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Integrated Modelling and Experimental Investigation of Next-Generation Microfluidic Fuel Cells

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Abstract: Human activity, industrial development, and social advancement require energy. The tremendous rise in global energy consumption, along with the environmental and economic constraints of conventional energy sources, has made clean, efficient, and sustainable alternatives essential. Fuel cells are popular for their high energy conversion efficiency and low environmental impact. However, inefficient water management, non-uniform gas flow, instability in temperature and pressure, membrane conductivity issues, and limitations in microfluidic channel design limit their adoption, thereby affecting performance and durability. This research models, simulates, and builds microfluidic channel-based fuel cells to improve energy delivery and system reliability. A cost-effective, scalable design strategy was developed using the Finite Element Method and COMSOL Multiphysics simulations. Fuel cell performance is examined with ion-exchange layers, optimised microfluidic geometries, and enhanced stack topologies. Five experiments examined current density improvement, the effect of water pH on PEM fuel cells, impurity-induced electrode corrosion, microchannel gas flow, and Taguchi method parameter optimisation. Researchers found that an ion-exchange layer lowers electrode deterioration and boosts efficiency, while optimised channel designs provide uniform gas delivery. Overall, the findings suggest a realistic approach to high-performance microfluidic fuel cell systems for energy applications.

Keywords: Fuel Cell; Proton Exchange Membrane (PEM); Microfluidic Channels; Energy Demand; Energy Consumption; Conventional Energy Sources; Environmental Impact; Energy Systems.

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1. Introduction

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Energy plays an indispensable role in sustaining human life and supporting the growth of modern civilisation. Almost every daily activity—whether domestic, industrial, or technological—relies on a stable and continuous supply of energy. As global reliance on electricity grows, the challenge of meeting rising demand with traditional energy systems has become increasingly critical [10]. The rising cost of conventional fuels, combined with the environmental impacts of fossil fuel consumption, has compelled researchers and industries to explore cleaner, more efficient alternatives. This increasing pressure on existing energy infrastructure underscores the need for technologies that deliver reliable power with minimal environmental impact. Fuel cells have emerged as a promising energy conversion technology capable of addressing many of these challenges. Their ability to convert chemical energy directly into electrical energy without combustion positions them at the forefront of modern clean energy solutions [11]. Due to their high efficiency, low emissions, and modular design, fuel cells are becoming attractive for a wide range of applications, including transportation, portable electronics, residential power systems, and large-scale industrial installations. Among the various fuel cell technologies, proton exchange membrane (PEM) fuel cells have attracted particular attention because they operate at relatively low temperatures, provide rapid start-up, and can be efficiently integrated into compact systems. The rapid depletion of fossil fuel reserves and growing concerns about climate change have accelerated the shift towards renewable energy alternatives. In this context, PEM fuel cells are considered ideal for community-level and rural electrification because they require only hydrogen and oxygen as reactants and produce water as the primary byproduct [12]. When coupled with renewable-driven electrolysis, PEM systems can even produce their own hydrogen fuel, creating a sustainable and circular energy cycle.

This characteristic makes them highly suitable for remote regions where transportation of conventional fuels is difficult or expensive. However, the practical implementation of such systems still faces obstacles, most notably performance degradation caused by corrosion and impurity-related issues in fuel cell components. One of the major operational challenges arises from the quality of water used in electrolysis for hydrogen production. In rural and remote areas, the available water often contains impurities that can accelerate electrode corrosion and reduce membrane efficiency [13]. Over time, this degradation leads to a significant drop in power output and reduces the lifespan of the fuel cell system. Therefore, improving material stability, optimising microfluidic channel structures, and enhancing membrane conductivity are essential steps toward achieving long-term reliability. Recent advancements in microfluidics have opened new possibilities for optimising fuel cell design. Microfluidic channels influence gas distribution, temperature uniformity, water management, and mass transport—parameters that directly affect fuel cell performance [14]. By carefully engineering channel geometry and flow characteristics, fuel delivery can be made more uniform, thereby improving current density and overall efficiency. Computational modelling tools such as COMSOL Multiphysics offer a powerful way to simulate these microfluidic behaviours, enabling researchers to refine designs before fabrication. The present research builds upon these developments by exploring a comprehensive approach that combines modelling, simulation, and experimental fabrication of microfluidic-channel-based PEM fuel cells. The primary goal is to address performance limitations caused by impurities, corrosion, and non-uniform gas flow [15]. The study introduces an ion-exchange layer to mitigate the effects of impure water and evaluates its impact on current density and electrode longevity. It also investigates alternative microfluidic channel geometries—including modified hexagonal structures and parallel arrays with obstacles—to improve gas flow uniformity.

Through systematic experimentation and simulation-driven optimisation, the research aims to develop a cost-effective, high-performance PEM fuel cell suitable for a wide range of applications. To validate the proposed concepts, a series of experiments was designed to focus on membrane behaviour, water-quality effects, electrode corrosion, gas-flow dynamics, and design optimisation using the Taguchi method. The integration of finite element analysis with real-world fabrication allows for a detailed comparison between simulated and experimental results, ensuring accuracy and reliability. Ultimately, this investigation contributes to the broader goal of developing sustainable energy solutions by improving the performance characteristics of PEM fuel cell systems. Energy remains a fundamental necessity for human activities as well as for industrial and societal growth. The continuous rise in global energy consumption, combined with the rising costs and environmental constraints of conventional energy sources, has intensified the pursuit of cleaner, more reliable alternatives. Fuel cells have emerged as a promising option due to their ability to generate electricity efficiently and with minimal environmental impact. However, several operational and structural challenges—such as water management, gas flow uniformity, temperature and pressure fluctuations, membrane conductivity, and microfluidic channel geometry—continue to limit their overall performance. Addressing these challenges is essential for enhancing the power output and long-term reliability of fuel-cell-based systems. The present research focuses on the modelling, simulation, and fabrication of microfluidic channel-based fuel cells to improve their energy-delivery capabilities. Finite Element Method (FEM) modelling and COMSOL Multiphysics simulations were employed to develop an economical, scalable approach for designing optimised fuel cell structures.

The study proposes that incorporating an ion-exchange layer, redesigning microfluidic channel geometries, and adopting a more coherent arrangement of fuel cell stacks can significantly enhance system-level performance. To validate this hypothesis, five systematic experiments were conducted. The first addressed the influence of ion-exchange membranes on current density. The second examined how water pH affects the behaviour of proton exchange membrane (PEM) fuel cells. A specially designed ion-exchange membrane was introduced and evaluated for both improving hydrogen production during electrolysis and

enhancing subsequent electrical generation using the produced hydrogen. The third experiment analysed the impact of water impurities on electrode corrosion. The fourth explored gas-flow characteristics within microfluidic structures, while the fifth applied the Taguchi method to determine the optimal parameter combinations for maximising power output in fuel cell arrays. The results demonstrate that the addition of an ion-exchange layer mitigates impurity-induced electrode degradation and significantly improves cell performance. Simulations further reveal that modified hexagonal channels and parallel flow paths with strategically placed obstacles result in a more uniform gas distribution. Optimisation using the Taguchi method confirms that fine-tuning key parameters can significantly enhance the fuel cell array's overall efficiency. Collectively, the findings offer a comprehensive pathway toward developing more robust, high-performance, microfluidic fuel cell systems suitable for future energy applications.

2. Literature Review

Microfluidic fuel cells (MFCs) have emerged as a promising subclass of fuel cell technologies due to their compact size, simplified architecture, and potential for integration into portable and distributed energy systems [1]. Unlike conventional fuel cells, which rely on bulky manifolds and complex sealing arrangements, microfluidic fuel cells use precisely engineered microchannels to control reactant transport, water management, and thermal behaviour. Early studies on microfluidic fuel cells demonstrated that laminar flow at the microscale enables stable separation of fuel and oxidant streams without the need for a physical membrane, thereby significantly simplifying system design [2]. However, membrane-less configurations often suffer from fuel crossover and limited power density, motivating the development of hybrid designs incorporating polymer electrolyte membranes. Proton exchange membrane fuel cells (PEMFCs) remain among the most widely studied and commercially viable fuel cell types due to their low operating temperature, high power density, and rapid start-up [3]. Extensive research has focused on improving PEM materials, catalyst utilisation, and electrode durability. Studies have shown that membrane hydration, proton conductivity, and resistance to chemical degradation are critical parameters governing PEMFC performance. Advanced membranes, including reinforced and composite structures, have been proposed to enhance mechanical strength and water retention while minimising gas crossover [4].

Water management has been identified as a dominant challenge in PEM fuel cells, particularly in microfluidic configurations where channel dimensions strongly influence mass transport. Insufficient hydration leads to membrane dry-out and increased ohmic losses, whereas excess water causes flooding of the gas diffusion layer and catalyst sites [5]. Researchers have investigated various strategies to address this issue, including optimised flow-field designs, hydrophobic surface treatments, and tailored gas diffusion layers. Computational studies have demonstrated that microchannel geometry plays a decisive role in controlling liquid water removal and reactant distribution [6]. Another critical aspect highlighted in the literature is the impact of water quality and impurities on fuel cell durability. Impurities introduced during electrolysis or from feed water can accelerate electrode corrosion, poison catalysts, and degrade membrane conductivity. Several investigations have explored the use of ion-exchange materials and filtration layers to mitigate impurity transport to sensitive components. These studies report improvements in current density stability and extended operational life, particularly in applications where access to high-purity water is limited [7]. K responds to this need by offering an integrated modelling and experimental investigation tailored to microfluidic PEM fuel cells [9].

3. Overview of Fuel Cell Technology

Global energy systems are undergoing rapid transformation as the world moves toward electrification. This shift is driven mainly by the urgency to reduce dependence on fossil fuels, coal, oil, and natural gas, which have long dominated industrial and residential energy needs. Although renewable energy sources such as solar and wind are becoming widespread, the total energy they produce remains insufficient to meet rising global demand. As a result, energy-conversion technologies capable of high efficiency and low environmental impact are gaining traction. Finite Element Method (FEM) and multiphysics simulations have become indispensable tools for analysing and optimising microfluidic fuel cell designs. COMSOL Multiphysics, in particular, has been widely used to model coupled phenomena such as fluid flow, species transport, electrochemical reactions, and heat transfer. Simulation-driven approaches allow rapid evaluation of design variations, reducing experimental cost and development time. Recent work increasingly combines FEM modelling with experimental validation to establish reliable design guidelines for next-generation fuel cell systems [8].

Despite significant progress, the literature indicates that integrated studies combining ion-exchange strategies, microfluidic geometry optimisation, and system-level performance enhancement remain limited. There is a clear need for comprehensive frameworks that unify modelling, fabrication, and experimental evaluation to address both efficiency and durability challenges. The present action. Among these, fuel cells have emerged as a promising alternative. Fuel cells are steadily replacing conventional systems such as internal combustion engines, steam turbines, and heavy batteries. They are now used in diverse applications ranging from small portable electronics to large-scale power generation and transportation. Numerous fuel cell types exist, each with its own characteristics, operating principles, advantages, and disadvantages. Fundamentally, a fuel cell

converts chemical energy directly into electrical energy without combustion. This electrochemical process occurs within a cell comprising an anode, a cathode, and an electrolyte. In a typical hydrogen fuel cell, hydrogen molecules reach the anode where a catalyst splits them into electrons and protons. The protons migrate through the electrolyte to the cathode, while electrons travel through an external circuit, generating electrical power. At the cathode, oxygen reacts with the incoming protons and electrons to produce water and heat (Figure 1).

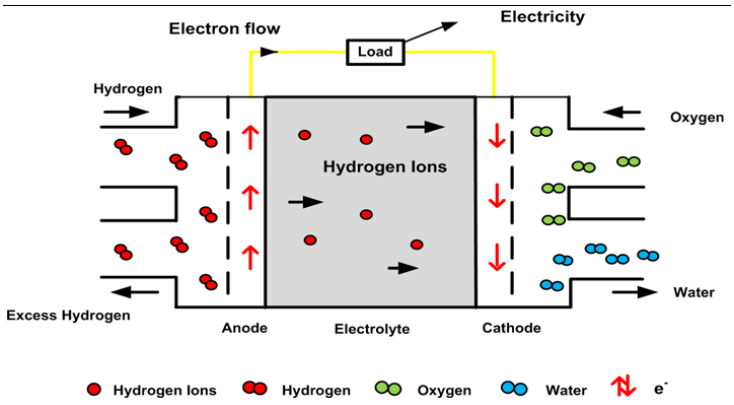

Figure 1: Schematic diagram of a proton exchange membrane fuel cell

Since a single cell generates less than 1-volt, multiple cells are connected in series to form a fuel cell stack. Heat is produced during the reaction due to internal resistances, but unlike combustion engines, fuel cells are not constrained by thermodynamic limits such as the Carnot efficiency. Because they do not degrade as batteries do and continue producing electricity as long as the fuel is supplied, fuel cells offer attractive long-term performance, high efficiency, and minimal emissions—making them suitable for both stationary and mobile applications.

3.1. Types of Fuel Cells and Their Operating Principles

Fuel cells are classified by the electrolyte they use and their operating temperature. Common types include:

3.1.1. Alkaline Fuel Cells (AFCs)

AFCs were among the earliest fuel cells developed. They typically use potassium hydroxide as the electrolyte and operate at relatively low temperatures around 160°C. AFCs are highly efficient but are prone to carbon dioxide contamination, which can degrade performance. They have been widely used in space and military systems, where cost constraints are less stringent. The findings of this study provide important insights into the interplay between material selection, microfluidic design, and overall fuel cell performance. The incorporation of an additional ion-exchange layer results in clear improvements in current density and voltage stability, particularly when operating with water sources containing impurities. This result confirms that pre-treatment and selective ion filtration can significantly reduce electrode degradation and enhance membrane longevity, which is essential for deployment in remote or resource-constrained environments.

3.1.2. Direct Methanol Fuel Cells (DMFCs)

DMFCs utilise liquid methanol directly as the fuel. Since they do not require hydrogen reforming, the design is simpler and compact. Operating between 120°C and 190°C, these cells are suitable for portable devices such as laptops and mobile electronics. Their major drawback is the high cost of catalysts and materials. The experimental comparison between different ion-exchange membrane chemistries highlights the sensitivity of PEM fuel cell performance to membrane composition and ionic selectivity. The superior response observed with tin-based arsenotungstate membranes suggests that ion-exchange capacity, chemical stability, and compatibility with the PEM environment are key factors governing effectiveness. These observations align with existing theoretical understanding while providing new experimental evidence for microfluidic fuel cell systems.

3.1.3. Phosphoric Acid Fuel Cells (PAFCs)

PAFCs employ phosphoric acid as the electrolyte, with carbon-based electrodes and platinum catalysts. Operating at around 200°C, they tolerate carbon monoxide better than some other types. Although they are less efficient electrically, their combined heat-and-power capability can raise overall efficiency above 80%. They remain one of the most commercially deployed

stationary fuel cell systems. From a fluid-dynamic perspective, the COMSOL simulations reveal that the microchannel geometry strongly influences the uniformity of the gas flow and the residence time. Modified hexagonal channels and parallel flow paths, with strategically placed obstacles, promote stable laminar flow and minimise dead zones. Such flow uniformity directly translates into more consistent reactant availability at the electrodes, leading to improved power output and reduced localised degradation.

3.1.4. Molten Carbonate Fuel Cells (MCFCs)

These cells operate at high temperatures (600–700°C) and use molten carbonate electrolytes. They can achieve efficiencies up to 50% and can operate with a variety of fuels, including reformed natural gas and coal-derived gases. Their main challenges include material corrosion and durability due to the demanding operating temperature. The application of Taguchi optimisation further strengthens the study by demonstrating how systematic parameter tuning can enhance system-level performance. By optimising channel configuration, stack arrangement, and flow modifiers, the proposed fuel cell array achieves higher power density without increasing system complexity. This approach underscores the value. Metallic BPs can be manufactured through processes such as stamping, embossing, or hydroforming. While graphite-based plates offer chemical stability, they are bulky and brittle, making metal plates preferable in automotive applications due to their thinness and mechanical strength.

3.2. Structure and Key Components of PEM Fuel Cells

PEM fuel cells consist of several layers that collectively form the membrane electrode assembly (MEA). The major components include (Figure 2).

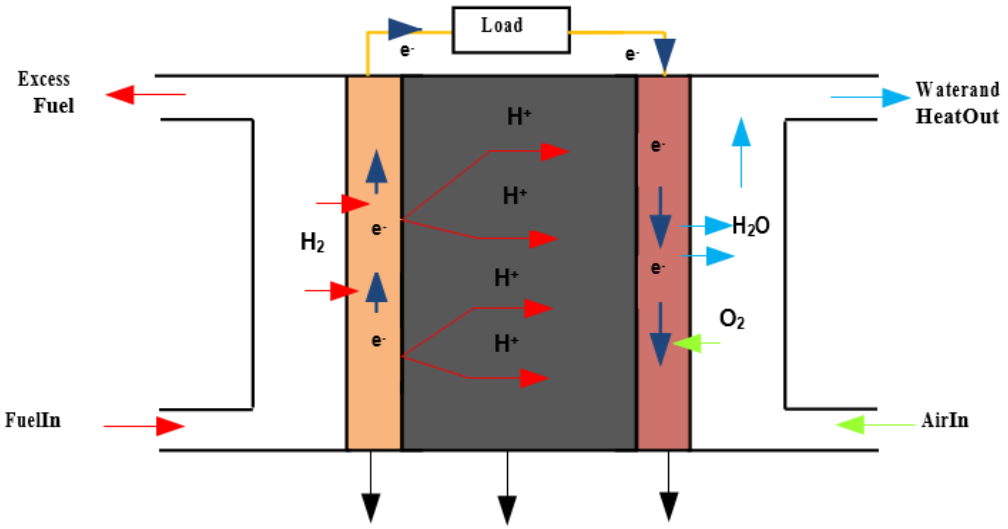

Figure 2: Electrochemical reactions and transport phenomena in a PEM fuel cell

3.2.1. Bipolar Plates (BPs)

Bipolar plates provide structural support for the fuel cell stack while distributing reactant gases across the MEA. They also serve as current collectors and thermal management elements, channelling coolant to regulate temperature. Their flow fields—serpentine, parallel, interdigitated, or pin-type—significantly influence gas distribution, water removal, and cell efficiency.

3.2.2. Gaskets

Gaskets seal the MEA to prevent gas leakage and protect the plates from contact with the acidic electrolyte. Materials such as silicone and PTFE are commonly used due to their high-temperature and chemical resistance.

3.2.3. Gas Diffusion Layer (GDL)

Located between the bipolar plate and the catalyst layer, the GDL is typically made of carbon fibre paper or cloth. It facilitates:

- Transport of gases to the Catalyst Layer
- Removal of water and heat
- Electrical Conduction
- Mechanical support for the MEA

The microporous layer (MPL) on the GDL helps regulate water transport through hydrophobic materials, such as PTFE.

3.2.4. Catalyst Layer (CL)

Each anode and cathode contains a catalyst layer where the electrochemical reactions occur. Platinum nanoparticles supported on carbon are commonly used to maximise reaction surface area. The CL must efficiently transport electrons, protons, and gases while providing high surface area and porosity.

3.2.5. Membrane (PEM)

The polymer membrane (commonly Nafion) allows proton conduction but must prevent gas crossover. Maintaining sufficient hydration is essential for high proton conductivity. Water management strategies are therefore critical to maintaining membrane performance and preventing cell dry-out or flooding: electrochemical Reactions and Fuel Cell Efficiency (Figure 3).

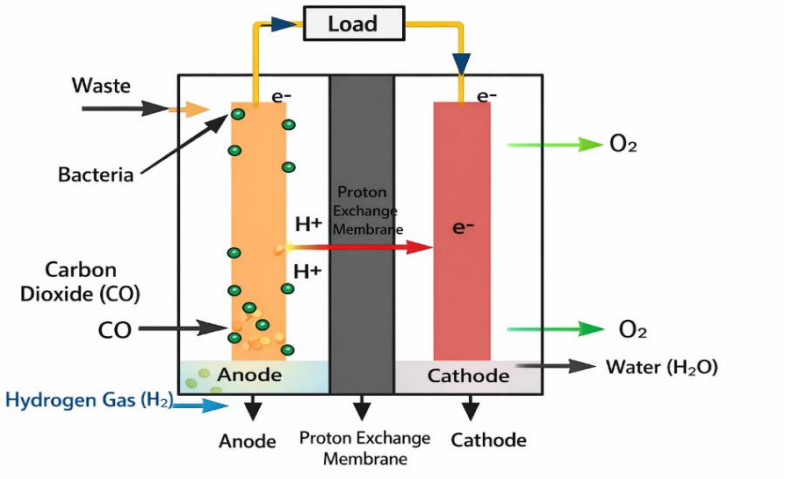

Figure 3: Conceptual illustration of charge transport and gas flow in a PEM Fuel cell

In a PEMFC, hydrogen is fed to the anode, where the catalyst facilitates the oxidation reaction:

- **Anode Reaction:** $H_2 \rightarrow 2H^+ + 2e^-$

The membrane allows only protons to pass through, while electrons flow through the external circuit to generate electricity. At the cathode, oxygen combines with the protons and electrons to form water:

- **Cathode Reaction:** $\frac{1}{2}O_2 + 2H^+ + 2e^- \rightarrow H_2O$
- **The Overall Reaction is:** $H_2 + \frac{1}{2}O_2 \rightarrow H_2O$ + heat

3.3. Fuel Cell Voltage and Losses

Although the ideal voltage of a PEM cell is about 1.23 V at room temperature, real operating voltages are lower due to several losses:

- **Activation Losses:** Caused by sluggish reaction kinetics, mainly at the cathode.
- **Ohmic Losses:** Arise from resistance in the membrane, electrodes, and electrical connections.
- **Mass Transport Losses:** Occur when reactant flow fails to keep up with consumption, especially at high current densities.

- **Fuel Crossover and Internal Currents:** Result from small amounts of hydrogen diffusing through the membrane or electrons leaking through unintended pathways.

These losses can be mathematically expressed and plotted in a polarization curve, as current increases, voltage drops, affecting overall efficiency.

3.4. Efficiency Considerations

Fuel cells convert chemical energy directly to electricity, bypassing the limitations of combustion systems. Because they operate efficiently over a broad temperature and power range, fuel cells are ideal for variable-demand applications such as vehicles. Efficiency is often expressed as the ratio of actual cell voltage to reversible voltage—a measure influenced by temperature, reactant pressure, and system design.

3.5. Water Management in PEM Fuel Cells

Effective water management is vital for PEMFC performance (Figure 4).

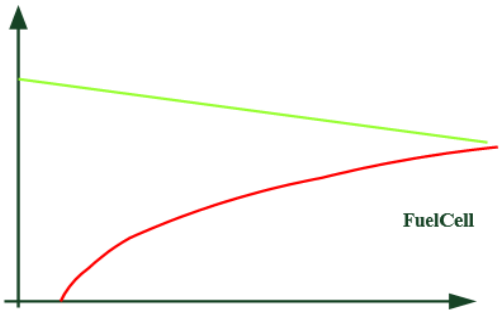

Figure 4: Polarisation curve of a fuel cell

The membrane must remain hydrated to sustain proton conductivity, yet excessive water can flood the electrodes and inhibit gas transport (Figure 5).

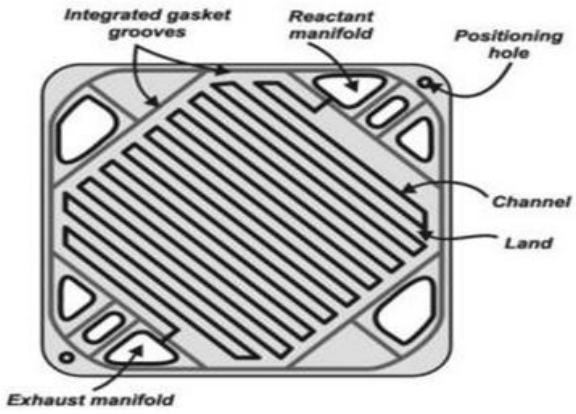

Figure 5: Serpentine flow field plate design for a PEM fuel cell

4. Conclusion

Research was conducted to determine the design and materials required for the ion-exchange layer to improve the performance of PEM fuel cells. Since the orientation and ion-exchange layer are critical to fuel cells, experiments were designed to assess the fuel cell's ability to deliver sufficient energy. The following conclusions have been drawn from the experiments conducted in the present research work. The first experiment examines the chemical used in the ion-exchange layer and its effect on the

device's electrical parameters, including anode-mesh degradation. The experiment was conducted to investigate the effect of an additional ion-exchange membrane on the PEM fuel cell's current density. The proposed cell may be used in remote regions where fresh water is difficult to obtain for electrolysis-based H2 and O2 synthesis for fuel cell-based power generation. The proposed fuel cell's time response was investigated using two types of chemicals to improve the performance of the ion-exchange layer. The investigations revealed that using a Tin (IV) arsenotungstate-based ion exchange membrane is superior to using Stannic (IV) oxoarsenotungstate in terms of voltage response, current density, and time response. The second experiment deals with the pH of the water before and after filtering through the ion-exchange layer. From the results, it can be concluded that the pH after filtering through the Tin (IV) arsenotungstate ion-exchange layer approaches neutrality. This can be beneficial, since impurities reaching the cell's electrodes would be reduced.

The third experiment evaluates the effect of an ion-exchange layer, an additional component in PEM-based fuel cells, on electrode corrosion. The investigations were carried out using visual analysis of the electrodes and XRD to estimate the extent of corrosion. Experimentation has shown that the inclusion of an ion-exchange layer in the PEM fuel cell enhances its performance by reducing electrode corrosion. The fourth experiment has been conducted to simulate microfluidic structures using COMSOL Multiphysics. FEM-based simulations were carried out to investigate the effects of geometric parameters on laminar flow and particle tracing. Time-dependent studies were performed on the microfluidic channel structures. It was observed that the hexagonal structure and the parallel channel with two sets of speed modifiers exhibit a constant fluid flow. Based on this observation, these two structures were investigated using Taguchi method-based optimisation of the power output from the constituent fuel cell units, as elaborated in the fifth experiment. In the experiment, six fuel cells were stacked in series along the hexagonal edges of the gas flow system to increase the voltage, and five such sub-systems were connected in parallel to enhance power. A COMSOL-based simulation was carried out to optimise the power of the resultant system. To maintain uniform gas flow in each fuel cell, different flap configurations were used. The parameter adjustment was carried out using the Taguchi optimisation technique. The simulation experiments showed that a nearly uniform gas flow can be maintained using the proposed technique, thereby enabling optimisation of fuel cell power density. Fabrication of the system is on our plan.

4.1. Scope of the Present Work

The scope of this manuscript is focused on the integrated design, modelling, and experimental evaluation of microfluidic proton exchange membrane fuel cells with enhanced performance and durability. The specific objectives addressed within this scope include:

- Development of FEM-based multiphysics models to analyse fluid flow, mass transport, and electrochemical behaviour in microfluidic fuel cell channels.
- Design and evaluation of ion-exchange layers for mitigating impurity-induced degradation in PEM fuel cells.
- Experimental investigation of the influence of membrane chemistry, water pH, and impurity filtration on current density and voltage response.
- Optimisation of microfluidic channel geometries to achieve uniform gas distribution and stable laminar flow.
- System-level performance enhancement through optimised stacking and parallelisation of fuel cell units using Taguchi-based methods.

The study primarily emphasises performance improvement and durability enhancement at the cell and sub-stack level. Large-scale manufacturing, long-term field deployment, and full techno-economic analysis are beyond the immediate scope but are recognised as important future considerations.

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Data Availability Statement: All experimental and modelling data generated in the course of this research on Integrated Modelling and Experimental Investigation of Next-Generation Microfluidic Fuel Cells are maintained by the corresponding author. Access to these materials will be provided to qualified researchers upon reasonable request. The datasets are not publicly archived owing to project-specific and institutional restrictions.

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Ethics and Consent Statement: The research was performed in accordance with established ethical guidelines. Necessary ethical approvals were obtained before the commencement of the study, and informed consent was secured from all relevant institutions and participants, where required.

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