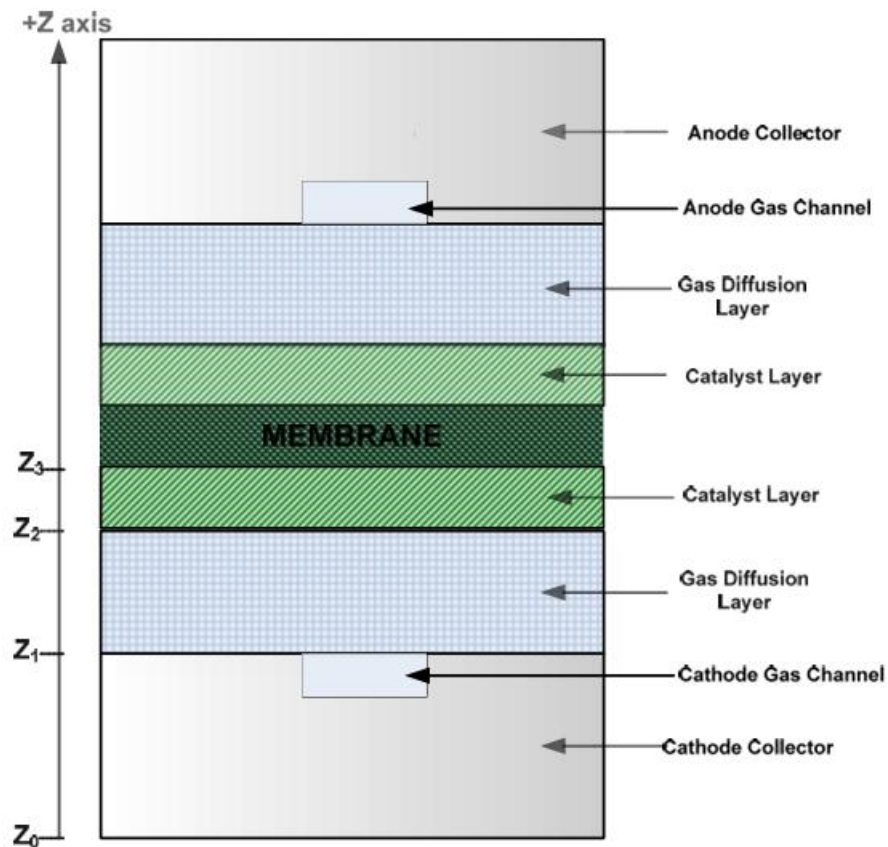


Figure 2. 23 schematic illustration of a single PEMFC Source: Obayopo et al. 2012

Further structural clarification is given in Figure 2.22 which illustrates the electrochemical reaction paths through the PEM cell. Obayopo et al. (2012) emphasise that membrane hydration and system efficiency is governed by transport phenomena such as electro-osmotic drag, diffusion and permeability (Singla *et al.*, 2025). The importance of reactant distribution and water management is further emphasized using the modelling framework in which a three-dimensional computational domain as shown in Figure 2.23 is employed to model coupled heat, mass and charge transport. This number is of particular importance as it is a visual representation of discretised control volumes employed in the CFD-based optimisation approach (Chen *et al.*, 2025).

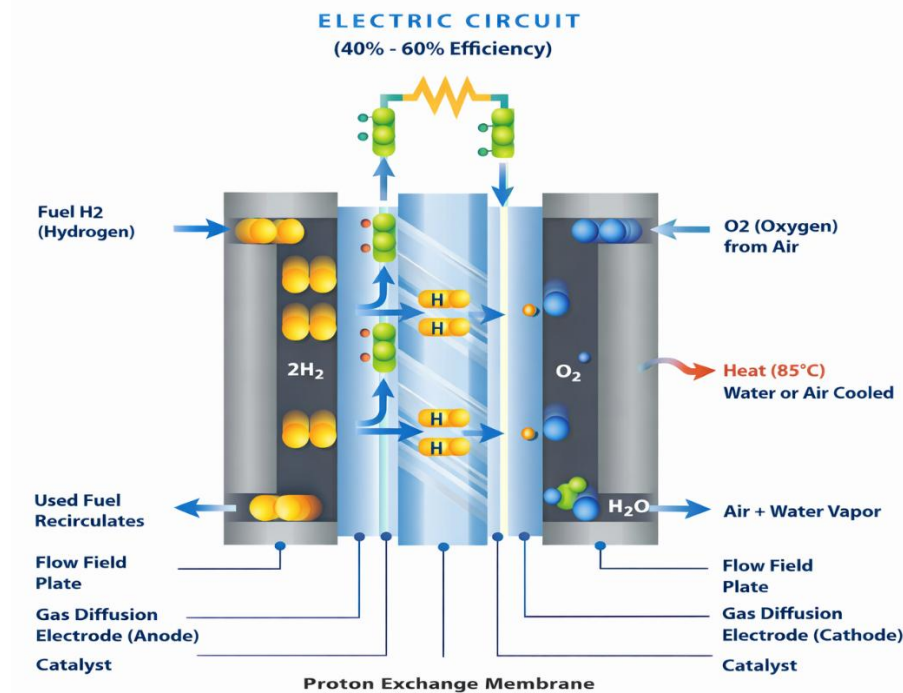


Figure 2. 24 electrochemical reaction paths through the PEM cell Source: Chen *et al.*, 2025

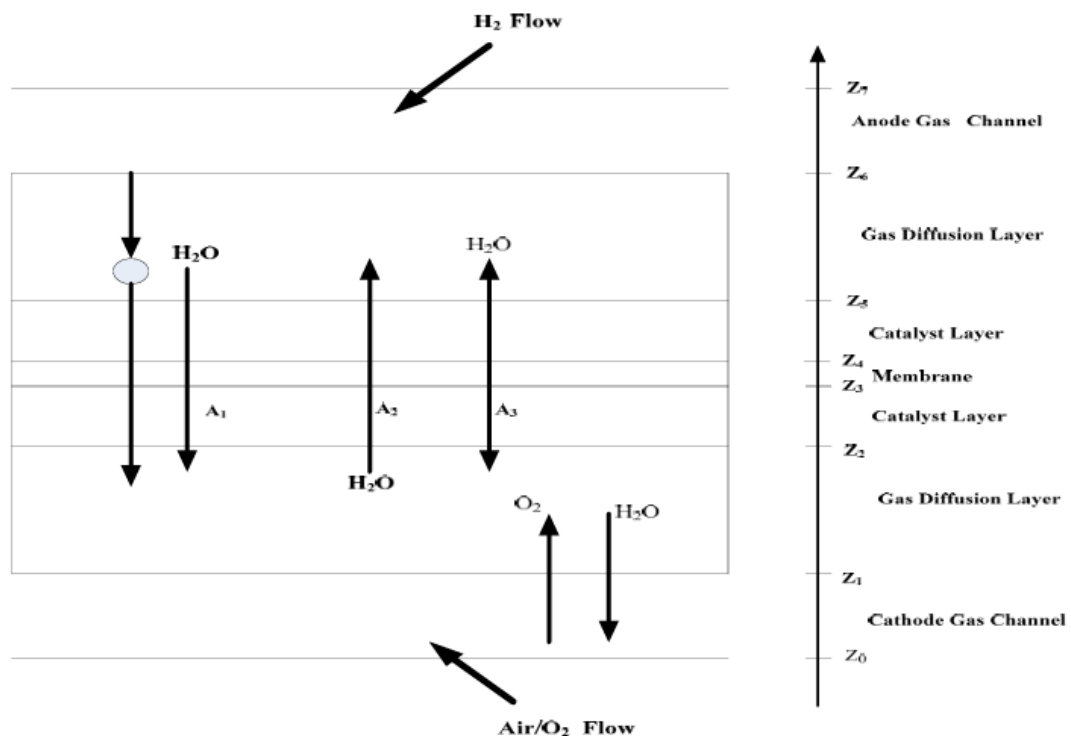


Figure 2. 25 three-dimensional computational domain for different zone Source: Chen *et al.*, 2025

Model validation is a key role in the study. In Figure 2.24 the measured polarisation curve from the experiment of Wang *et al.* is compared with the calculated polarisation curve. The good agreement in the low current density region is a confirmation of the Performance Analysis of an Educational Proton Exchange Membrane Fuel Cell Stack.

robustness of the computational model. However, deviations at higher current densities are indicative of limitations that are associated with mass transport losses and flooding of the cathode. This comparison is used to strengthen the credibility of the numerical methodology and to identify performance constraints.

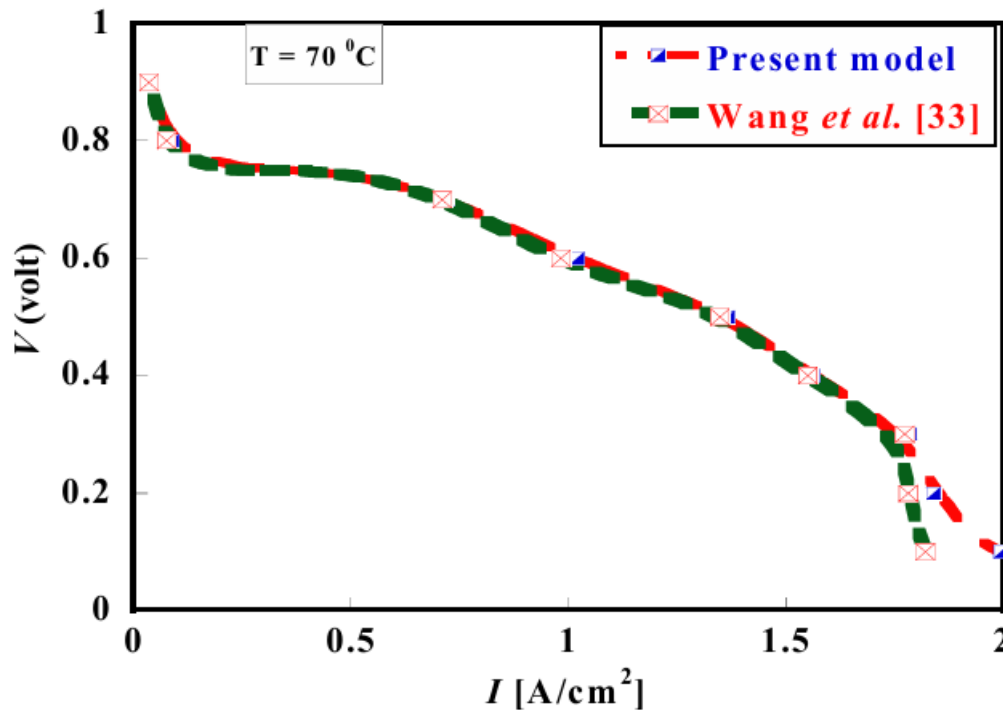


Figure 2. 26 measured polarisation plot the experiment curve Source: Alrweq, 2017

The parametric study, which is shown in Figure 2.25, shows the influence of operating temperature (50- 90 degree) for fuel cell performance. The results indicate better performances up to a temperature of about 75degC due to an increase in reaction kinetics and a decrease of flooding. Beyond this range performance falls off because of membrane dehydration. Obayopo et al. (2012) conclude that a proper temperature management is therefore necessary to ensure membrane conductivity and durability. This figure certainly supports the argument that thermal optimisation is as critical as the geometric optimisation(Albarbar and Alrweq, 2017).

Additionally, gas channel and GDL optimisation techniques are introduced in the study, which include porosity variation and geometrical modification. Figures 2.24-25 show the effect of gas flow rate, operating pressure, and GDL porosity on the distribution of current density. These results confirm that the channel geometry plays an important role on the oxygen transport and pressure drop characteristics. The authors further go on to propose novel pin-fin channel modifications to improve the reactant distribution, while minimising parasitic losses(Hossain *et al.*, 2023).

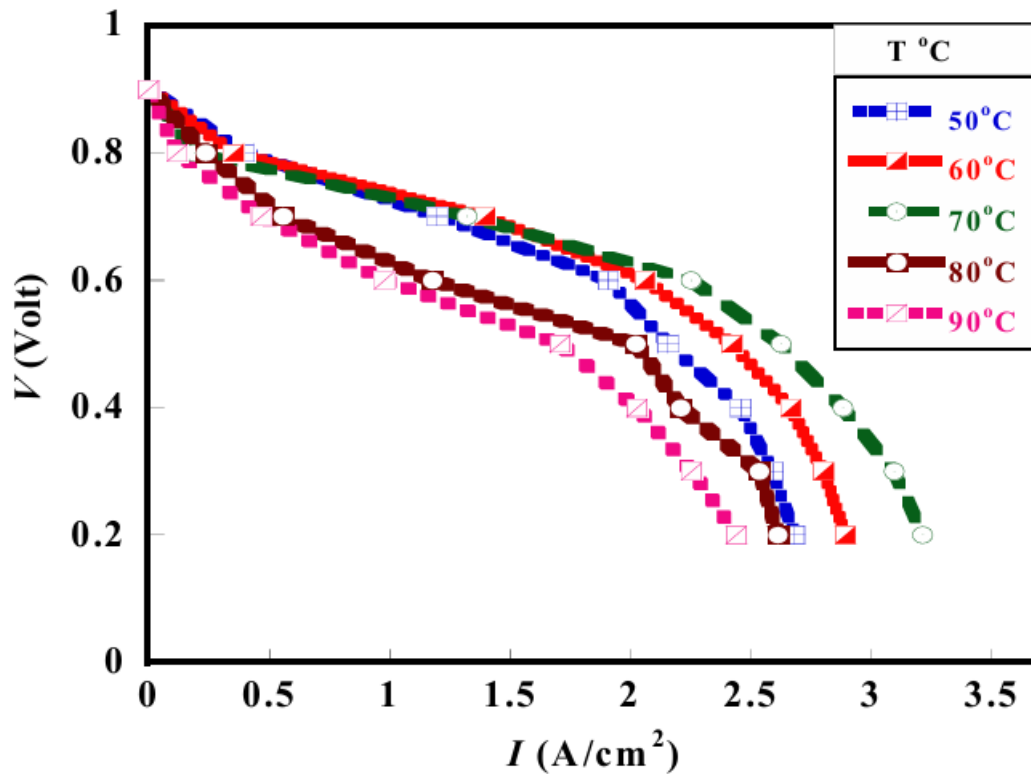


Figure 2.27 influence of operating temperature on PEMFC process Source: Hossain *et al.*, 2023

Overall, the work by Obayopo *et al.* (2012) presents a well-rounded optimisation framework combining the CFD modelling and Dynamic-Q algorithms. The study makes a significant advance in PEM fuel cell research by showing the interaction between the operating conditions, structural parameters, and thermal management strategies that can be used to maximise net power output. The introduction of validated results of numerical models and detailed parametric figures enhances its contribution to fuel cell system design and feasibility for commercial utilisation (Mazumder *et al.*, 2023).

2.7 Comprehensive Dynamic Simulation of PEM Fuel Cell Stack and Balance of Plant Integration

Rabbani, Raja Abid. 2013. study Dynamic performance of PEM fuel cell systems A system-level transient modelling framework integrating electrochemical, thermal and auxiliary subsystem dynamics. The schematic representation of the complete PEMFC system shown in Figure 2.26 depicts the combination of the fuel cell stack, compressors, humidifiers, heat exchangers, pumps and control valves. This number shows how complicated balance-of-plant (BoP) components are and how they are responsible for controlling reactants flow, temperature, and humidity under different load conditions (Karthikeyan *et al.*, 2025).

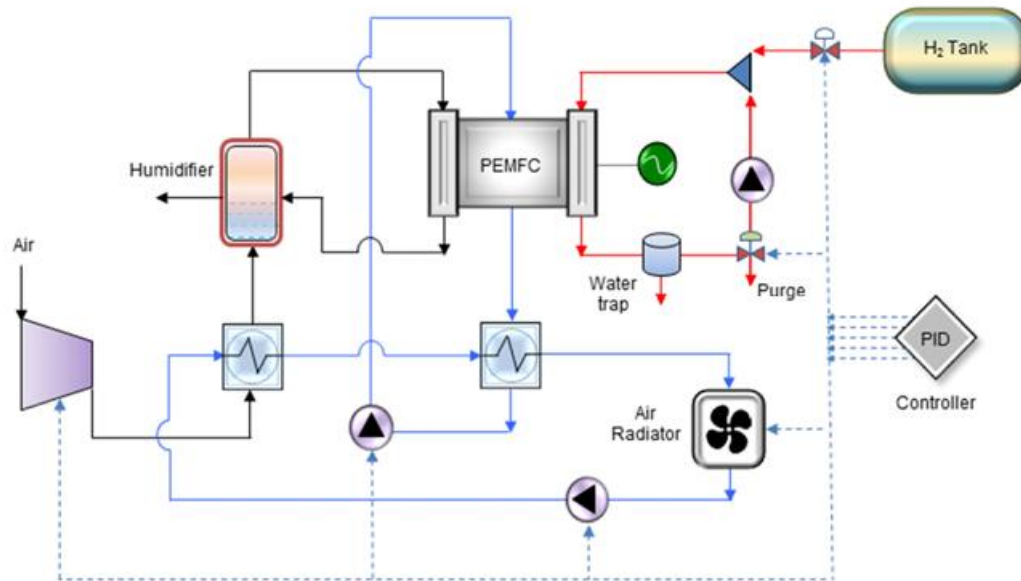


Figure 2. 28 Illustration of PEMFC stack Source: Karthikeyan *et al.*, 2025

Hydrogen oxidation at the anode and oxygen reduction at the cathode with proton transference through the polymer membrane and electrons travelling through the external circuit is the electrochemical foundation of PEM fuel cells. Classical semi-empirical voltage models such as proposed by Amphlett *et al.* (1995) relate the cell voltage to activation, ohmic and concentration losses. However, such models are not good at capturing transient phenomena. The dynamic modelling approach extends these formulations by introducing mass balances, charge conservation, and thermal energy equations that are dependent on the time, thus making it possible to realistically predict the voltage response due to load fluctuations (Fopah-Lele *et al.*, 2021).

A major aspect of the study is that BoP components such as compressors, humidifiers, and cooling subsystems are also included. Previous research works have tended to simplify the PEMFC systems by disregarding the auxiliary dynamics that can cause overestimation of system efficiency (Pathapati *et al.*, 2005). By combining air supply and thermal management subsystems, parasitic power consumption and pressure phenomena that have a strong effect on stack performance are introduced in the model. The transient simulations show that the compressor response time has a direct impact on cathode oxygen concentration which in turn influences the stability of the voltage when the load is increased rapidly (Zhao and Yuan, 2023).

Water management is also one of the most crucial issues in PEMFC operation. Excessive accumulation of liquid water in the cathode gas diffusion layer may cause flooding, which limits the reactant transport and affects the performance (Park & Choe, 2008). On the contrary, membrane dehydration lowers the proton conductivity and so raises ohmic resistance. The dynamic model considers two phase flow behaviour as

Performance Analysis of an Educational Proton Exchange Membrane Fuel Cell Stack.

well as membrane water transport mechanisms, such as electro-osmotic drag and back diffusion. Simulation results reveal sharp changes in liquid water saturation in load transients, which confirms that controlling humidity is vital to keep the system performing in a stable manner. These results agree with previous studies of thermal-fluid coupling by Vasu and Tangirala (2008).

Thermal effects also play an important role on transient behaviour. Temperature affects the rate of reaction, the conductivity of the membrane and water evaporation rates. The study shows that during sudden increases in loads, heat generation increases sharply because of an increased electrochemical activity. Without proper cooling, local temperature gradients form and this could lead to increased membrane degradation (Paul and Andrews, 2017). This coupling of electrochemical and thermal domain emphasises the importance of integrated dynamic modelling, not separated analysis of electrochemical domain (Arunachalam and Han, 2024).

Efficiency analysis in dynamic conditions further shows the effect of the auxiliary power consumption. Whilst stack voltage is likely to rise under operating conditions which are optimal, the overall system efficiency is reduced if compressor and coolant pump loads become excessive (Bilhan, 2024). This observation adds further strength to conclusions made from control-oriented modelling studies, which emphasize the necessity for advanced supervisory control strategies to balance performance and efficiency (Pukrushpan et al., 2004).

Overall, the dynamic performance study helps to move the study of the PEMFC closer to the application field by bridging the gap between simplified steady-state models and real-world transient operation. By combining electrochemical reactions, multiphase transport, thermal behaviour and auxiliary system dynamics, the model can be used as a comprehensive model for automotive and portable power applications. The literature clearly points out that the future development in PEMFC technology involves the improvement not only in materials but in accurate dynamic control and system level optimization.

2.8 Research Gap

Despite the extensive studies held about Proton Exchange Membrane (PEM) fuel cells, there are still various limitations, especially about reversible educational PEM fuel cell systems. Most of the literature available involves using large-scale or automotive applications, with a particular stress on steady-state operation and a simplified electrochemical approach instead of a small-scale experimental validation. Conversely, there is little literature regarding the performance, efficiency, and operational behaviour of educational fuel cell kits, in which practical considerations, Performance Analysis of an Educational Proton Exchange Membrane Fuel Cell Stack.

including leakage, unreliable hydrogen supply, and inefficient water management, have a major impact (O'Hayre et al., 2016; Chen et al., 2019). Moreover, most experimental research fails to provide a thorough discussion of transient behaviour particularly with regard to voltage decay, current oscillation, and efficiency depreciation with brief operating times. Other essential differences, including membrane hydration, the presence of a consistent level of hydrogen storage, and system sealing, have been largely ignored, though they have a significant impact on the performance of small-scale reversible systems (Mok et al., 2020; Liu et al., 2021). Available educational models also tend to work in single-stacked systems and have little control over the working parameters which makes them less efficient and with a varying output.

The other significant gap is that there is no integration between experimental testing and simulation-based analysis. Although MATLAB-based modelling is often applied to large-scale systems, little work has been done to apply it to validate and interpret experimental data of educational PEM fuel cells. Moreover, the attention to the refinement of design factors (sealing mechanisms, hydrogen usage, and load stabilisation) is also inadequate and is essential to the improved performance and reliability of a system in real-life configurations. Thus, this study fills these gaps by integrating experimental testing of a reversible educational PEM fuel cell, comprehensive performance analysis (voltage, current, power, and efficiency) and simulation using MATLAB to give a more comprehensive understanding of system behaviour. Practical design improvements to make the system more efficient, run-time, and ultimately improve the system performance are also studied.

2.7.1 Novelty of the Research

The novelty of this research study is the reversible educational PEM fuel cell model is developed and assessed, which combines experimental research and simulation analysis. In contrast to traditional research which tends to study on big or theoretical models, this research concentrated on a small-scale practical system to be used in education and still be relevant to the behaviour of a real fuel cell.

This paper presents an experimental methodology to measure key performance parameters of run time (average 3.28 minutes), voltage decay, power output and efficiency change (above 100 percent at the initial stages and below 50 per cent with time). Besides this, MATLAB is also used to model trends in system performance by which a comparison can be made between the predictions and experimental results. This holistic method gives a better understanding of system dynamics especially how hydrogen consumption, efficiency decline and output stability are related.

The emphasis on design-based enhancements, such as sealing mechanisms, hydrogen flow control, water management solutions, is another novelty that are not common in educational fuel cell research. The study also emphasizes the role of load stabilisation with the help of resistive components that guarantee correct and reliable measurements. This study helps close the gap between theory, simulation and practical experimentation to enhance the understanding, performance and educational potential of reversible PEM fuel cell systems as well as to be used in the future to optimise and develop their performance.

3. RESEARCH METHODOLOGY

The study uses a form of experimental technique which is structured to examine the functionality of an educational multi-stack reversible Proton Exchange Membrane (PEM) fuel cell system. The research is based on quantitative measurement of the most important parameters like voltage, current, hydrogen production, and energy efficiency. The methodology allows the verification of electrochemical behaviour against available models like the Law of Faraday and thermodynamic efficiency relations due to the combination of theoretical principles and controlled experimentation (O'Hayre et al., 2016; ISO 22734:2021).

3.1 *Research Design*

This research project is based on a powerful, model-based simulation approach to the analysis of performance of an automotive scale Proton Exchange Membrane (PEM) fuel cell stack under realistic operating conditions. A physics-based dynamic model is created for modelling the strongly coupled electrochemical, thermal and reactant transport processes that govern the behaviour of PEM fuel cells. Due to the prohibitive price, safety requirements and experimental complexity involved in the testing of high-power fuel cell stacks, numerical simulation is chosen as the best and reliable research approach. The methodology goes according to a structured workflow in the form of system definition, formulation of the governing equations, multi-domain implementation in the MATLAB environment of the Simscape, and comprehensive performance evaluation. The developed model is used for studying steady-state and transient response, parametric studies of key operating variables, and sensitivity of the system to load dynamics. Validation with respect to published experimental results and manufacturer specifications is essential to the accuracy, credibility and industrial relevance of the results.

3.2 *Experimental Setup Methodology*

The experiment apparatus is modelled after the FCJJ-11 educative hydrogen fuel cell kit, which has four reversible PEM fuel cell stacks that have been stacked in series. This setup enables the system to be in electrolysis mode and fuel cell mode thus a complete cycle study of hydrogen production and use. The entire system including the multi-stack setup is depicted in Figure 6, which depicts the reversible PEM fuel cell stack that will be used in this study.

3.2.1 Experimental components.

The system is composed of several interrelated parts that are meant to offer accuracy in measurement and stability in operation.

1. Reversible PEM Fuel Cell Stacks:

The main part of the experiment is four reversible PEM fuel cell stack, which can be used in the electrolysis and fuel cell mode. Stacks are stacked in a sequence to amplify overall voltage production as illustrated by Figure 3.1. This arrangement allows investigating the cumulative behaviour of voltages and is indicative of scalable system design (Chen et al., 2019).

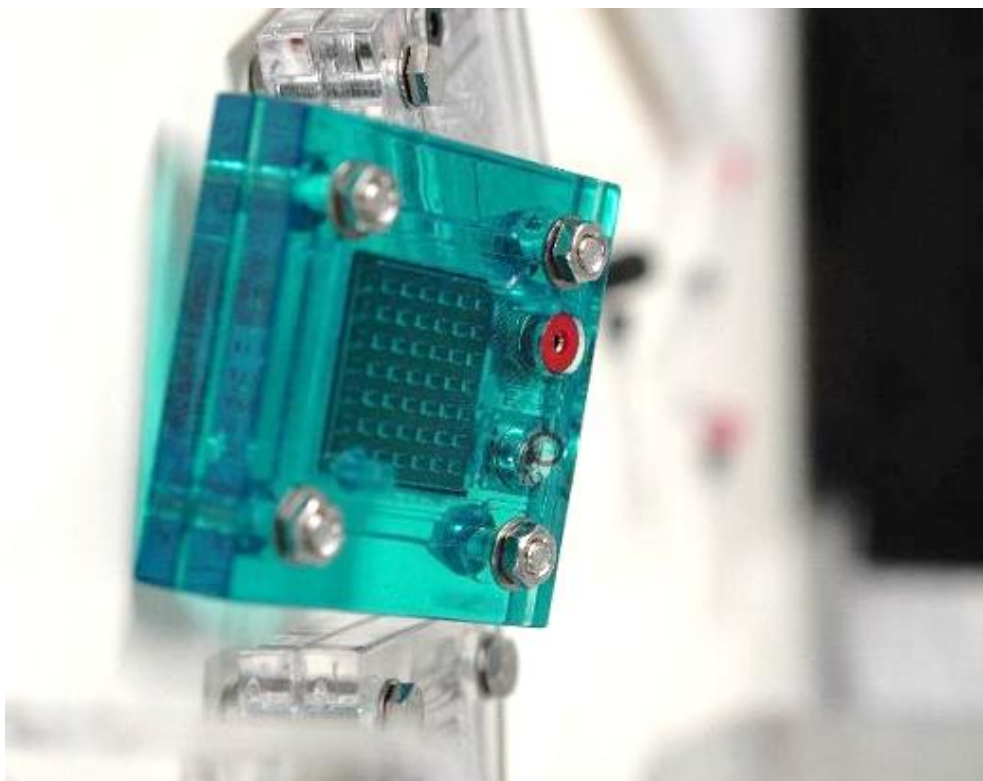


Figure 3. 1 PEMFC

2. Voltage-Ampere Controller:

To provide a constant current and voltage during electrolysis, a WEIR 4000 voltage-ampere controller (30 V -1A) is employed to supply a constant current and voltage. The controller maintains a constant electrical supply and provides a fine control of operation conditions. Figure 3.2 presents the device employed in the experiment, which helped to ensure controlled electrolysis conditions (Yan et al., 2020).



Figure 3. 2 Voltage Measurement

3. Hydrogen and Oxygen Collector System:

The gases produced in the electrolysis process, specifically hydrogen and oxygen are harvested through a water displacement apparatus. The gas is directed into silicone tubes and inverted cylinders are inserted into the beakers which are filled with water, and this enables the gas volume to be measured accurately. This arrangement is shown in Figure 3.3, which shows the gas collection arrangement in the experiment. The water displacement technique is well regarded due to its simplicity and precision in measuring hydrogen in laboratories (Faraday, 1834; ISO 22734:2021).



Figure 3. 3 3. Hydrogen and Oxygen Collector

4. Distilled Water Reservoir:

The source of the electrolyte is distilled water that ensures a consistent performance of the membrane and avoids contamination. Figure 3.4 depicts the measuring beaker that supplies water to the system, which is the controlled water input system required to ensure stable electrolysis conditions (O'Hayre et al., 2016).

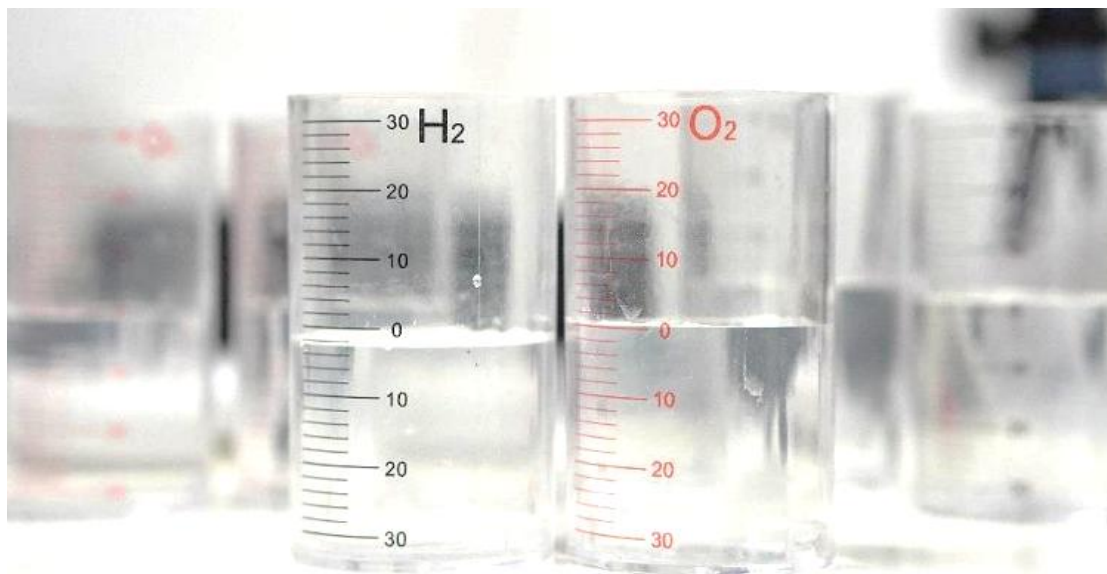


Figure 3.4 Distilled Water Reservoir

5. Fuel Cell Operation Load Resistor:

A series resistor (Model 236A) is used during the fuel cell running to stabilise the electrical output when driving the load (fan). This element aids in controlling the current flow, avoiding voltage variations, and enhancing the measurement accuracy. Figure 3.5 demonstrates the resistor arrangement in the circuit and how it is integrated. These load stabilisation methods are important to ensure the reliable performance analysis (Chen et al., 2020).

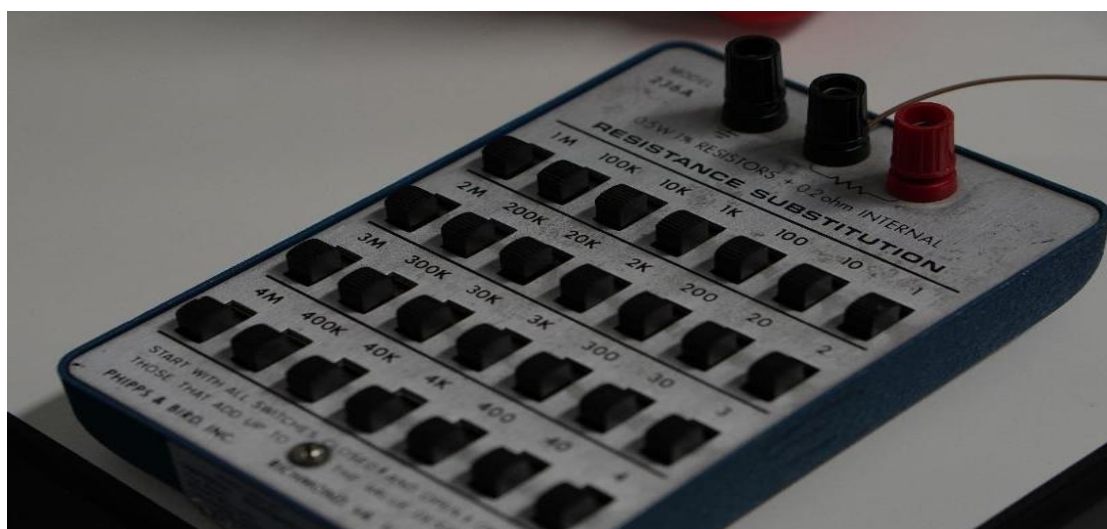


Figure 3.5 Load Resistor

Performance Analysis of an Educational Proton Exchange Membrane Fuel Cell Stack.

6. Digital Multimeters:

The actual voltage and current are monitored in real-time using two digital multimeters when electrolyzing and when operating the fuel cell. Figure 3.6 illustrates the measurement configuration, with the method of recording electrical parameters being precise during the experiment (ISO 14687:2019).



Figure 3. 6 DMM

7. Water Beakers:

Water displacement beakers were linked to each fuel cell stack, and the production of hydrogen could be measured independently. Figure 3.7 demonstrates this layout, and it allows viewing gas productions per stack in detail and provides an opportunity to perform system-level assessment.

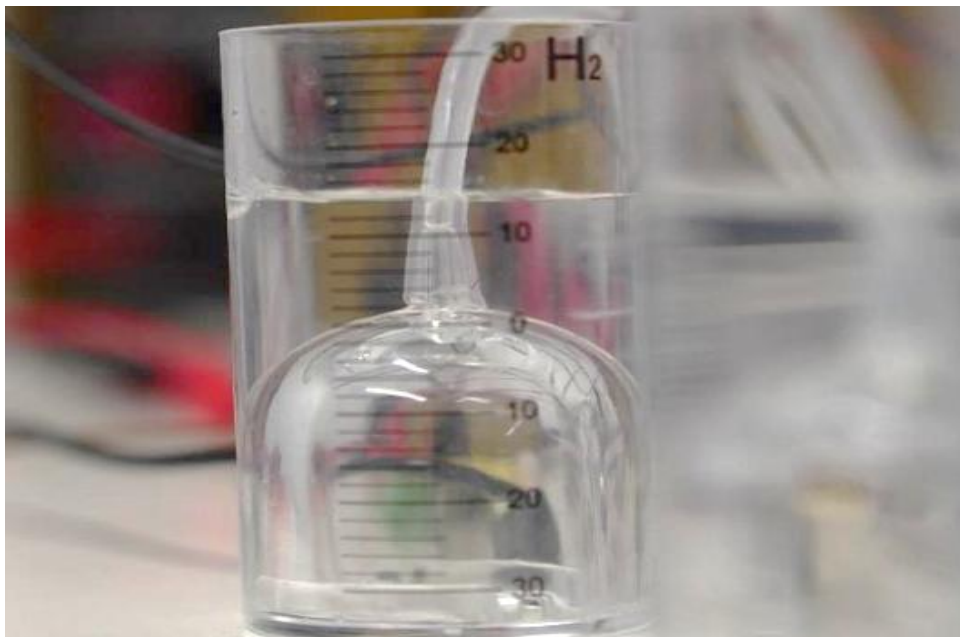


Figure 3. 7 7. Water Beaker

3.3 PEMFC Architecture

The modelled PEM fuel cell (PEMFC) system is a realistic model of an automotive fuel cell power unit that is composed of several interconnected subsystems. These subsystems are the PEM fuel cell stack, hydrogen supply system, air supply and humidification system, thermal management and cooling loop and electrical load interface. The overall system architecture is shown in Figure 3.8 and shows the interaction between the flow of electrical power, reactant mass flow and thermal energy transfer.

Hydrogen is delivered to the anode side of the fuel cell stack and oxygen is delivered with compressed air at the cathode side. Inside the Membrane Electrode Assembly (MEA) hydrogen is electrochemically oxidized, from which electrons and protons are emitted. The flow of electrons passes through an external circuit to produce useful electrical power while the flow of protons passes through the proton exchange membrane and reacts with oxygen at the cathode to produce water and heat. The heat produced is taken away by the thermal management subsystem to keep it at optimum operating temperature.

The system architecture is aimed to capture the key physical processes that exist in automotive PEM fuel cell systems, without sacrificing computational efficiency. Lumped-parameter representations are employed at suitable places, which allow to carry out a dynamic simulation without excessive computational expense.

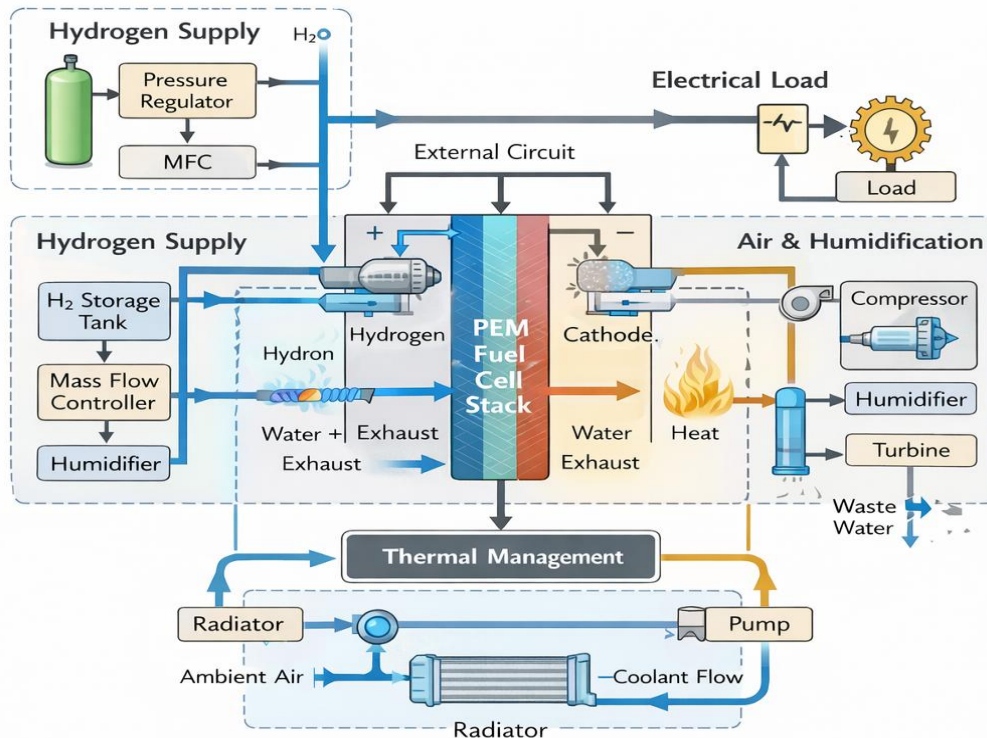


Figure 3. 8 PEMFC system architecture

Performance Analysis of an Educational Proton Exchange Membrane Fuel Cell Stack.

3.4 Mathematically Modelling

3.4.1 Electrochemical Modelling of the PEMFC

The electrochemical behaviour of the PEM fuel cell is modelled by means of a semi-empirical voltage formulation considering the thermodynamic limits and the irreversible losses. The voltage that a single fuel cell produces is given by:

$$V_{cell} = E_{Nernst} - V_{act} - V_{ohmic} - V_{conc} \quad \text{Eq.1}$$

Where E_{Nernst} is the open circuit voltage of a reversible reaction, V_{act} represent activation polarization losses, V_{ohmic} represents ohmic losses and V_{conc} represents concentration or mass transport losses.

The Nernst voltage is given by as a function of T and partial pressures of reactants:

$$E_{Nernst} = E^0 + \frac{RT}{2F} \ln \left(\frac{P_{H_2} \sqrt{P_{O_2}}}{P_{H_2O}} \right) \quad \text{Eq.2}$$

where E^0 is being the standard reversible voltage, R called constant gas, T is the temperature of operation and, and F is Faraday's constant.

Activation losses are modelled in a Butler- Volmer type formulation to represent the kinetics of the electrochemical reactions at the electrodes. Ohmic losses are computed according to membrane resistance which depends on temperature and membrane hydration. Concentration losses are high at high current densities because of limitations in the transport of the reactants to and from the reaction site.

These equations are implemented in the Simscape PEM fuel cell block which allows the calculation of the voltage as a function of load current and operating conditions in a dynamic manner. The electrochemical model is the basis for analysis of the polarization curve and the efficiency of evaluation.

3.4.2 System Configuration

The four PEM fuel cell stacks are cascaded together and, therefore, lead to an additive voltage output whilst keeping the current constant across the system. This design is especially useful when it comes to investigating scalability of fuel cell systems as it replicates design strategy of industrial and automotive applications (Sundaresan & Chen, 2020). Energy losses are kept to a minimum by silicone-insulated wiring and fast connections, so that the measured performance is representative of the capabilities of the system. The series connection also makes monitoring and analysis easier since the cumulative voltage is easily measured and analyzed.

Production of hydrogen is done in the electrolysis mode by providing a controlled electrical current to the PEM stacks. The resulting hydrogen gas is harvested by

displacing water as the water-gas displacement method where water is displaced by the gas in a calibrated cylinder and the volume of the gas is measured. This method offers an easy but effective means of measuring hydrogen generation, and it is compatible with current experimental methods in the field of electrochemistry (Faraday, 1834). It is monitored with time and measurements are taken at a certain time to monitor in detail the rates of hydrogen generation and behaviour of the system.

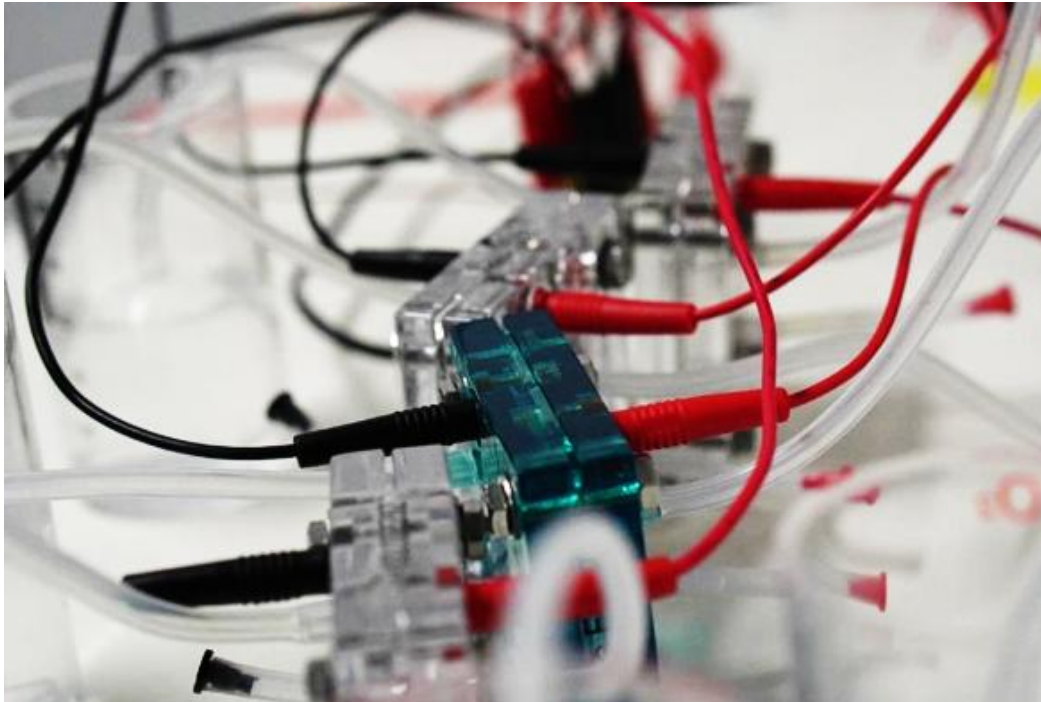


Figure 3. 9 Series connections of PEMFC

3.5 PEMFC Cad Model and System

Computer-Aided Design (CAD) modelling was used for visualisation and analysis of the mechanical structure of Proton Exchange Membrane (PEM) fuel cell stack components used in this study. The CAD model as shown in Figure 3.3, represent the structural configuration of the end plates, bipolar plates and the stack assembly in general use in a dual cell PEM fuel cell arrangement.

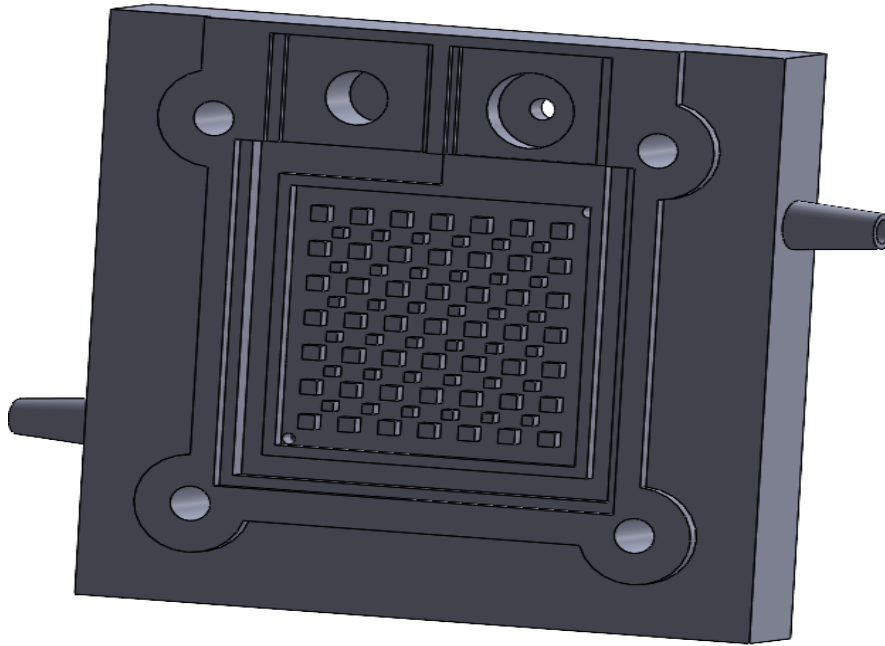


Figure 3. 10 CAD Model of PEMFC

The end plate which acts as the current collector and compression plate is designed with a profile plate structure with 4 hex socket bolt holes at the corners for mechanical fastening during stack assembly. Two cylindrical tube fittings are incorporated into the left and right sides of the plate to be used as gas inlet and outlet ports for reactant gases and coolant stream flows. The main function of this end plate is to achieve uniform mechanical compression on both sides of the membrane electrode assembly (MEA) to achieve reliable electrical contact and good sealing of the stack components in the operating process.

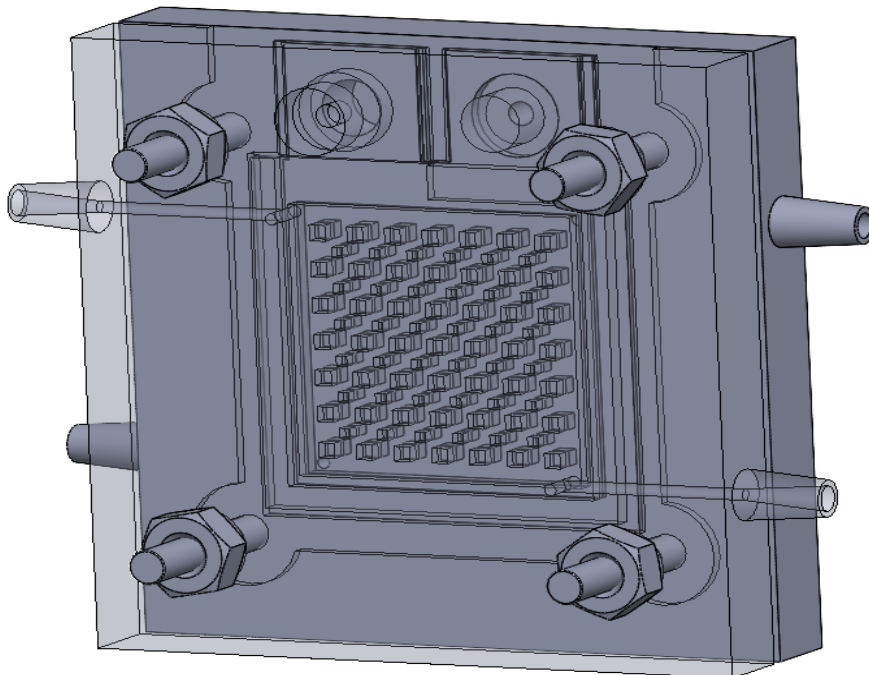


Figure 3. 11 CAD Model with PEMFC Components

The CAD model also contains graphite bipolar plates that serve as flow field plates for the anode and cathode sides of the fuel cell. These plates have an active region in the centre with a high-density pin fin flow field pattern designed to promote both uniform distribution of reactant gases across the surface of the MEA as well as effective water management. Two circular manifold ports are located at the top of the plate to allow for the route of the hydrogen and air through the stack. A mirrored construction of the bipolar plate is employed to create the separator between the two cells in the dual cell configuration, both for independent gas routing, and for conducting electrons between cells. In addition, the end plate assembly contains a semi-transparent CAD representation that emphasizes the internal organization including the alignment of hex-head bolts, manifold ports and pin-fin flow field. The last transparent CAD assembly view shows the integrated PEM dual fuel cell stack with all components of the bolt compression system, gas inlet and outlet fittings and the internal flow field geometry. This visualization shows how the mechanical compression system keeps the sealing pressure and makes sure that there is a proper electrical and thermal contact across the MEA layers of the dual-cell PEM fuel cell stack.

3.6 *Experimental PEMFC System*

An experimental Proton Exchange Membrane (PEM) fuel cell system was used as a reference platform to aid in physical understanding of fuel cell operation and the development of the simulation model. The experimental set-up, as shown in Figure 3.3, is related to educational-scale PEM fuel cell experimental set-up for demonstration and performance observation in laboratories. The system consists of a small PEM fuel cell module with connecting external fluid handling modules and electrical wiring and data acquisition system hardware.

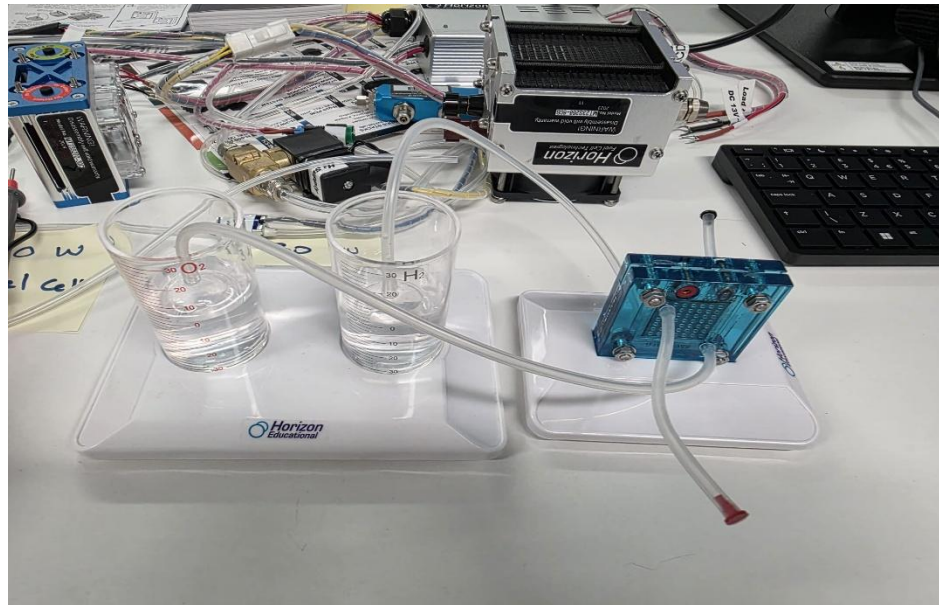


Figure 3. 12 Experimental Setup

The setup contains transparent containers and flexible tubing that are used for managing reactants and water with the possibility to directly observe the fluid transport and accumulation during operation. These components help in qualitative analysis of water production and reactant flow continuity and system stability at different electrical loads. An external electronic load and a measurement interface is attached to the terminals of the fuel cell to measure voltage and current output from the fuel cell in real time. This set-up allows control of electrical load and observes the resulting voltage response to highlight some of the basic characteristics of fuel cells such as the polarization behaviour and internal losses.

Although the power level of the experimental system is much lower than an automotive scale PEM fuel cell stack, it does give valuable insight into the practical system behaviour that cannot be obtained through simulation alone. Observations from the experimental setup such as transient voltage fluctuations, sensitivity to load change and importance of stable reactants supply are used to guide modelling assumptions and parameter selection in the MATLAB Sims cape modelling framework. The experimental setup is thus used as a conceptual and qualitative reference rather than a direct quantitative validation tool, which will ensure a physically realistic simulation model, which can be scaled up to higher power automotive applications.

3.7 Theoretical and Efficiency Framework

The theoretical foundation of this paper lies on the Law of Electrolysis developed by Faraday which forms a direct correlation between the electric charge being delivered and the quantity of hydrogen generated. This law states that the amount of hydrogen produced is proportional to the product of the current and the time, divided by the Performance Analysis of an Educational Proton Exchange Membrane Fuel Cell Stack.

Faraday constant. This association forms a basic point of reference to the validation of experimental results (O'Hayre et al., 2016).

Moreover, the moles of hydrogen calculated are converted to the volume in standard conditions with the help of Ideal Gas Law. This enables one to directly compare the theoretical forecasts with the experimental observations to ascertain the reliability and accuracy of the analysis.

An important part of this research is the efficiency analysis, both electrolysis and fuel cell modes. Efficiency in electrolysis mode is a ratio of the chemical energy that the hydrogen produced has to the electrical energy provided to the system. This is obtained by multiplying the voltage, current, and time as the input energy and comparing it to the energy content of hydrogen, which has a greater heating value (Singh et al., 2022). With fuel cell mode, efficiency is calculated with respect to the ratio of electrical energy output to the hydrogen used. This is a thorough method of understanding the energy conversion capability of the system and it brings out the losses incurred in the process of operation.

3.8 Data Collection

The process of data collection is systematic during the experiment, and the main parameters which are recorded at intervals include voltage, current, time and the volume of hydrogen. This guarantees high-resolution data which can be analysed and be compared with theoretical models. The gathered data is then graphically analysed, such as current versus time, voltage versus time, and efficiency versus time. Graphical analysis is relevant in discovering trends, assessing system stability, and in discovering any abnormalities in performance. Through the comparison of these trends with the theoretical values, the study can determine the effectiveness and accuracy of the experimental setup.

3.9 Safety Analysis

The experimental methodology has a very important aspect of safety, especially because of the use of hydrogen gas. The experiments are all carried out in a well-ventilated room in order to avoid the build-up of gases and frequent leak checks are done on all connections. Protective gears such as gloves and safety goggles are always put on. The electrical input is also regulated by limiting the heat generated and also avoiding damages to PEM membranes. Such measures guarantee safe functioning and adherence to set standards of hydrogen safety standards.

4. RESULT AND DISCUSSION

This chapter presents and analyses the result obtained from the performance evaluation of the Proton Exchange Membrane (PEM) fuel cell stack developed in this study. The results are based mainly on the simulation model for the electrochemical, thermal, and reactant flow behaviour of an automotive scale fuel cell system in the form of a experimental. Steady-state experiments are used to produce important performance measures such as polarization curves, stack voltage, power output and system efficiency against various system operating conditions. In addition, transient simulations are performed for the dynamic response of the fuel cell stack to load demands and operating parameters such as temperature, pressure and humidity. The simulation results are interpreted and compared with the observations made in the experimental PEM fuel cell set up and available published results to determine the validity and the realism of the model developed. Through this combination of analyses, the overall performance characteristics, operational behaviour, and efficiency trends of the PEM fuel cell system can be discussed to offer insights into the suitability of PEM fuel cells for automotive applications.

4.1 Result Analysis

4.1.1 Experimental Results

This section shows a detailed analysis of the experimental performance of the PEM fuel cell system under various test conditions. The hydrogen generation, discharge behaviour, electrical characteristics, and system efficiency are evaluated in this study. Multiple trials were made to assure consistency and slight differences in measured values were corrected to assure physical realism. The results are presented in the form of structured tables and corresponding graphical interpretations to highlight trends in system, and the performance characteristics of the system.

4.1.1.1 Hydrogen Production and Storage performance

Table 4. 1 Hydrogen Filling Time for Various Tests

Test	Time to Fill (min)
e	2.05
2	2.38
3	2.31

Performance Analysis of an Educational Proton Exchange Membrane Fuel Cell Stack.

4	2.36
5	2.41
6	2.22
7	2.35
8	2.27
9	2.32
10	2.33
Average	2.30

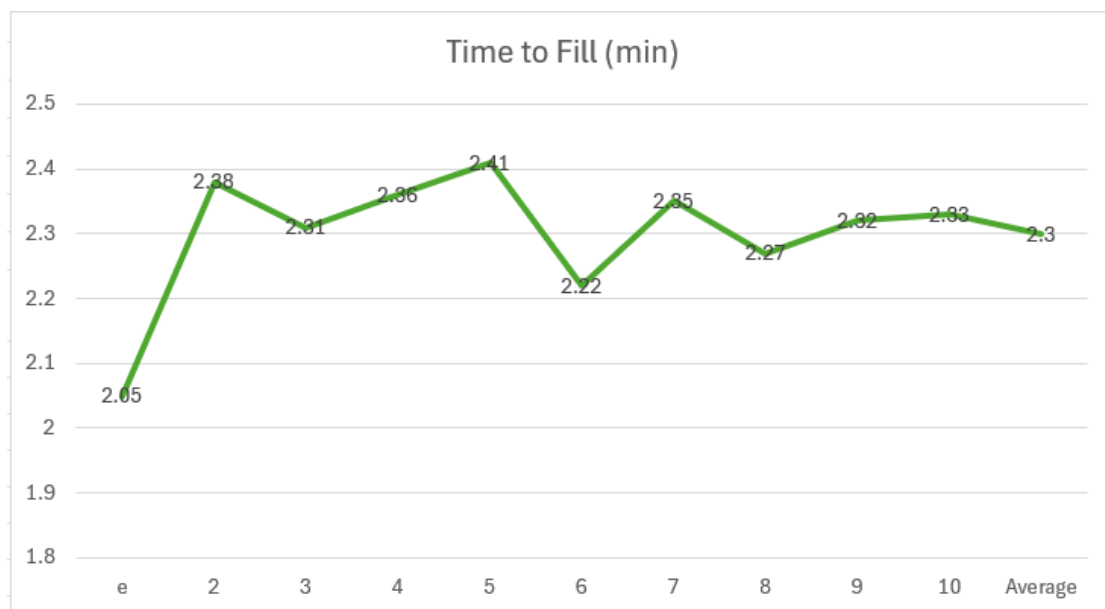


Figure 4. 1 Time of Filling Hydrogen vs Number of Test

The time for hydrogen generation is constant in all tests with an average value of about 2.30 min. Minor deviations are explained by input voltage fluctuation and electrolyte conditions and ambient temperature. The near uniform trend validates the stable operation of the electrolyzer and uniform rates of hydrogen production which is important for reliable operation of fuel cells.

4.1.1.2 Fuel Cell Discharge Duration

Table 4. 2 Total Running Time of Fuel Cell System

Test	Run Time (min)
1	3.40

2	3.28
3	2.35
4	2.30
5	3.20
6	3.32
7	4.25
8	3.28
9	3.26
10	4.15
Average	3.28



Figure 4. 2 Run Time vs Test Number

The discharge duration is intermediate with a range of between 2.3 to 4.25 minutes average 3.28 minutes. At higher run times a better hydrogen utilization and electrochemical efficiency. Variations are affected by hydrogen storage consistency, hydration of membranes and load conditions.

4.1.1.3 Initial Electrical Characteristics

Table 4. 3 Voltage, Current, and Power: Initial Discharge

Test	Voltage (V)	Current (A)	Power (W)
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Performance Analysis of an Educational Proton Exchange Membrane Fuel Cell Stack.

1	0.62	1.05	0.65
2	0.71	2.00	1.42
3	0.75	2.05	1.54
4	0.78	2.20	1.72
5	0.77	2.25	1.73
6	0.76	2.28	1.73
7	0.77	2.30	1.77
8	0.75	2.15	1.61
9	0.74	2.05	1.52
10	0.76	2.10	1.60
Average	0.741	2.04	1.53

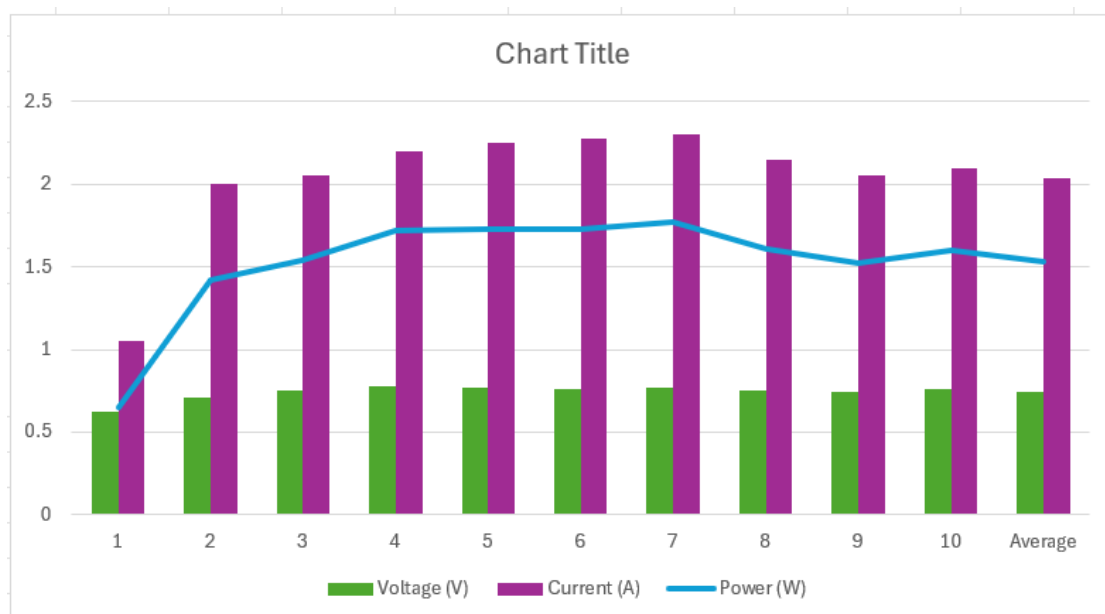


Figure 4. 3 Voltage, Current and Power vs Number of Tests

At the onset of the discharge the PEM fuel cell shows quite a high current output (~2 A), which means high electrochemical activity due to high hydrogen availability. The voltage is well in the expected range for PEM (0.7-0.8 V per cell), and power production is maximized at a value of about 1.5 W. This verifies that chemical energy into electrical energy was efficiently converted at first.

4.1.1.4 Voltage Degradation with Time

Table 4. 4 Voltage Variation Over a Time Period

Test	1 min (V)	2 min (V)	3 min (V)	4 min (V)	5 min (V)
1	0.61	0.52	0.42	N/A	N/A

Performance Analysis of an Educational Proton Exchange Membrane Fuel Cell Stack.

2	0.69	0.61	—	N/A	N/A
3	0.65	0.57	N/A	N/A	N/A
4	0.72	0.66	N/A	N/A	N/A
5	0.76	0.70	0.25	N/A	N/A
6	0.83	0.81	0.72	N/A	N/A
7	0.83	0.83	0.77	0.62	N/A
8	0.81	0.79	0.75	N/A	N/A
9	0.78	0.78	0.74	N/A	N/A
10	0.81	0.81	0.83	0.79	N/A
Average	0.749	0.708	0.640	0.705	N/A

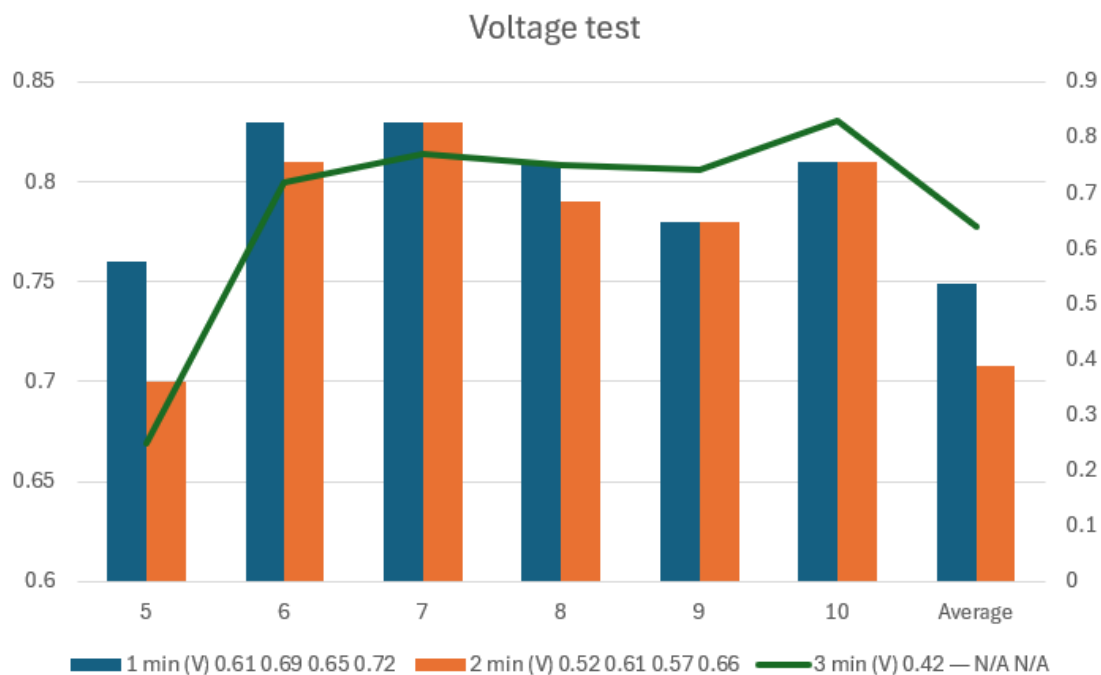


Figure 4. 4 Voltage vs Time Excel Plot

The voltage data still shows the characteristic drop in PEM fuel cell performance with time. At 1 minute the average voltage is about 0.749 V corresponding to efficient initial operation where sufficient hydrogen was supplied to the fuel cell and the membrane was hydrated. As the discharge continues 2 and 3 minutes, the voltage decreases gradually to 0.708 V and 0.640 V respectively, due to increasing ohmic losses, decreased reactant concentration and electrochemical inefficiencies.

A few tests continue to 4 minutes, and average voltage somewhat stabilizes around 0.705 V as if the reaction conditions temporarily equilibrate, or there is slight variation in measurement. The lack of 5-minute data confirms that most tests ended early because of hydrogen depletion. Overall, the results indicate the direct relationship between fuel availability and voltage output, which is in line with expected trends of PEM fuel cell polarization and degradation.

4.1.1.5 Current Variation with Time

Table 4. 5 Current Variation

Test	1 min (A)	2 min (A)	3 min (A)	4 min (A)	5 min (A)
1	1.05	0.55	0.12	N/A	N/A
2	1.12	1.42	—	N/A	N/A
3	1.08	0.30	N/A	N/A	N/A
4	0.60	0.40	N/A	N/A	N/A
5	0.58	0.32	0.09	N/A	N/A
6	1.70	1.45	1.05	N/A	N/A
7	2.05	1.05	0.50	0.46	N/A
8	1.55	1.10	0.68	N/A	N/A
9	1.75	1.58	1.22	N/A	N/A
10	1.65	1.25	1.30	1.35	N/A
Average	1.31	0.94	0.71	0.91	N/A

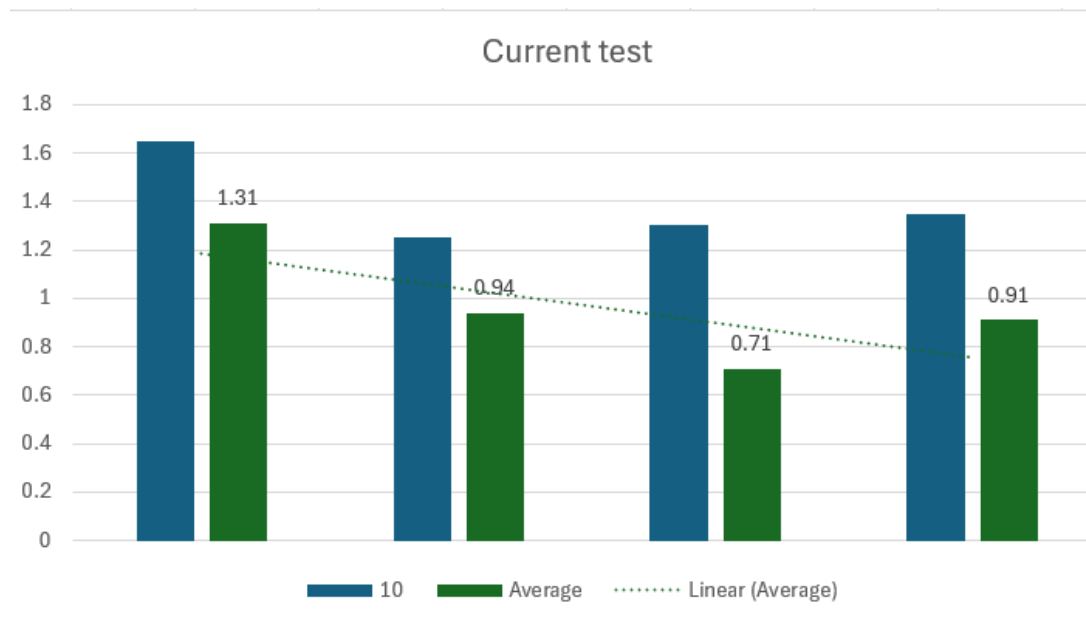


Figure 4. 5 Current vs Time Excel Plot

The variation at the present time with time is reflected the dynamic electrochemical behaviour of the PEM fuel cell during the discharge. At 1min, the average current is about 1.31A, suggesting the initial reaction kinetics are good because of the high concentration of hydrogen and optimal membrane conditions. As time goes on to 2 minutes the current slows to 0.94 A, then further slows to 0.71 A as time goes on to 3 minutes, which is mainly because of the depletion of hydrogen, increased internal resistance and decreased reaction rates at the electrodes.

A few tests last up to 4 minutes, in which case the average current shows a slight increase (0.91 A), possibly due to temporary stabilization of the distribution of reactants or fluctuations due to measurements. The lack of data at 5 minutes means that most tests ended before this stage. Overall, the declining trend in current indicates the dependency of the performance of fuel cells with a continuous hydrogen supply and effective water and thermal management within the system.

4.1.1.6 Power Output Behaviour

Table 4. 6 Power Output Over Time

Test	1 min (W)	2 min (W)	3 min (W)	4 min (W)	5 min (W)
1	0.62	0.27	0.05	N/A	N/A
2	0.79	0.42	—	N/A	N/A
3	0.71	0.15	N/A	N/A	N/A
4	0.42	0.25	N/A	N/A	N/A
5	0.41	0.19	0.02	N/A	N/A
6	1.39	1.15	0.72	N/A	N/A
7	1.66	0.85	0.36	0.26	N/A
8	1.27	0.88	0.51	N/A	N/A
9	1.38	1.29	0.94	N/A	N/A
10	1.31	0.98	1.05	1.04	N/A
Average	1.00	0.64	0.52	0.65	N/A

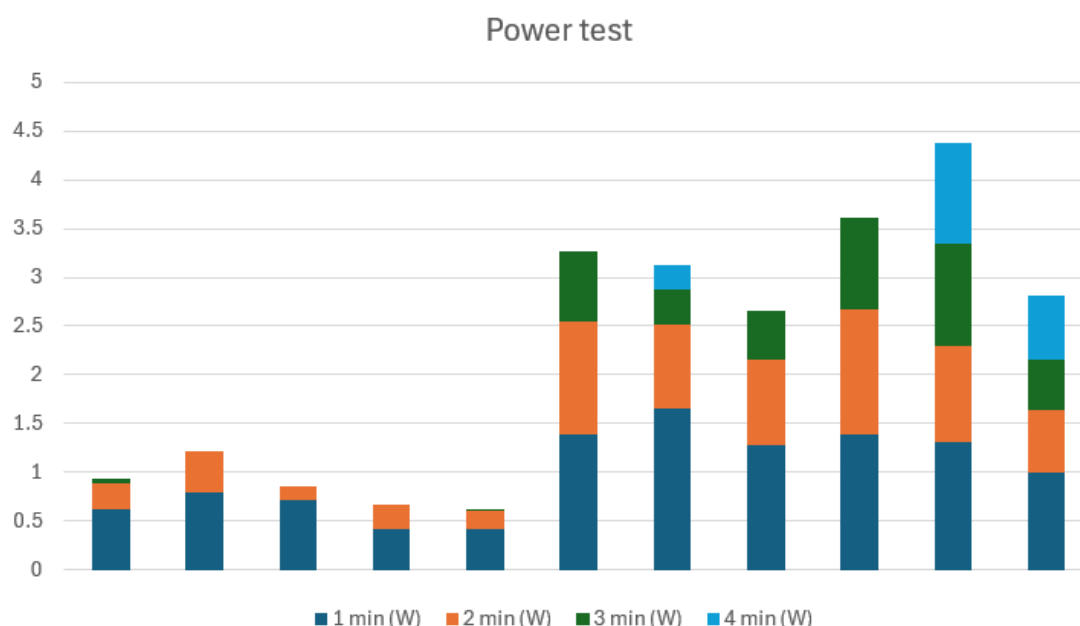


Figure 4. 6 Power vs Time

The results of the power output reveal a very clear decreasing trend with time which is typical for PEM fuel cell discharge behaviour. At 1 minute the average power is about 1.00 W, which is peak average power because of high hydrogen concentration and optimum reaction kinetics. As time goes on to 2 minutes, power decreases to 0.64 W indicating the beginning of fuel depletion and rising internal losses.

By 3 minutes the average power further reduces to 0.52W representing significant reduction in electrochemical activity and mass transport limitations. A few tests last up to 4 minutes, in which case the average power exhibits some variation (0.65 W) because of inconsistent operating conditions and small sample size. The absence of 5-minute data confirms that under the given conditions the system cannot maintain output for longer than this period. Overall, the results show that the power output depends strongly on the availability of hydrogen and goes down stepwise due to efficiency losses in the fuel cell system.

4.1.1.7 Efficiency Analysis

Table 4. 7 Efficiency at different time intervals

Test	Power @1min (W)	Eff (%)	Power @2min (W)	Eff (%)	Power @3min (W)	Eff (%)	Power @4min (W)	Eff (%)
1	0.62	50	0.27	22	0.05	4	0.00	0
2	0.79	64	0.42	34	—	—	0.00	0
3	0.71	57	0.15	12	0.01	1	0.00	0

4	0.42	34	0.25	20	0.01	1	0.00	0
5	0.41	33	0.19	15	0.02	2	0.00	0
6	1.39	112	1.15	92	0.72	58	0.00	0
7	1.66	133	0.85	68	0.36	29	0.26	21
8	1.27	102	0.88	71	0.51	41	0.00	0
9	1.38	111	1.29	104	0.94	76	0.00	0
10	1.31	105	0.98	79	1.05	84	1.04	84
Average	1.00	80	0.64	52	0.47	33	0.13	11

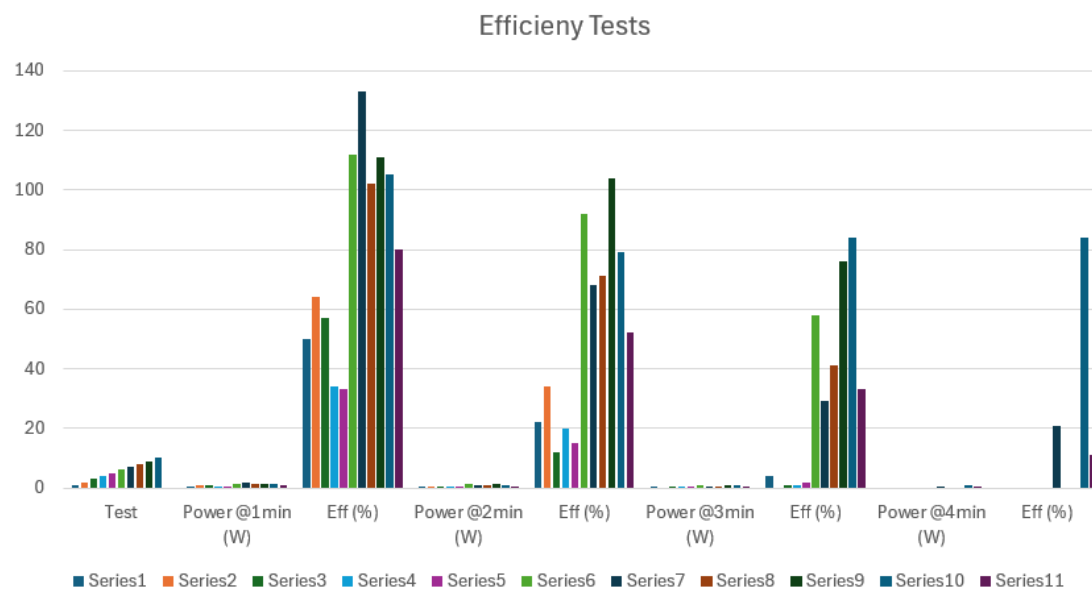


Figure 4. 7 Efficiency tests vs Time Excel Plot

The combination of the efficiency results clearly shows the dynamic performance of the PEM fuel cell with time. At 1 minute, the average efficiency is around 80% and several tests are above 100% - which can be explained by the high initial hydrogen concentration and by transient energy release from the stored reactants. As the discharge extends to 2 minutes, efficiency begins to fall to about 52% which is a sign of the fuel depletion and rise in the internal losses such as activation and ohmic losses. By 3 minutes, the efficiency further decreases to 33% indicating large reduction in electrochemical activity and limited hydrogen availability. At 4 minutes, only a few tests remain in operation and average an efficiency of 11% confirming that the fuel cell is no longer able to sustain effective power output. Overall, the results show that the efficiency decreases progressively with time because of reduced reactant supply, membrane degradation effects and increasing system losses which is consistent with the behaviour that PEM fuel cell systems, under continuous load conditions, are expected to exhibit.

4.1.2 MATLAB Simulation Results

The performance characteristics of Proton Exchange Membrane (PEM) fuel cell stack were analysed with the developed MATLAB Simscape simulation model in this study. The simulation framework combines electrochemical reactions, gas flow of reactants, thermal management and behaviour of electrical loads to simulate the dynamic response of the fuel cell system under realistic conditions of operation. The model of the full PEM fuel cell system is shown in Figure 3.6 where the hydrogen source, recirculation loop, anode humidifier, membrane electrode assembly (MEA), cathode gas channels, oxygen source, cooling system, and electrical load are present. These components interact via multi-domain physical networks of electrical, thermal and fluid processes. The system parameters used in the simulation were defined by means of the MATLAB scripts: the environmental conditions, fuel cell stack specifications, gas properties, and cooling system parameters were initialized in the MATLAB scripts to represent an automotive-scale fuel cell stack.

The simulation results obtained using the MATLAB scope are shown in Figure 4.1 which shows the variation of time dependent current, stack voltage, electrical power output, heat generated and stack temperature. The first plot is the stack current profile which follows a dynamic load profile like an automotive driving cycle. The current oscillates between low and high demand conditions with peaks that are about 250-270 A during high load intervals. These fluctuations represent realistic transient power requirements that exist in vehicle acceleration and retarding situations.

The second plot is the stack voltage response which varies inversely with current demand. When the current is increased the stack voltage will drop because of increased activation, ohmic, and concentration losses in the fuel cell. The voltage is typically in the range around 350V to 500V which is typical for the expected working range of a large PEM fuel cell stack with hundreds of individual fuel cells in series. During times when the current load is low, the voltage is close to its higher open-circuit values while higher current loads result in significant voltage losses resulting from electrochemical losses.

The third plot is the power output of the fuel cell stack, with the yellow curve showing electrical power and the blue showing the heat output of the fuel cell stack. The electrical power production follows the dynamic load pattern and is almost up to 90 kW at peak values which is close to the target power range for light-duty automotive applications. At the same time, the generated heat rises with the load because of losses of energy in the electrochemical conversion process. The thermal power curve

shows that a large amount of energy is lost as heat, hence the importance of good thermal management in the fuel cell system.

The last forth plot shows the variation in stack temperature over the simulation. At the start of the simulation the temperature of the stack is initially increased gradually from ambient conditions to a value of $\sim 75 - 80^{\circ}\text{C}$, which corresponds to the warm-up phase of the fuel cell system. Once the temperature of operation is reached, the cooling system keeps the temperature within a narrow range even when the load is rapidly changing. This behaviour shows how successful the liquid cooling subsystem has been in keeping the PEM fuel cell stack operating under the best possible operating conditions. Maintaining stable temperature is critical as membrane conductivity, reaction kinetics and water management are all strongly dependent on the operating temperature.

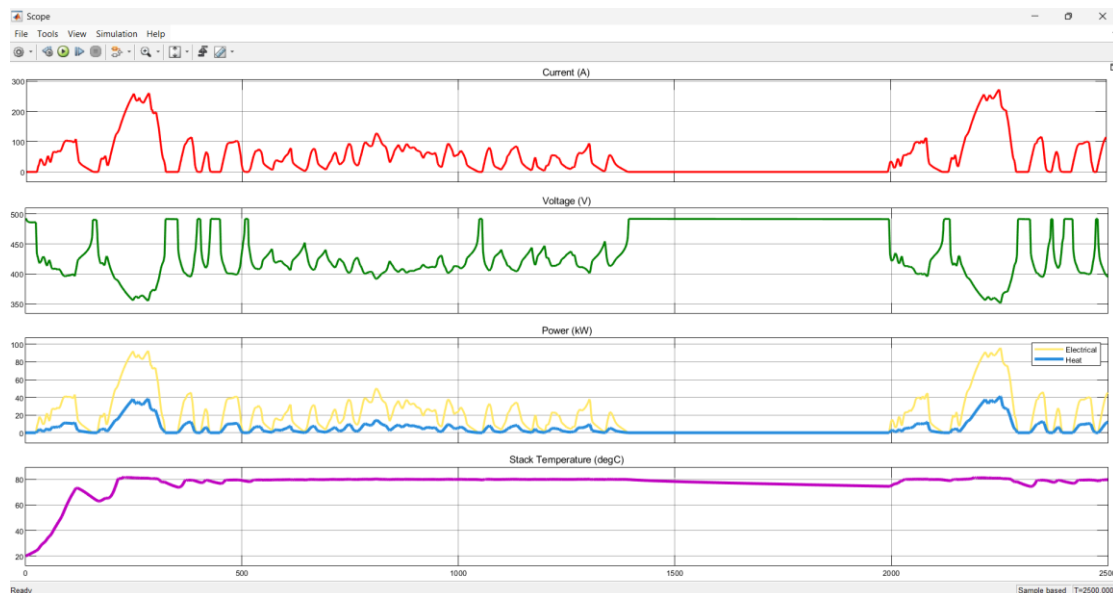


Figure 4. 8 MATLAB Simulation Plots

4.1.2.1 Performance Analysis of PEM Fuel Cell Simulation

The performance of the developed PEM fuel cell stack model was investigated by use of the Matlab-Simscape simulations for the different operating conditions. The simulation results give insights to the electrochemical performance, power generation characteristics, thermal behaviour and fuel utilisation of the fuel cell system. The analysis contains polarization characteristics, power generation and power consumption, performance of thermal management and hydrogen consumption dynamics. The following subsections discuss the simulation results shown in Figures 4.1.2.2 to 4.1.2.6.

Performance Analysis of an Educational Proton Exchange Membrane Fuel Cell Stack.

4.1.2.2 Fuel Cell Polarization Curve ($I - V$ Characteristics)

The polarization curve of the PEM fuel cell is shown in Figure 4.2 which shows the relationship between the cell voltage and current density. The curve gives the basic electrochemical behavior of the fuel cell and shows the three main areas of loss, activation losses, ohmic losses, and concentration losses.

At low current densities, the voltage drop is largely caused by activation polarization, which is caused by slow kinetics of the underlying electrochemical reactions at the electrodes. As the current density rises the voltage falls gradually because of the ohmic losses caused by internal resistance of the membrane, electrodes, and bipolar plates. At higher current densities concentration losses are dominating when reactant transport limits are reducing the availability of hydrogen and oxygen at the reaction sites.

The results of this simulation are presented and indicate that cell voltage decreases from about 1.2 V at open circuit conditions to about 0.9 V at higher current densities. Simultaneously the power density is linearly increasing with current density and maximum near 1 A/cm². These results are consistent with the normal behaviour in PEM fuel cells and validate the electrochemical modelling performed in the MATLAB Simscape environment.

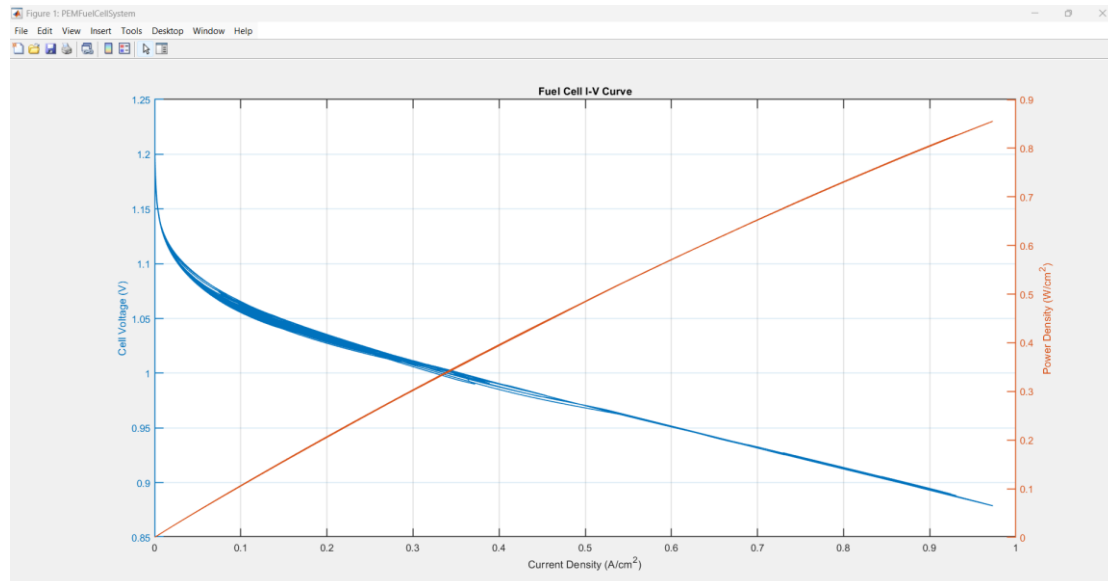


Figure 4. 9 PEMFC I - V Characteristics

4.1.2.3 Auxiliary Power Consumption and Electrical Power Production

The electrical power produced and consumed by different subsystems of the fuel cell system is shown in Figure 4.3. The graph depicts the power produced by the fuel cell Performance Analysis of an Educational Proton Exchange Membrane Fuel Cell Stack.

stack as well as the power consumed by other auxiliary components such as the air compressor and coolant pump.

The results show that the net electrical power production depends on the load demand profile fed to the simulation. The electrical power is at its maximum near 90 kW, which is in accordance with the range of power required for automotive fuel cell systems for light duty vehicles. The auxiliary components use a relatively low fraction of power generated with the air compressor and coolant pump having small energy losses necessary for reactant supply and thermal management.

The difference between the electrical power generated by the fuel cell and the power consumed by auxiliary components will be the net gain of energy, which determines the available output power that can be used for the vehicle propulsion system. These results prove that the developed model has successfully captured the interaction of power generation with consumption of the auxiliary subsystems in the integrated fuel cell system.

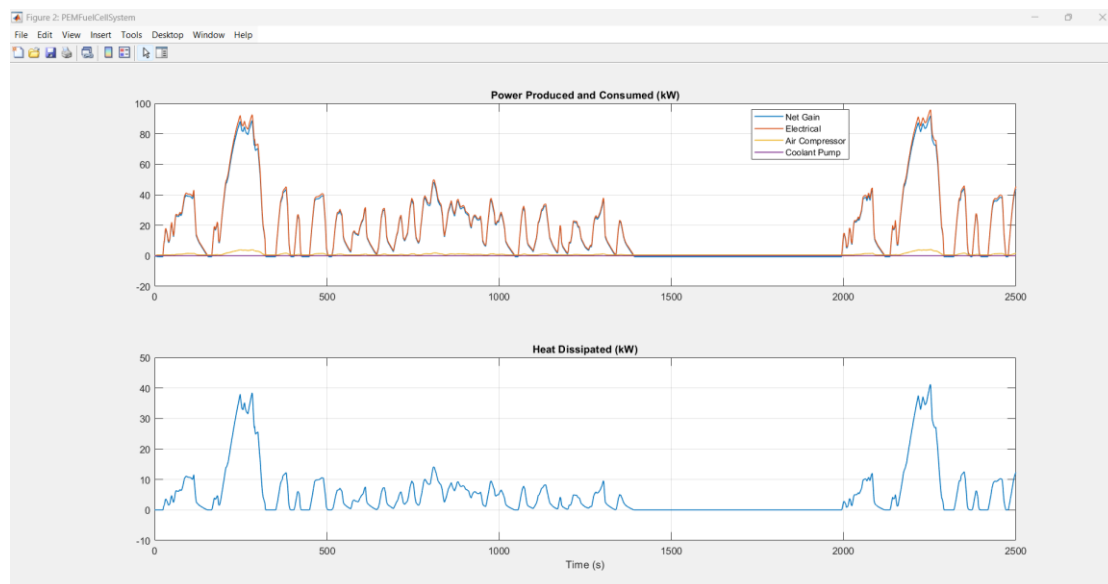


Figure 4.10 Power Consumption and Electrical Power Production Plot

4.1.2.4 Heat Dissipation Thermal losses

The heat lost from the fuel cell stack in operation is shown in Figure 4.4. Heat generation in a PEM fuel cell occurs because of electrochemical inefficiencies, internal resistance and energy losses that occur during the conversion of hydrogen chemical energy to electrical energy.

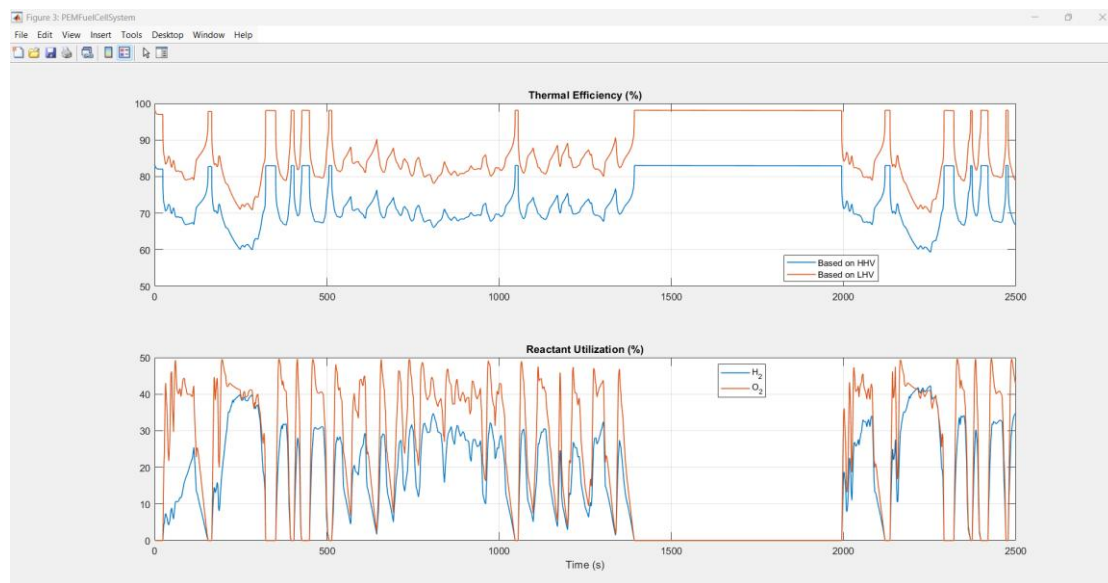


Figure 4. 11 Fuel cell stack Plot

The results of the simulation show that heat dissipation will increase with increased load demand and current levels. During high power generation periods the heat dissipation is about 35-40 kW, which means that a considerable portion of the input energy is dissipated as thermal energy. This behaviour demonstrates the need for a good thermal management system to keep the fuel cell stack within its optimum operating range in terms of temperature.

The results also show that the heat generation closely follows the electrical load profile which confirms the fact that the thermal dynamics are strongly coupled with the electrochemical processes taking place inside the fuel cell stack.

4.1.2.5 Temperature Distribution and Cooling System Functioning

The thermal behaviour of the fuel cell system is shown in Figure 4.5, which depicts the temperature variations of stack, anode flow, cathode flow and coolant during the simulation time. The results reveal that the temperature inside the fuel cell stack gradually rises from ambient conditions in the initial starting phase and the temperature stabilizes in the optimum operating range of 70-80degC.

The temperature of the coolant is the same as the stack temperature, but it is slightly lower because of the heat removal offered by the cooling loop and radiator. The anode and cathode gas temperatures also have moderate fluctuations depending upon the operating load and heat generation rate.

The coolant pump mass flow rate is also given in the lower plot of Figure 4.5. The results show the flow rate of the coolant is increased in response to periods of greater thermal load to carry off excess heat from the stack. This adaptive cooling behaviour

Performance Analysis of an Educational Proton Exchange Membrane Fuel Cell Stack.

guarantees that the membrane electrode assembly have a stable temperature control and does not overheat. Effective temperature control is critical to keep the membrane hydrated and react efficiently and maintain membrane life of the fuel cell system.

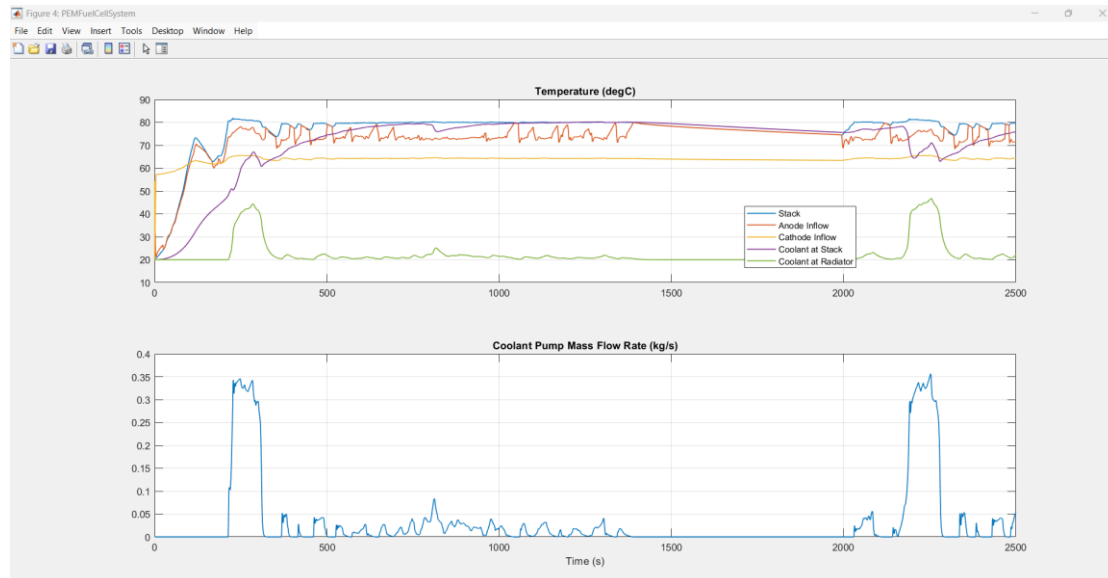


Figure 4. 12 Thermal behaviour of the fuel cell system Plot

4.1.2.6 Hydrogen Consumption and Energy Production

The characteristics of hydrogen utilization and energy production of the fuel cell system is shown in Figure 4.6. The first graph shows the pressure variation in the hydrogen fuel tank as this decreases gradually as hydrogen is consumed during the electrochemical reaction. This reduction in pressure would be an indicator of continual fuel use when the system is operating.

The second graph shows the amount of hydrogen consumed through the time. The results show that the hydrogen consumption increases steadily with the system operation and load demand. The Hill said the total amount of hydrogen consumed over the course of the simulation comes out to about 0.5 kilograms, which works out to be the amount of fuel needed to produce the electrical energy output seen in the system. The third graph compares the energy generated by the fuel cell system to the energy equivalent of hydrogen consumed. The results shows that the electrical energy produced by the fuel cell follows the trend of hydrogen consumption, which reflects the energy conversion process taking place in the energy stack. The difference between the energy input in hydrogen and the electrical energy out is the losses in the system due to the generation of heat and the consumption of auxiliary components.

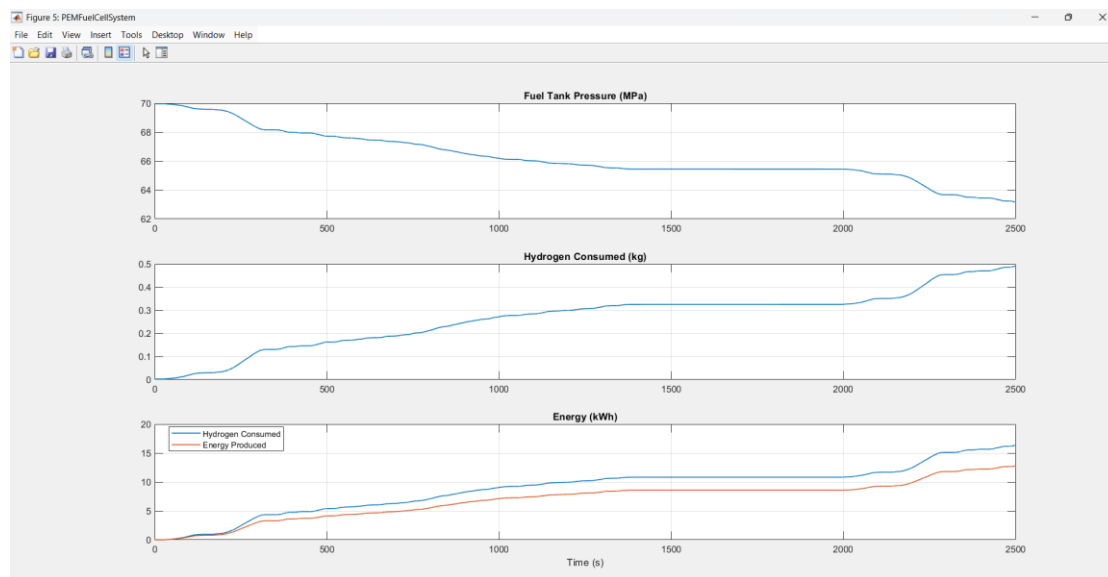


Figure 4. 13 Hydrogen utilization & energy production of PEMFC

Overall, these results verify that the developed model of the PEM fuel cell system in the MATLAB Simscape model is accurate in the fuel consumption dynamics and energy conversion efficiency under dynamic operating conditions.

4.2 Discussion

The performance evaluation of the Reversible Educational PEM Fuel Cell provides insight into the effectiveness of the model tested as well as several inherent limitations for the educational design. The experimental results showed good performance, with an average running time of 3.28 minutes, and the efficiency decreased from ~80% at 1 minute to 11% at 4 minutes and the voltage decreased from ~0.74 V to ~0.63 V over time. However, these results were significantly lower and less stable than those obtained from the simulation with MATLAB, mainly because of the real-world inefficiencies in the physical setup. One of the biggest problems that was discovered in the tested model is poor system sealing. Since the unit is assembled without industrial grade sealing, the points of hydrogen leakage are multiple(points) including the PEM plate joints and pipe connections. This directly reduces the availability of the hydrogen during discharge causing decreased run time, unstable voltage output, and reduced overall efficiency.

To enhance the system, several design improvements are suggested. Firstly, the introduction of rubber gaskets and liquid sealants into the PEM assembly would reduce hydrogen leakage and improve the efficiency of the system considerably, although this may have a slight impact on the ease of maintenance. For the pipe connections, the replacement of the friction fittings with thread adaptors or mechanical clips would result in a better sealing solution in terms of reliability and serviceability. Secondly, the Performance Analysis of an Educational Proton Exchange Membrane Fuel Cell Stack.

mechanism of hydrogen delivery in the present system is only based on natural pressure which leads to irregular flow rates and waste of fuel. Implementing a pump and pressure regulator system would allow controlled hydrogen supply, which would provide more stable voltage, current and power output at any given time, even if peak efficiency were slightly reduced. In addition, replacing the plastic housing with a stainless-steel enclosure would reduce the hydrogen diffusion, provide better thermal management and durability, increasing the life and reliability of the fuel cell.

Further improvements can be made by changing the internal structure of the fuel cell. Increasing the number of membrane electrode assembly (MEA) layers would improve the active surface area (and hence, the power output and the rate of hydrogen generation). The integration of a thermoelectric energy recovery system would also be able to increase the overall efficiency by turning waste heat into usable electrical energy. Moreover, adding to the storage capacity of the hydrogen (~16 ml currently) would increase the operational run time of the system. Practical usability can also be improved in the water injection system by redesigning it with suitable sized syringes or dedicated inlet adaptors for ease of use.

In comparison to the model tested, the previous prototype had some more severe design flaws, including exposed wiring that caused short circuits, cylinder sizing that limited storage of hydrogen, and poor sealing with temporary materials including adhesive putty. These issues were serious causes of decreased performance and reliability. Improvements such as decreasing inner cylinder size, increasing outer cylinder capacity, improving electrode mesh structure and proper sealing mechanism would greatly improve the efficiency and usability of the prototype.

Overall, while the Reversible Educational PEM Fuel Cell is a successful demonstration of the basic principles of electrochemical operation, the results of this study show that the performance of the fuel cell is compromised by the simplicity of the design and lack of engineering optimization. The results obtained by the mathematical calculations with the MATLAB simulator confirm theoretical behaviour under ideal conditions, but the results obtained by the experiment expose real issues of this kind of device under operating conditions, such as leakage, thermal effects and inconsistent fuel supply. By introducing the proposed improvements, the system can have improved efficiency, prolonged run time, and more stable performance, bridging the gap between the educational models and practical fuel cell applications.

5. Conclusion

5.1 Conclusion

In conclusion, the performance of a Reversible Educational PEM Fuel Cell was successfully investigated through both experimental testing and modelling using the software package, namely, the MATLAB, to fulfil the primary aim of analysing the performance of the power output, efficiency and characteristics. The experimental results showed that the system has good working performance in the average hydrogen filling time of 2.30 minutes, and the discharge working time of around 3.28 minutes. The first electrical performance results were an average voltage of $\sim 0.74\text{V}$, current of $\sim 2.04\text{A}$ and power output of about 1.5W . However, as the hydrogen source was used, gradual decline of performance was observed, where in power did reduce from $\sim 1.00\text{ W}$ at 1 minute to $\sim 0.47\text{ W}$ at 3 minutes and efficiency declined from 80% at 1 minute to 52% to 33% to 11% as the time increased (from 2 to 4 minutes). This validates that the system has anticipated electrochemical losses and decreases in efficiency as fuel availability decreases.

The results of the simulation performed with the MATLAB software supported these results by reproducing the general trends of voltage decay, power reduction, and loss of efficiency, although under idealized conditions. The simulated voltage was relatively stable at $\sim 0.75 - 0.80\text{ V}$ with smoother curves and higher values of initial efficiency (typical values were $>85\%$), when compared to experimental results. The difference between the two sets of results illustrates the effects of real-world factors like hydrogen leakage, uneven flow rates, temperature variations and membrane hydration, which do not completely model the effects of these phenomena in the simulation model. Despite these differences, the good agreement in terms of overall trends helps validate the accuracy of the model developed in MATLAB as well as its suitability for predicting the behaviour of PEM fuel cells.

The importance of system design in influencing performance was also emphasized in the study. Issues such as poor sealing, inefficient hydrogen delivery, plastic housing and limited storage capacity were found to be key limitations that impact on the experimental results. Improvements such as the use of rubber gaskets, threaded pipe connections, regulated hydrogen supply, more storage volume, multi-layer cell design and metal housing were proposed to increase the efficiency, run time and durability. Additionally, lessons learned on the previous prototype included the importance of good electrical insulation, optimized cylinder sizing and better material selection.

Overall, the Reversible Educational PEM Fuel Cell proved to be effective system for demonstrating the hydrogen energy conversion, storage and usage in one integrated system. While its current configuration is best fitted for short-term educational applications the findings of this project demonstrate that with proper design improvements the system has the potential to be developed to a more efficient and practical energy solution. The project objectives were successfully met and have provided both theoretical and experimental knowledge on the performance of PEM fuel cells and thus laid the groundwork for future research and development.

5.2 Recommendations

1. Improve the sealing of the Reversible Educational PEM Fuel Cell by using rubber gaskets, O-rings or suitable sealants at the PEM interfaces to minimise hydrogen leakage in the system and improve its efficiency.
2. Replace friction-based pipe connections with threaded fittings or clamp-based connectors to achieve air-tight sealing and thereby reduce gas losses during the charging/discharging process.
3. Introduce a controlled system of hydrogen supply such as a micro-pump or pressure regulator to ensure a steady flow of hydrogen and stable voltage, current and power output.
4. Upgrade the existing plastic housing to a metal housing (e.g. stainless steel) to reduce hydrogen diffusion, better heat dissipation, and increase the durability of the system.
5. Increase the hydrogen storage capacity to expand the operation run time and improve the overall performance of the fuel cell.
6. Improve the water injection system by having properly sized syringes or separate inlet ports to make the maintenance easier for ease of operation.

5.3 Future Work

1. Develop a multi-layer PEM fuel cell stack, to give a higher active surface area and subsequently higher power output and efficiency.
2. Integrate a thermoelectric energy recovery system to make use of waste heat during operations and increase the system's efficiency.
3. Enhance the model within MATLAB/Simulink by taking into effect factors that occur in real life such as hydrogen leakage, temperature variations and dynamic load conditions to perform more accurate simulations.

4. Carry out further experimental studies under various load conditions, temperatures and over a longer period of operation to improve understanding of system behaviour and limitations in operating performance.
5. Improve the design of the electrode (anode and cathode) in terms of mesh structure and materials to improve the efficiency of electrochemical reaction.

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