Advanced Energy Conversion Materials
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Research Article

Performance Optimisation of Proton Exchange Membrane Fuel Cell by Modifying Anode Flow Field Design

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Received: 2 April 2024; **Revised:** 20 June 2024; **Accepted:** 21 June 2024

Abstract: The study addresses the problem of optimizing the performance of proton exchange membrane (PEM) fuel cells, which are crucial for clean and efficient energy production. Traditional internal combustion (I.C.) engines are less efficient, with efficiencies below 35%, and contribute significantly to pollution. In contrast, PEM fuel cells have the potential for higher efficiencies and cleaner operation. This research is important as it seeks to enhance the efficiency of PEM fuel cells, thereby promoting sustainable energy solutions. The methods used in this study involved designing a 12W capacity PEM fuel cell with both conventional and modified anode flow field designs. Performance optimization was carried out by comparing these designs under various operational conditions, measuring overall voltage efficiencies. The important results showed that the modified anode flow field design achieved an overall voltage efficiency of 45.52%, compared to 42.43% for the conventional design. This improvement of 7.2% in efficiency is significant and highlights the benefits of optimizing the anode flow field in PEM fuel cells. From these results, it can be concluded that modifying the anode flow field can lead to substantial improvements in fuel cell performance. The novelty of this work lies in its detailed experimental comparison and quantitative evidence of the enhanced performance of the modified anode flow field design, advancing previous efforts in the literature by providing clear and significant efficiency gains. This study goes beyond prior research by demonstrating a practical approach to increasing the efficiency of PEM fuel cells, which is essential for their broader application in clean energy technologies.

***Keywords*:** anode, flow field design, fuel cell, optimisation, voltage efficiency

Nomenclatures

PEM	Proton exchange membrane
PEMFC	Proton exchange membrane fuel cell
I.C.	Internal combustion (engine)
MEA	Membrane electrode assembly
GDL	Gas diffusion layer
FRG	Fibre reinforced glass

DOI: https://doi.org/10.37256/aecm.5220244684

RTV	Room temperature vulcanizing
MEA	Membrane electrode assembly
HT-PEM	High-temperature proton exchange membrane (fuel cells)
FCEVs	Fuel cells power electric vehicles
ΔG	Change in gibbs function
ΔH	Change in enthalpy

1. Introduction

A fuel cell is an electrochemical device that converts chemical energy directly into electrical energy through the reaction of a fuel (typically hydrogen) with an oxidizing agent (usually oxygen or air). Unlike conventional combustion-based power generation, fuel cells operate with high efficiency and low emissions, making them a promising technology for various applications ranging from portable electronics to stationary power generation and transportation. Fuel cells are characterized by their ability to generate electricity continuously as long as fuel and oxidant are supplied. They are classified based on the type of electrolyte they employ, such as proton exchange membrane fuel cells (PEMFCs), which use a solid polymer electrolyte to conduct protons.

1.1 *Applications*

Fuel cells find applications in diverse fields due to their efficiency, low environmental impact, and versatility. Some primary applications include:

(1) Transportation: Fuel cells power electric vehicles (FCEVs), offering long driving ranges and quick refueling times compared to battery electric vehicles.

(2) Stationary power generation: They provide clean and reliable electricity for residential, commercial, and industrial applications, offering both grid-connected and off-grid solutions.

(3) Portable power: Fuel cells are used in portable electronics like laptops, smartphones, and drones, where long-lasting power sources are essential.

(4) Backup power systems: They serve as backup power sources for critical infrastructure such as hospitals, data centers, and telecommunications networks.

1.2 *Previous studies*

Numerous studies have explored various aspects of fuel cell technology, including optimization of electrode materials, enhancement of efficiency through novel designs, and integration into hybrid power systems. Previous research has focused on improving the performance, durability, and cost-effectiveness of fuel cells to facilitate broader adoption across different sectors.

1.3 *Fundamentals of fuel cell operation*

$$2H_2 + O_2 \rightarrow 2H_2O + \Delta_{(HEAT)} \tag{1}$$

The fuel cell can produce electricity as long as fuel is constantly supplied.

1.4 *Design and functionality*

A typical fuel cell consists of two electrodes sandwiching an electrolyte. Hydrogen is supplied to the anode, while oxygen is directed to the cathode [1]. At the anode, hydrogen molecules are split into protons and electrons.

The proton-conducting polymer membranes act as electrolytes in PEM fuel cells, and hydrogen is generally used as fuel. The hydrogen molecules are oxidised on the anode side, and protons are transferred through the membrane to the cathode side. Electrons are stripped from hydrogen molecules and move to the cathode by an external circuit, which produces electricity. Consequently, it is on the cathode side and forms water and heat [2, 3]. Polymer electrolyte membrane (PEM) fuel cells working at high temperatures with different membranes are called High-temperature PEM fuel cells [1].

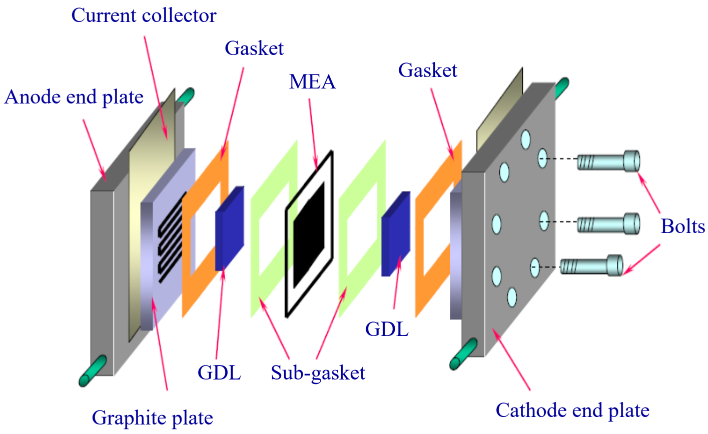


Figure 1. Schematics of fuel cell assembly with different essential components [4]

Figure 2. Micro serpentine bipolar flow plate [4]

In general, the flow field designed should be good for reducing the pressure drop with a proper mass transfer rate through the carbon diffusion layer on the catalyst for the reaction. The two basic channel configurations adapted are:

(1) Serpentine channel, and

(2) Parallel channel.

The serpentine channel is a flow path that runs continuously from its starting point to the endpoint. The primary advantage of this type of channel is that in a continuous serpentine flow field, the path remains uninterrupted from beginning to end.

Moreover, an obstruction such as a water droplet in the path will not block all activity downstream of the obstruction, making it another advantage of the serpentine flow path. In an obstructed serpentine channel, the reactant gas is forced to bypass the channel by flowing under the current collecting rib through the porous backing layer and emerges in an adjacent channel [5, 6]. The bypass flow can then diffuse back toward the obstruction's location so that the obstruction's net effect will be an increased pressure drop but no loss of active area. In a parallel configuration, an obstruction in one channel results in flow redistribution among the remaining channels and a dead zone downstream of the blockage. Parallel flow channels require less mass flow per channel for an equivalent stoichiometry and provide more uniform species distribution and reduced pressure drop [7]. Since the hydrogen reaction is typically not rate limiting, and water blockage in the humidified anode can occur, a serpentine arrangement is generally used for the anode in smaller PEM fuel cells [6]. As the active area of cells gets huge, a combined parallel/serpentine arrangement is often utilised. Some studies on PEM Fuel Cells under different loading conditions [8]. The general components are shown in Figure 1, and the general flow field of the fuel cell is shown in Figure 2.

1.5 *Fuel supply and reforming*

Hydrogen fuel can be supplied from various sources, facilitated by integrating fuel reformers into the system. These reformers enable hydrogen from substances other than pure hydrogen gas, expanding the range of feasible fuel sources.

1.6 *Challenges and considerations*

The flow of electrons from the anode to the cathode can affect the performance of PEMFCs, particularly concerning issues like hydrogen sulfide poisoning and recovery. These challenges are especially pertinent in biomass-fueled PEMFC systems [9, 10].

1.7 *Advancements and challenges in PEMFC technology*

The field of PEMFCs has seen significant advancements and encountered various challenges. Recent research contributions highlight technological progress while also addressing hurdles that impede widespread adoption [11, 12].

1.8 *Recent research contributions*

Studies by Tellez-Cruz et al. [13] delve into the current state and hurdles in PEMFC technology, providing valuable insights for further development. Wang et al. [14] review the progress in PEM fuel cell and electrolysis cell technologies alongside hydrogen infrastructure development, highlighting crucial areas for future focus. Yu et al. [15] propose a novel approach integrating thermochemical cycles and PEM fuel cells for hydrogen and power production, emphasizing environmental considerations. Wan et al. [16] introduce an analytical method for optimising water management in PEM fuel cells under various operating conditions, contributing to improved efficiency and durability. Chammam et al. [17] conduct a multi-objective optimisation of a PEM fuel cell-based energy system, aiming for enhanced performance and versatility.

Interestingly, Mehregan et al. [18] explore the performance and optimisation of combined heat and power systems integrating PEM fuel cells and Stirling engines, offering promising avenues for efficient energy utilisation. Xu et al. [19] present a comprehensive evaluation and optimisation framework for PEM fuel cell degradation, addressing crucial reliability and longevity concerns. Wilberforce et al. [20] compare parametric estimation techniques for PEM fuel cells using metaheuristics algorithms, facilitating more accurate modeling and prediction. Zhang et al. [21] conducted a detailed simulation study on the spatial distribution characteristics in segmented PEM fuel cells, advancing understanding of their complex internal dynamics. Ćalasan et al. [22] propose two novel approaches for mathematical modeling and parameter estimation of PEM fuel cells, offering refined system design and optimisation tools. Ismaeel et al. [23] assess the performance of a rime-ice algorithm for estimating PEM fuel cell parameters, contributing to enhanced operational control and reliability. Lastly, Wei et al. [24] introduce a hierarchical thermal management strategy for PEM fuel cells using a machine learning approach, promising improved temperature regulation and overall performance. These studies signify the dynamic landscape of PEMFC research, addressing various aspects crucial for advancing the technology towards widespread adoption and sustainable energy applications.

1.9 *Previous studies*

Numerous studies have explored various aspects of fuel cell technology, including optimization of electrode materials, enhancement of efficiency through novel designs, and integration into hybrid power systems. Previous research has focused on improving the performance, durability, and cost-effectiveness of fuel cells to facilitate broader adoption across different sectors [25].

1.10 *Suitability of the proposed method*

The proposed method is uniquely suitable for the flow field due to its design, computational efficiency, and scalability. Unlike existing approaches like disturbances of fluid by a flow pattern, our method introduces flow field in simple, which affects significantly performance, and reliability.

By elucidating these aspects, this paper aims to contribute valuable insights into the ongoing evolution and application of fuel cell technology, paving the way for enhanced efficiency, sustainability, and broader adoption across various sectors.

2. Materials and methods

The materials and methods section outlines the procedures and techniques employed in developing and evaluating the PEM fuel cell system to enhance its performance. This section encompasses the construction of the fuel cell prototype, experimental setup, data collection methods, and analytical approaches utilised for performance assessment. The following paragraphs detail each aspect of the materials and methods employed in this study.

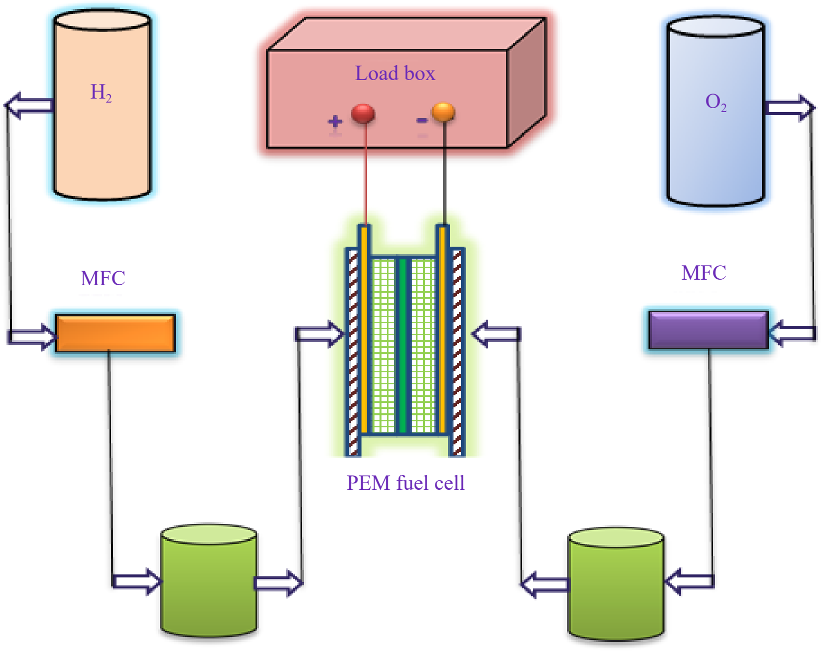


Figure 3. Schematic diagram of PEM fuel cell

2.1 *Fuel cell design and components*

The PEM fuel cell was assembled using various standard components typical in fuel cell research. These components were carefully selected to ensure compatibility and optimise performance. The proton exchange membrane (PEM) fuel cell consists of several key components working in tandem to facilitate the conversion of chemical energy into electrical energy. At the heart of the fuel cell lies the membrane electrode assembly (MEA), which comprises the proton exchange membrane (PEM), the anode catalyst layer, and the cathode catalyst layer. The PEM selectively conducts protons while blocking electrons, typically composed of a perfluorinated sulfonic acid polymer like Nafion. The anode and cathode electrodes, often made of platinum nanoparticles supported on carbon, facilitate the hydrogen oxidation and oxygen reduction reactions, respectively. Bipolar plates provide electrical conductivity between cells and channels for reactant flow, while gas diffusion layers (GDLs) distribute gases uniformly over the electrode surfaces. End plates enclose the stack and provide mechanical support, while current collectors collect and conduct electrical current to the external circuit. A coolant system manages temperature, ensuring optimal operating conditions. Hydrogen and oxygen supply systems deliver reactant gases, while a humidification system maintains hydration levels. Gas separator plates prevent the cross-mixing of gases, enhancing efficiency. Together, these components form a sophisticated system capable of producing clean electrical energy from hydrogen and oxygen, with water as the only byproduct. A schematic diagram of the PEM fuel cell is shown in Figure 3.

In the realm of proton exchange membrane (PEM) fuel cells, several key governing equations and boundary conditions dictate their operational dynamics and performance. Central to their function is the principle of mass conservation, encompassing the transport of hydrogen, oxygen (or air), water vapor, and other species across the cell's components. This equation ensures the balanced distribution and interaction of gases and ions within the fuel cell, crucial for sustained electrochemical reactions. Complementing mass conservation, species transport equations govern the diffusion and migration of ions, particularly protons, through the PEM membrane and electrodes. These equations typically incorporate Fick's law of diffusion alongside the kinetics of electrochemical reactions at the anode and cathode. For instance, hydrogen oxidation at the anode and oxygen reduction at the cathode are pivotal reactions influencing overall cell performance and efficiency. Electrical current conservation equations manage the flow of electrons through the external circuit, linking the anode and cathode. These equations determine the electrical efficiency of the cell by balancing the electrochemical reaction rates with the external load.

Energy conservation equations play a critical role in PEM fuel cells, accounting for heat generation and dissipation due to electrochemical processes and thermal transport mechanisms. They help regulate temperature gradients within the cell, influencing both performance and durability. Water management equations address the crucial task of controlling water within the fuel cell. Proper hydration of the PEM membrane is vital for optimal conductivity and preventing dehydration or flooding, which can impair cell efficiency [26, 27].

Boundary conditions at the anode and cathode define the inlet composition, flow rates of hydrogen and oxygen (or air), as well as temperature and pressure conditions. These conditions shape the environment in which electrochemical reactions occur, directly impacting the cell's output and stability.

2.1.1 *Gasket and aluminium end plates for PEMFC*

The flow field plays a pivotal role in facilitating the movement of reactant gases within the fuel cell, serving as the conduit through which gases are distributed to the electrodes for electrochemical reactions to occur. The flow field comprises a network of channels meticulously designed to optimise gas distribution and minimise flow resistance. Various materials are utilised for bipolar plates, including aluminium, copper, graphite, and other conductive materials, each chosen for its unique properties and suitability for an application. In our model, graphite stands out as the material of choice for bipolar plates owing to its excellent conductivity, corrosion resistance, and durability under the demanding operating conditions of fuel cells. The dimensions of the bipolar plates are carefully specified to ensure compatibility with the fuel cell system's overall design and performance requirements. In this case, the square plate measures 75 × 75 × 4 mm, balancing structural integrity and weight considerations. The compact size allows efficient integration within the fuel cell stack while maintaining adequate surface area for gas flow distribution.

Furthermore, graphite material for bipolar plates offers additional advantages beyond its electrical conductivity. Graphite's inherent inertness and resistance to chemical corrosion make it well-suited for prolonged exposure to aggressive environments typical of fuel cell operation. Its lightweight nature also contributes to the overall weight reduction of the fuel cell stack, promoting portability and ease of handling. Overall, selecting graphite bipolar plates with specific dimensions underscores a deliberate effort to optimise the fuel cell system's performance, reliability, and efficiency. By leveraging graphite's unique properties and carefully tailoring the plate dimensions, engineers can ensure robust gas flow management and sustained operation of the fuel cell under diverse operating conditions.

2.1.2 *FRG gaskets and RTV adhesive*

Fibre Reinforced Glass (FRG) gasket and Room Temperature Vulcanising (RTV) silicon adhesive is used to assemble the module [1]. Gasket and adhesive are used for the following reasons:

(1) To adjust the thickness of the MEA (FRG gasket).

(2) To arrest gas cross between anode and cathode (silicone adhesive).

(3) To arrest hydrogen leaks to the atmosphere (silicone adhesive).

2.1.3 *End plates and fasteners*

The end plates of a fuel cell stack serve a critical role in providing structural integrity and facilitating proper sealing and compression between the components. Typically composed of a rigid material such as aluminium, these end plates hold single cells together and entire stacks, utilising clamping bolts or similar structures for secure assembly [2, 5]. Their primary function is to exert the necessary compression to ensure tight electrical and thermal contact between the various elements of the fuel cell [2, 3]. The importance of maintaining high rigidity in the end plates cannot be overstated, as any buckling or deformation under stress can lead to uneven compression, resulting in issues such as gas leakage and compromised electrical and thermal conductivity [2, 3], to streamline the design and reduce the number of components, end plates are sometimes engineered to serve as current collectors, consolidating multiple functions into a single component. In this configuration, the end plates are typically constructed from a rigid, conductive material with current leads connected [2, 5].

However, to prevent short-circuiting, precautions must be taken to insulate the clamping bolts from the end plates. In our model, aluminium is chosen as the material for the end plates due to its favourable combination of strength, conductivity, and corrosion resistance. Each fuel cell in the stack has two end plates, one for the anode and one for the cathode, ensuring uniform support and compression across the entire assembly. Despite their essential role, end plates are not without their drawbacks. Issues such as fluid leakage between the end plates and the formation of metallic ions due to electrochemical reactions can lead to damage and deterioration of the fuel cell over time [11, 14, 15]. However, through careful design and material selection, these challenges can be mitigated to ensure the longevity and reliability of the fuel cell stack. Notably, the end plates of a fuel cell stack represent a crucial component that provides mechanical support, facilitates proper sealing, and ensures optimal electrical and thermal conductivity within the system. By carefully addressing design considerations and potential challenges, such as material selection and insulation techniques, engineers can optimise the performance and durability of fuel cell stacks for various applications.

2.1.4 *Stack assembly*

The stack configuration in a fuel cell system plays a crucial role in generating a usable voltage, as individual cells need to be connected in series to achieve this. This collection of fuel cells connected in series is commonly called a 'stack' [1, 6, 9]. One of the most straightforward methods to achieve this is connecting one cell's anode to the next cell's cathode along a continuous line. Within the stack, the membrane-electrode-assembly (MEA) is typically situated between a pair of bipolar plates, which are equipped with machined flow fields designed to distribute fuel and oxidant to the anode and cathode, respectively [1, 7]. For proper sealing, gaskets are bonded over the bipolar plates using silicon adhesive. The aluminium end plates are securely fastened using bolts and nuts, forming a solid block structure. It's worth noting that certain membranes are engineered to withstand high temperatures, particularly in applications such as high-temperature proton exchange membrane fuel cells [25]. This characteristic is crucial for maintaining the integrity and functionality of the fuel cell stack under operating conditions that involve elevated temperatures. Furthermore, much modeling can be done before the stack assembly [26, 27] to imply that theoretical analyses and simulations can aid in optimising the design and performance of the stack before its physical assembly. By conducting modeling studies beforehand, engineers can fine-tune various parameters to maximise the efficiency and reliability of the fuel cell stack. The following are the operating parameters adopted in PEM fuel cells:

(1) Cell operating temperature - up to 70 °C.

(2) Hydrogen humidification temperature - up to 65 °C.

(3) Oxygen humidification temperature - up to 65 °C.

(4) The flow rate for hydrogen and oxygen is 0.7 lpm and 1 lpm, respectively, for 1 A of output.
(5) Minimum operating voltage - 0.60 V-0.65 V.

2.2 *Modification strategies*

The modification strategies implemented in this study were devised to address specific shortcomings and optimise the performance of the PEM fuel cell system. These strategies encompassed enhancements in the fuel cell design facets, targeting areas such as flow field configuration, humidification system, current collector materials, and torque distribution during assembly.

2.2.1 *Better flow field design*

The flow field design was modified to enhance gas distribution and optimise mass transport within the fuel cell. This modification involved altering the geometry of the flow channels and optimising the layout to minimise flow maldistribution and improve uniformity.

2.2.2 *Humidification system improvement*

Improvements were made to the humidification system to ensure adequate hydration of the PEM and optimise proton conductivity, which involved enhancing water management strategies within the fuel cell, such as optimising the design of water channels and introducing advanced humidification membranes.

2.2.3 *Current collectors coating*

The current collectors were coated with electrically conducting materials such as platinum or carbon-based coatings to enhance electrical conductivity and reduce contact resistance. This coating facilitated efficient electron transfer between the electrodes and current collectors, improving overall cell performance.

2.2.4 *Torque distribution for end plates*

Special attention was given to the torque distribution during the tightening of end plates to ensure proper sealing and avoid gas leakages. Torque distribution tools and techniques were employed to achieve uniform compression across the fuel cell stack, thereby minimising the risk of gas leakage and ensuring consistent performance. Hence, constructing and assembling a fuel cell stack involves intricate processes and considerations. From the arrangement of cells in series to the sealing mechanisms and choice of materials, each aspect contributes to the overall functionality and performance of the stack.

3. Experimental setup of proposed design

The experimental setup consisted of a test rig with the modified PEM fuel cell and associated components. Mass flow controllers were used to regulate the flow rates of hydrogen and oxygen gases, while temperature and pressure sensors monitored operating conditions. The design of the flow field for PEMFC has been completed, and the fabricated and experimental setups are presented below in Figure 4.

The theoretical voltage of a PEM fuel cell can be calculated using the Nernst equation, which relates the cell voltage to the standard electrode potentials of the half-reactions involved and the activities of the reactants [28]. Table 1 below shows the specifications for the proton exchange membrane fuel cell, which has been designed and fabricated. Additionally, a comparison of the operating conditions of the PEM fuel cell is shown in Table 2. Tables 3 and 4 contain the MEA and system specifications, respectively.

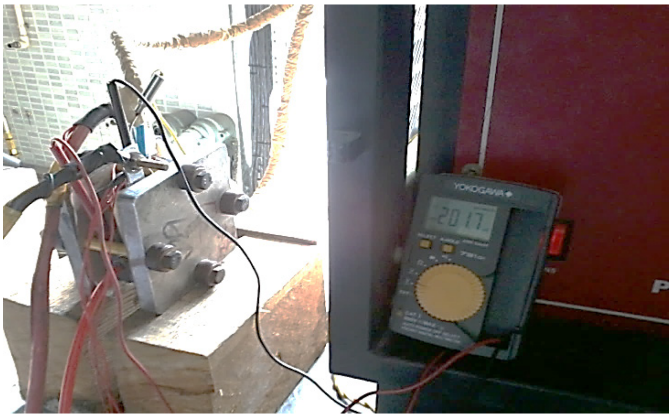


Figure 4. Experimental setup

Table 1. Specifications of PEM fuel cell

S. No.	Components	Make and dimensions
1.	Bi-polar plates	Graphite plates
2.	Flow field method:- Anode	Parallel flow with 1 mm and 1.5 mm groove, and 1 mm depth with 25 cm^2 flow field area
	Flow field method:- Cathode	Parallel flow with 1 mm and 1.5 mm groove, and 1 mm depth with 25 cm^2 flow field area
3.	End plates	Aluminium plate
4.	Gaskets	FRG gaskets
5.	Fasteners	M8 × 1.25 mild steel bolts - 8 No

Table 2. Comparison of operating condition of PEM fuel cell

Parameters	India	Abroad
Minimum operating voltage	0.6 V	0.6 V
Maximum current	250 to 300 mA/cm^2	1,000 mA/cm^2
Operating temperature	60 °C	70 °C

Table 3. Specification of MEA

Parameter	Specification
Size of MEA	5 cm × 5 cm
Electrode area/module	25 cm^2
Electrode material	Carbon cloth
Electrolyte material	Membrane (Nafion)
Catalyst	Platinum

Table 4. Specification of the system

Parameter	Specification
No. of cells	Single-cell
Electrode area	25 cm^2
Hydrogen supply	By cylinder
Oxygen supply	By cylinder
Current collector plate	Copper plates 0.2 mm
Open circuit voltage	0.85 V

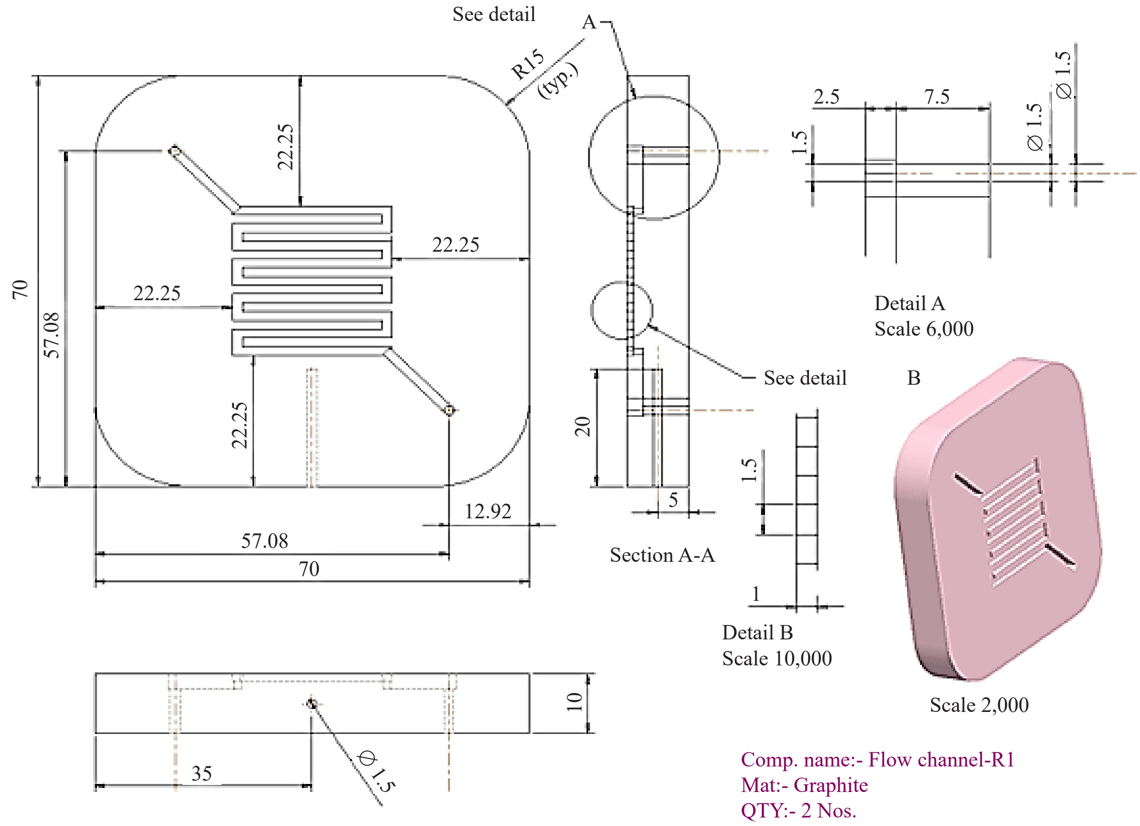


Figure 5. Modified flow field design

3.1 *Modification of anode flow field design for efficiency enhancement*

The design of the flow field channel, with a width and depth of 1mm each, represents a deliberate choice aimed at optimising gas distribution and enhancing performance within the PEM fuel cell system. Maintaining uniform dimensions for both the width and depth of the channel suggests a balanced approach to ensure consistent flow characteristics throughout the cell. One notable feature of the design is the incorporation of double entries for both the port entry and exit points. This configuration is strategically employed to facilitate smoother gas flow transitions, minimising turbulence and pressure differentials within the channel (see Figure 5). By providing dual entry points, the design aims to promote a more even distribution of gases across the entire length of the flow field, thereby mitigating the risk of localised concentration gradients or uneven reactant utilisation. A critical consideration in the design rationale is the increased number of turns in the flow field channel, leading to a phenomenon known as gas stagnation. This occurrence happens when gas flow slows down or comes to a halt in some areas of the channel, typically near bends or corners. While increased turbulence may result from this phenomenon, it also presents an opportunity to enhance diffusivity within the fuel cell. When managed effectively, gas stagnation can promote better mixing of reactants and improve mass transport properties within the fuel cell. By allowing gases more time to interact with the catalyst-coated membrane surface, the design seeks to maximise the utilisation of active reaction sites and optimise electrochemical performance, which is expected to translate into higher overall efficiency and improved voltage output from the fuel cell system.

Furthermore, the deliberate introduction of gas stagnation zones aligns with enhancing diffusivity within the PEM fuel cell. Diffusivity, which refers to the rate at which gases can permeate through a medium, plays a crucial role in determining the efficiency and performance of fuel cells. By strategically manipulating flow dynamics and gas distribution patterns, the design aims to leverage gas stagnation phenomena to promote more efficient diffusion of reactants across the electrode-electrolyte interface.

Hence, the design features of the flow field channel, including its dimensions, dual entry points, and deliberate introduction of gas stagnation, are carefully orchestrated to optimise gas distribution, promote diffusivity, and enhance overall performance within the PEM fuel cell system. Through these design considerations, the aim is to achieve more efficient utilisation of reactants, maximise electrochemical activity, and ultimately improve the efficiency and viability of fuel cell technology for various applications.

4. Result and discussion

The experiment utilised essential setups commonly found in fuel cell research, including fuel cells, mass flow controllers, fuel cylinders, oxidants, and various electrical components for load measurements. Its primary focus was to evaluate the performance of a proton exchange membrane (PEM) fuel cell using an isothermal and three-dimensional mass transfer model. The fuel cell's flow path was designed with a serpentine gas channel consisting of 20 passes. This channel geometry and the associated coordinate system are illustrated in Figure 5. Within this setup, a thin membrane-electrode-assembly (MEA) was positioned between the anode and cathode diffusion layers, serving as the core structure of the fuel cell.

Additionally, the experiment's methodology and modelling approach would have been scrutinised to assess the reliability and accuracy of the results obtained. Factors such as model assumptions, boundary conditions, and validation procedures would have been discussed to ensure the robustness of the conclusions drawn from the experiment. The performance of the current PEM fuel cell design has been thoroughly examined, and data have been collected. Figure 6(a) illustrates the comparative polarisation curves of the existing design, while Figure 6(b) depicts the comparative polarisation curves for the new anode flow field design.

The ratio of the Gibbs function change to the enthalpy change in the overall cell reaction determines the fuel cell thermodynamic efficiency. The Gibbs function change measures the electrical work, and the enthalpy change measures the heating value of the fuel.

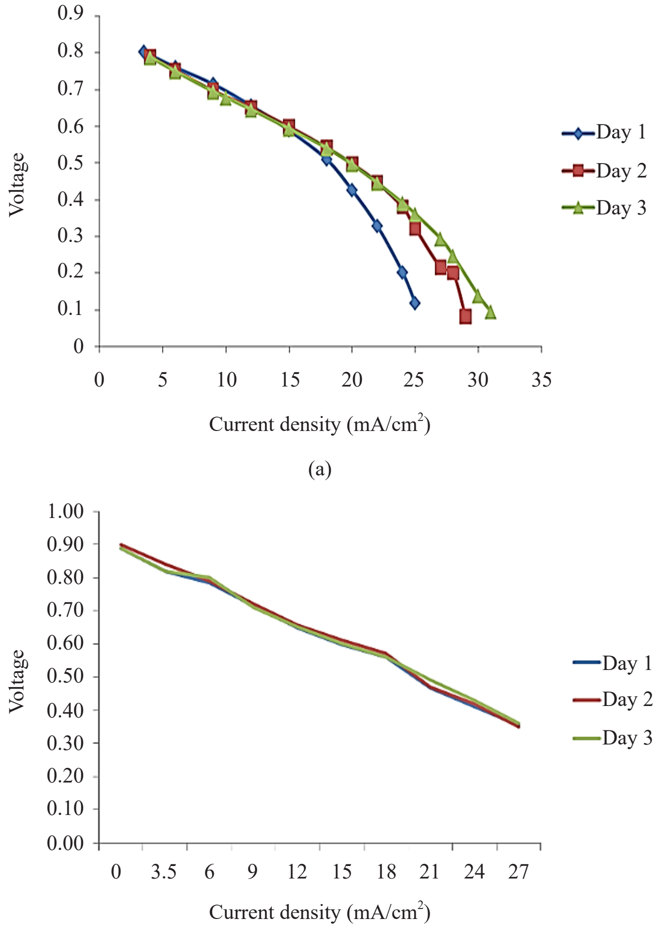
$$\text{Efficiency} = (\Delta G / \Delta H)$$

For the hydrogen-oxygen reaction:

$$\Delta H = \text{-68,317 cal/g mole of } H_2\text{; } \Delta G = \text{-56,690 cal/g mole of } H_2$$

Hence, the efficiency of the ideal fuel cell [29] is as follows:

$$\text{Efficiency} = (56{,}690 / 68{,}317) = 83\%$$



(a)

(b)

Figure 6. (a) Comparative polarisation curves of existing design, (b) Comparative polarisation curves for new anode flow field design

Another measure of fuel cell efficiency is the "Voltage Efficiency", which is the ratio of the actual voltage under operating conditions to the theoretical cell voltage.

For Conventional design:

$$\text{Voltage Efficiency} = (\text{Actual Voltage}) / (\text{Theoretical Voltage})$$

$$= (V_A / V_T) = (V_A / 1.23)$$

Hence:

$$\text{Voltage Efficiency} = V_A / 1.23$$

$$= 0.522 / 1.23$$

$$= 42.43\%$$

For Modified design:

$$\text{Maximum power output} = 10.080 \text{ W at } 18 \text{ A}$$

$$\text{The overall optimum voltage of the setup is } V = 0.560 \text{ (at 18 A)}$$

Hence,

$$\text{Voltage Efficiency} = V_A / 1.23$$

$$= 0.560 / 1.23$$

$$= 45.52\%$$

Table 5 comprehensively compares the conventional and modified flow field configurations, offering insights into the performance enhancements achieved through the modification. The results indicate improvements in voltage efficiency, a critical metric for fuel cell performance assessment. The modified flow field achieved a voltage efficiency of 45.52%, compared to 42.43% for the conventional counterpart. This 7.2% increase in efficiency underscores the substantial benefits derived from optimizing the anode flow field in PEM fuel cells.

Table 5. Comparison of conventional and modified flow fields results

Parameters	General design	Modified anode design
Ideal efficiency	83%	83%
Voltage efficiency	42.43%	45.52%
Water collection	25 ml/h	40 ml/h
Cell heating	Non-uniform	Uniform
Voltage fluctuation	Up to 10 V	Up to 0.7 V

Understanding the interrelationships between temperature, voltage, and current density, as well as the impact of cathode gas flow rates, is crucial for optimizing the performance of PEM fuel cells.

Temperature plays a fundamental role in PEM fuel cell operation. Higher temperatures generally enhance electrochemical kinetics and ion conductivity within the cell, resulting in improved reaction rates at both the anode and cathode. This phenomenon translates into higher current densities achievable at a given voltage level. While the open-circuit voltage remains relatively stable with temperature changes due to thermodynamic constraints, the polarization curve shifts upwards as temperature increases. Therefore, operating PEM fuel cells at elevated temperatures can lead to higher power outputs and efficiencies, albeit careful thermal management is necessary to mitigate potential degradation risks. Conversely, cathode gas flow rates directly influence oxygen availability and distribution at the electrode surface. Increasing the gas flow rate at the cathode enhances oxygen transport, thereby improving reaction kinetics and reducing mass transport losses. This improvement typically results in lower polarization losses and higher voltage outputs at a given current density. Moreover, adequate gas flow rates support higher current densities by ensuring sufficient reactant supply and minimizing concentration gradients near the electrode, crucial for maintaining consistent performance across various operational conditions.

Optimizing these parameters involves striking a balance between maximizing reactant utilization and minimizing parasitic losses, such as pressure drop. Advanced flow field designs and computational modeling techniques are essential tools for achieving optimal gas distribution and enhancing overall PEM fuel cell performance. By understanding and optimizing the interplay between temperature and cathode gas flow rates, researchers and engineers can enhance efficiency, durability, and reliability, advancing PEM fuel cell technology toward broader applications in sustainable energy systems.

The discussion surrounding these results likely delved into the factors contributing to the observed differences in efficiency. Key considerations would include the impact of the modified flow field design on gas distribution, mass transport, and electrochemical reactions within the fuel cell. The design alterations, such as changes in flow channel geometry or the introduction of flow modifiers, would have influenced these aspects, potentially leading to enhanced performance. Higher efficiency in fuel cells holds promise for various sectors, including transportation, stationary power generation, and portable electronics. The ability to extract more electrical energy from a given quantity of fuel translates to increased range, longer operational lifespans, and improved efficiency in energy conversion systems.

In summary, the experiment provided valuable insights into the performance improvements achievable through modifications to the flow field design in PEM fuel cells. The results underscored the importance of ongoing research and innovation in fuel cell technology to enhance efficiency and accelerate its adoption in diverse applications.

5. Conclusion

• In conclusion, the comparison between the conventional fuel cell and the modified anode-designed fuel cell highlights a significant advancement in efficiency. With the conventional fuel cell demonstrating a voltage efficiency of 42.43% and the modified anode-designed fuel cell achieving 45.52%, it is evident that the modification to the anode flow field has yielded tangible benefits. The 7.2% increase in efficiency signifies a notable enhancement in the performance of the fuel cell system, which is reproducible.

• This improvement holds promising implications for various sectors, particularly in renewable energy and transportation. Higher efficiency translates to more effective resource utilisation and reduced emissions, ultimately contributing to a cleaner and more sustainable energy landscape. Furthermore, the enhanced efficiency of the modified fuel cell system could potentially lead to cost savings and greater competitiveness in the market.

• Overall, the findings underscore the importance of continuous innovation and optimisation in fuel cell technology. By refining the design and operation of fuel cells, we can unlock higher levels of efficiency and pave the way for a greener and more efficient energy future. Further research and development in this area will be instrumental in realising the full potential of fuel cell technology and accelerating its widespread adoption across various applications.

5.1 *Future recommendations*

• Exploration of scaling effects: Investigate the scalability of the modified anode-designed fuel cell technology to larger systems. Assess how the observed efficiency improvements scale with size and consider the implications for industrial and grid-scale applications.

• Long-term durability studies: Conduct comprehensive durability studies to assess the long-term performance and stability of the modified fuel cell design under various operating conditions. This includes evaluating degradation mechanisms and developing strategies to mitigate them.

• Optimization of operating parameters: Further optimize the operating parameters such as flow rates, temperature profiles, and catalyst loading to maximize the efficiency gains observed with the modified anode design. Utilize advanced modeling and simulation techniques for predictive analysis.

• Integration with renewable energy sources: Explore synergies between modified fuel cell systems and renewable energy sources such as solar and wind power. Investigate hybrid systems that enhance overall energy efficiency and reliability.

• Cost reduction strategies: Investigate cost-effective manufacturing techniques and materials for the modified fuel cell components. Assess the economic viability and potential for mass production to reduce overall system costs and enhance market competitiveness.

• Environmental impact assessment: Conduct a comprehensive life cycle assessment (LCA) to evaluate the environmental footprint of the modified fuel cell technology compared to conventional systems. Identify opportunities for further reducing carbon emissions and environmental impact.

• Market penetration and policy support: Advocate for supportive policies and incentives that promote the adoption of high-efficiency fuel cell technologies in various sectors. Collaborate with policymakers and industry stakeholders to accelerate market penetration and deployment.

Conflict of interest

The authors have no conflicts of interest. The authors alone are responsible for the work and writing of the paper.

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