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Elaf N. Mahrous
Department of Mechanical Engineering, Jubail Industrial College, P.O. Box: 10099, Jubail Industrial City-31961, Kingdom of Saudi Arabia

Ahmad Jamal
Department of Mechanical Engineering, Jubail Industrial College, P.O. Box: 10099, Jubail Industrial City-31961, Kingdom of Saudi Arabia

Muhammad Saleem
Department of Civil Engineering, Jubail Industrial College, P.O. Box: 10099, Jubail Industrial City-31961, Kingdom of Saudi Arabia, i_am_saleem@yahoo.com

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REVIEW

Enhancing Green Energy Solutions through PEMFC: A Comprehensive Review of Modeling, Efficiency, Performance Metrics, and Future Opportunities

Elaf N. Mahrous [a], Ahmad Jamal [a], Muhammad Saleem [b,*]

[a] Department of Mechanical Engineering, Jubail Industrial College, P.O. Box: 10099, Jubail Industrial City-31961, Kingdom of Saudi Arabia
[b] Department of Civil Engineering, Jubail Industrial College, P.O. Box: 10099, Jubail Industrial City-31961, Kingdom of Saudi Arabia

ABSTRACT

Polymer Electrolyte Membrane Fuel Cells (PEMFCs) are a promising technology for clean and efficient energy production. PEMFC was initially developed for the space programs in the 1960s, but today, it finds its application in numerous engineering applications. Growing concerns about fossil fuel depletion and global warming, along with recent advances in renewable energy and the hydrogen economy, have further supported its development. This comprehensive review consolidates modeling approaches, performance analyses, thermal management strategies, and future prospects of PEMFC technology. The analysis of the characteristics of Voltage-Current (V-I) and subsequent examination of the fuel cell's efficiency include the evaluation of thermal and other input parameters. For instance, adopting the optimum thickness of catalyst layers of the anode (0.0231 mm) and cathode (0.0315 mm) current collectors enhances the performance of PEMFC by 6.8%. Experimental results show PEMFC performance peaks at 65°C, with lower temperatures reducing power. Optimal humidity improves performance, but excess causes flooding. Active water cooling enhances thermal management, boosting power density and stability compared to passive cooling. It is also noticed that altering the temperature and input values of the fuel cell results in variations in voltage losses. Compilation of the scattered work and providing the readers with an inventory to comprehend about the gaps in this particular research area for future work advocates the novelty of this review paper.

Keywords: Fuel cell, Polymer electrolyte membrane, Proton exchange membrane, Gas channel, High-temperature PEMFC, Environmental sustainability

1. Introduction

The advent of industrial development has resulted in a substantial growth in the energy demand globally. Development has been going on in the three crucial areas of locating, extracting and utilizing energy. The most sustainable supply of energy by far can be from renewable energy sources such as wind, solar, geothermal, hydroelectric, etc. [1]. These days, one of the most widely adapted sources of renewable energy is solar energy harnessed by Photo-Voltaic Cells (PVC). Enormous research has been conducted to enhance the power output and efficiency of PVC. For instance, Chen et al. [2] presented a comprehensive review of non-data driven solar irradiance estimation method based on Maximum Power Point Tracking (MPPT) using two models namely IV-G and I-G for 37 climate patterns. They also studied the effect of MPPT on irradiance estimation. Whereas, Wei et al. [3] proposed Global Maximum Power Point Tracking (GMPPT) technique to mitigate the PV losses due to Partial Shading Conditions (PSC). To further improve

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* Corresponding author.
E-mail address: i_am_saleem@yahoo.com, saleemm@rcjy.edu.sa (M. Saleem).

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the solar system, Harrison and Alombah [4] and Harrison et al. [5] proposed a new power-electronics-based Photo-Voltaic Emulator (PVE) and a new type of controller, i.e., Modified Shift Controller (M-SC) for the PVE, respectively.

1.1. Economic and environmental analysis

Economic and environmental impact is the driving force in the global adaptation of the renewable energy sources. In this context, Kushwaha and Bhattacharjee [6], conducted a Techno-Economic Environmental (TEE) study of an off-grid microgrid for rural India, comparing the Slime Mould Algorithm (SMA) with Particle Swarm Optimization (PSO). Various configurations solar PV, Wind Turbines (WT), Diesel and Methanol Generators (DG-MG), batteries, and converters were evaluated. Results showed the PV-WT-MG-DGs-battery-converter system optimized with SMA outperformed PSO in parameter accuracy, avoiding local minima, and computational efficiency. The study demonstrates SMA's effectiveness in designing cost-efficient, reliable, and eco-friendly off-grid energy solutions for rural development.

Kushwaha and Bhattacharjee [7], in a recent study developed a Socio-Techno-Economic Environmental (STEE)-based objective function for optimal sizing of a hybrid renewable energy system (HRES) to enhance rural power reliability. Using the novel Marine Predator's Algorithm (MPA), it evaluated the configurations of Phot-Voltaic (PV), Wind Turbine (WT), Battery (BAT), Biogas Generator (BG), and Diesel Generator (DG), and found it to be optimal due to superior economic, environmental, social factors and global optimization, achieving a cost of energy of $0.1799/kWh, lower than existing literature. This cost of energy value can be a means to look for energy resources that have least impact on environment and economically viable. Kushwaha and Bhattacharjee [8], in their review on hybrid renewable energy systems (HRES) highlighted the potential of HRES as cost-effective, reliable, and environmentally friendly alternatives to conventional systems. Despite advances, challenges remain in optimizing parameters and addressing gaps through further research to maximize HRES benefits, ensuring sustainable and resilient energy solutions.

Kushwaha et al. [9] proposed a mavin load scheduling approach for standalone hybrid microgrids integrating renewable sources like PV and wind, along with storage and conventional generators. This strategy reduces power costs, load shedding, and emissions while enhancing energy efficiency. By employing demand response, deferrable loads, and optimized dispatch, the approach improves system reliability and achieves significant cost savings and environmental benefits in hybrid microgrid operations. However, in the present study this approach is not used as, this approach is more relevant to system-wide energy management contexts, whereas our work aims to deepen understanding and improve the intrinsic performance characteristics of PEMFC components through detailed flow modeling.

Recent studies emphasize the importance of economic and environmental assessments in advancing PEMFC and hybrid renewable systems. Al Makky et al. [10] analyzed a solar-wind-fuel cell system in Oman, achieving an LCOE of $0.1449/kWh, LCOH of $5.67/kg, and significant carbon reductions. Elmariami et al. [11] highlighted $155 million in cost savings and a 7.7 Mt CO_2 reduction through wind turbine LCA. Nassar et al. [12] proposed Libya's hybrid wind, solar, and pumped hydro system with an LCOE of $132.1/MWh, zero power loss, and 11,624 kt CO_2 savings, demonstrating decentralized viability. Makhzom et al. [13] reported Libya's electricity emissions at 1253 kg CO_2/MWh. Abdunnabi et al. [14] identified household energy savings of over 6,650 TWh, reducing 6.54 Mt CO_2 and social costs by $333.54 million. Bouramdane [15] found hydrogen production significantly impacts global warming, with AFCs being the most eco-friendly, advocating for green hydrogen and renewables.

Overall, these studies highlight the necessity of combining lifecycle costs, operational efficiencies, and environmental impacts to guide sustainable deployment of PEMFC and hybrid renewable systems. Future research should focus on process optimization, renewable integration, and comprehensive lifecycle assessments to advance cleaner, cost-effective energy solutions aligned with global sustainability goals.

1.2. Hydrogen as a fuel

Hydrogen as an energy carrier, on the other hand, can be a one of the most useful and widely used fuel for energy production. Water electrolysis provides an effective method for generating hydrogen using renewable sources such as solar energy [16]. Hydrogen can be produced by various means such as diverse electrolysis methods [17], electrochemical and photocatalytic reactions [18], and even from solid waste [19]. The electrical energy generated from these renewable sources exhibits an intermittent nature. An essential challenge for all forms of renewable energy lies in the efficient storage of energy across various time scales. The produced hydrogen serves as the energy carrier, capable of being stored to provide power for varying durations to various facilities such

as telecommunication stations and serve as an alternative to power grids run by diesel generators [20].

The global hydrogen production capacity from electrolyzers was estimated to reach 5 GW by the end of 2024. The hydrogen market is driven by increasing demand for clean energy solutions and the depletion of oil reserves. In 2024, the global hydrogen market was valued at approximately USD 262.13 billion and is expected to grow to about USD 556.56 billion by 2034 [21]. The combination of hydrogen with electrochemical energy conversion technology, specifically fuel cells, has been acknowledged as a dependable, safe, and environmentally friendly energy solution when integrated with renewable energy sources [22].

1.3. Polymer electrolyte membrane fuel cell (PEMFC)

A fuel cell is an electrochemical cell that has the capacity to directly and continuously convert the chemical energy of fuels, including hydrogen, methanol, ethanol, and natural gas, as electrical energy. An electrolyte that conducts protons is employed in a fuel cell. It is imperative that the separating electrolyte prevents any collision between the fuel (e.g., hydrogen) at the anodic side and oxygen at the cathodic side, as such a collision would result in a chemical combustion of hydrogen in oxygen. In order to generate protons ($H+$) and electrons, hydrogen undergoes catalytic oxidation at the anode. It is distinctive in that the electrolyte permits the passage of ions, such as $H+$, but not electrons. Electrons are compelled to migrate from the anode to the cathode through the external circuit by this electrolyte. Protons are transported from the electrolyte to the cathode, where they react with oxygen and incoming electrons from the external circuit to generate water. Through this process, electricity is directly generated through the transit of electrons. Consequently, hydrogen is the energy carrier in a fuel cell, as it is produced through water electrolysis. Inherently, fuel cells have a higher efficiency than conventional energy conversion technologies, and they emit significantly fewer greenhouse gases, as a result of the electrochemical character of the energy conversion process. A fuel cell's efficacy is not influenced by the power unit's capacity or the power output's load level. When operating at a low load of less than 50 kW, a fuel cell with a rated power of, for example, 50 kW will exhibit a higher efficiency. This is opposed to a thermal engine [22].

Fuel cells, as energy conversion devices, has the benefit of modularity, allowing them to be constructed over a diverse spectrum of power scales, ranging from few hundred watts to kilowatts and megawatts. Consequently, fuel cell-based power units may be developed in a decentralized fashion, situated near customers, hence diminishing the expenses associated with power transmission [22].

Sulfuric acid was employed as the electrolyte in the initial fuel cell developed by W. R. Grove in 1838. F. T. Bacon employed alkaline electrolyte in the first demonstration fuel cell approximately 100 years later. This electrolyte was subsequently utilized for the first space application in the 1960s. Current applications of fuel cell technology include automobiles, portable appliances, and large-scale power generation facilities. Its advancement has been substantially fostered by the growing apprehensions regarding the depletion of fossil fuels and the effects of global warming, as well as recent prospective associations with renewable energy sources and the growing hydrogen economy [22].

Recent research on and development of fuel cell has resulted in the emergence of a solid Polymer Electrolyte Membrane (PEM). The fuel cell possessing this membrane is called Polymer Electrolyte Membrane Fuel Cell (PEMFC). PEM exhibits mechanical strength and flexibility, enabling a simple and practical construction of all-solid cells with water as the sole liquid in the system. Furthermore, the polymer electrolyte serves as the cell separator material, demonstrating exceptional resistance to the crossing of gaseous reactants. Moreover, the functional areas for ion transport are chemically integrated into the polymer, resulting in reduced complexity regarding sealing, linking, assembling, and handling for PEMFC compared to other fuel cell types utilizing liquid electrolytes. PEMFCs possess a slender polymer electrolyte membrane. The advantages of PEM include high efficiency, power density, less corrosion, and superior operational performance. Polymer Electrolyte Membrane Fuel Cells (PEMFCs) are considered significant technical innovations in chemical engineering due to their rapid startup and operation at very low temperatures, namely below 80°C. Ultimately, PEMFCs are environmentally friendly as they release no harmful gases such as sulfur and nitrogen oxides [22].

Typically, the terms "Polymer Electrolyte Membrane (PEM)" and "Proton Exchange Membrane (PEM)" are used interchangeably to refer to the same type of membrane. However, in the context of hydrogen fuel cells, the term "Proton Exchange Membrane" is most commonly used. In contrast, for other types of fuel cells, the term "Polymer Electrolyte Membrane" is more frequently employed. Essentially, a Polymer Electrolyte Membrane is, in fact, a Proton Exchange Membrane that functions as the electrolyte in the fuel cell. In other words, Polymer Electrolyte Membrane is the structural name

and Proton Exchange Membrane is the functional name of the membrane used in fuel cell. Hence in the present text, PEMFC is going to represent both the interchangeable terms “Proton Exchange Membrane” and “Polymer Electrolyte Membrane”.

The configuration of the Gas Channel (GC) structure has significant importance in the field of Polymer Electrolyte Membrane Fuel Cell (PEMFC) investigation. This is primarily due to the fact that the flow pattern of the two-phase system resulting from the GC geometry significantly impacts the operational efficiency of the Polymer Electrolyte Membrane (PEM) stack. The three most often used geometries of GC are the straight parallel channel, the serpentine channel, and the interdigitated channel. Furthermore, the inclusion of a cascade flow field channel and either a pin or mesh flow field channel is also taken into consideration [23]. To explore the intricate gas-liquid two-phase flow phenomena seen in the gas diffusion layer of the Proton Exchange Membrane (PEM) fuel cell, a research study selected three separate straight gas channels (GCs). These GCs possessed rectangular and trapezoidal channel cross-sections, while maintaining equal cross-sectional areas [24]. In order to avoid loss of voltage in the fuel cell, stacked electrical connection is made with the help of bipolar plates that make the connection over the electrode surface. These bipolar plates also serve as a barrier between the electrode gases. Some other operating problems might occur in the fuel cell. Several factors contribute to the degradation of fuel cells, including electrode delamination, significant cell corrosion, aging of cell components caused by mechanical and thermal stressors, and contamination of the fuel cell by carbon monoxide (CO). The contamination issues can be reduced by physically removing the gases such as CO and oxidizing the H_2 gas with the help of oxygen or peroxide [23].

It has been observed that the research work done by different researchers in an effort to propose mathematical or numerical models of PEMFC is scattered and no review paper encompasses the entire research work in this particular area. Therefore, the present review paper presents the compilation of all such research papers for the readers to find all the relevant work in one document.

This paper reviews the principles of fuel cells, mathematical models for PEMFC steady-state and transient phenomena proposed by various researchers, thermal management strategies for PEMFC, and current research challenges related to enhancing performance and cost-effectiveness. It also highlights recent advancements in optimizing fuel cell components, such as the catalyst layers, gas diffusion layers, and cooling mechanisms, through analytical, numerical, and experimental techniques. Furthermore, the work emphasizes the importance of integrating advanced control and design strategies, such as genetic algorithms and heat pipes, to enhance fuel cell performance and durability under different operating conditions. Through this paper, the immediate and long-term benefits of comprehending the fuel cell technology for future energy needs can be envisioned.

This review paper uniquely consolidates scattered research findings into a comprehensive inventory, systematically identifying critical gaps within this specific field. By doing so, it offers valuable insights that pave the way for targeted future investigations. The novelty of this work lies in its integrative approach and its strategic mapping of unexplored areas, thereby advancing the understanding of the research landscape and guiding subsequent scholarly efforts.

2. Materials and methodology

2.1. Review methodology

This review adopts a systematic approach to synthesize reliable and concise information on Polymer Electrolyte Membrane Fuel Cells (PEMFCs), emphasizing modeling and performance enhancement research. The process begins with identifying key issues in current fuel cell technology and exploring mathematical models describing steady-state and transient behaviors. Literature selection involved four systematic stages: database searches using targeted keywords across Scopus, Web of Science, PubMed, and DOAJ; application of inclusion and exclusion criteria; screening titles and abstracts; and detailed assessment of full texts. An initial pool of 156 peer-reviewed articles was narrowed to 39 highly relevant studies focused on PEMFC modeling, performance improvement, and economic considerations, as illustrated in Fig. 1. To ensure quality and reduce bias, only peer-reviewed publications encompassing case studies, reviews, and research articles were included. The methodology prioritized recent literature from December 1990 to December 2024, leveraging Boolean searches to identify pertinent data while avoiding duplication. This systematic process provides a comprehensive foundation for analyzing current challenges and proposing future research directions aimed at optimizing PEMFC performance and cost-effectiveness.

2.2. Assumptions, limitations, and uncertainties

There are still significant gaps in research that need to be addressed, even with recent breakthroughs. The prediction accuracy of current models is restricted

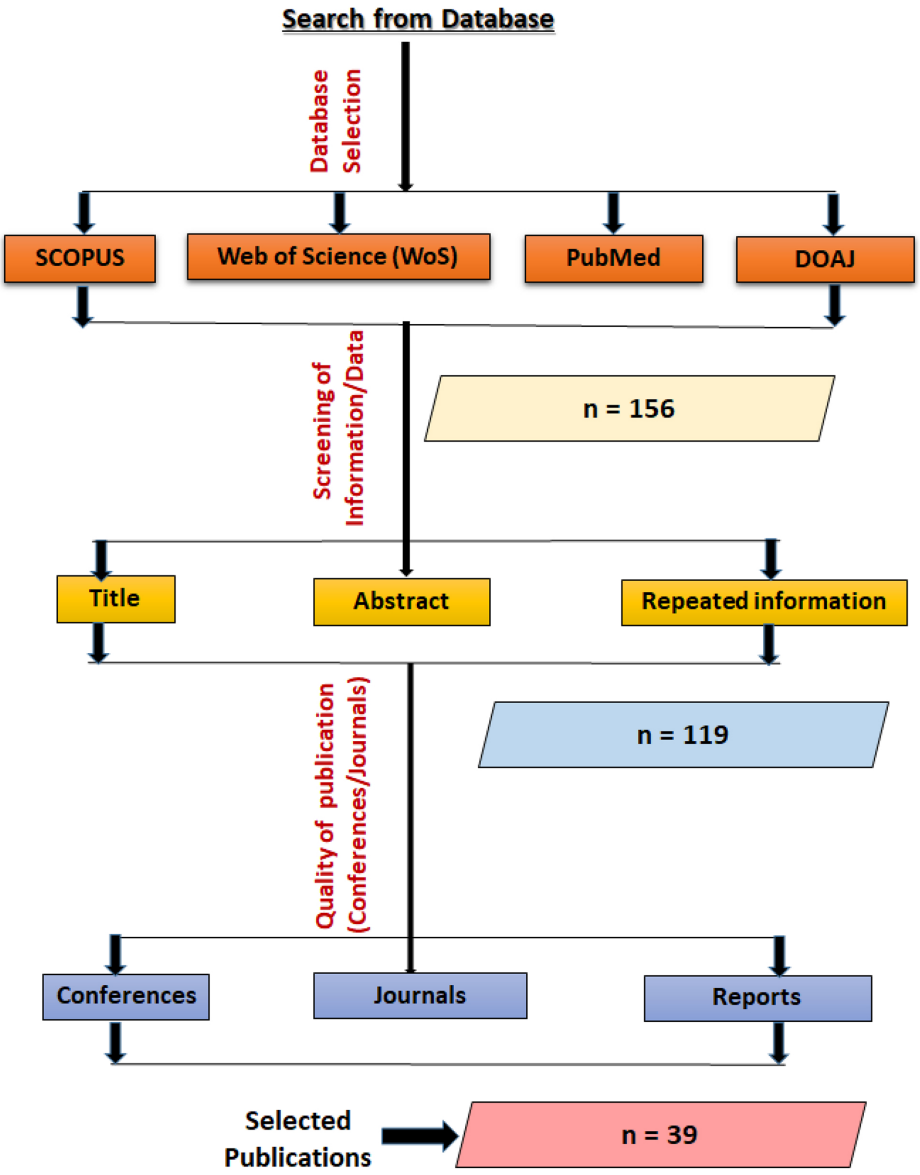


Fig. 1. Review process and methodology.

by the fact that they frequently oversimplify intricate processes, which include water management, electrochemical kinetics, and thermal impacts. In addition, the integration of these models into complete dynamic control systems is still in its early phases, which limits the ability to optimize operations in real time.

In addition to that, the current study is subject to a number of limitations, including the fact that it depends on simplified models that may not be able to completely represent the complicated electrochemical kinetics, water management, and thermal phenomena, which means that the prediction accuracy of the study might be affected. The practical applicability of these models is limited by the fact that their integration into real-time control systems is still in its early stages of development.

The uncertainty in the power output is related to the most important parameters in a fuel cell:

- Incoming flow of oxidant.
- Fuel (H_2) input.
- Dimensions and arrangement of Polymer electrolyte Membrane (PEM).

Overall uncertainty in the maximum power output measurement can be attributed to individual uncertainties in ohmic losses, losses due to poor system design or poor workmanship. These individual uncertainties contribute to the overall uncertainty, which

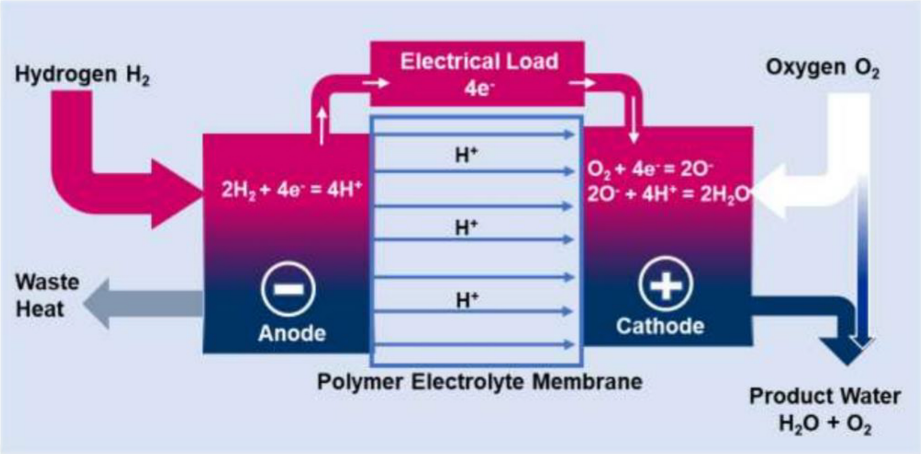


Fig. 2. Schematic diagram of PEMFC [4].

can be expressed as [25],

The total uncertainties

$$= \sqrt{\sum (\text{Individual uncertainty})^2}$$

3. Results and discussion

3.1. Polymeric materials for FCs

Proton Exchange Membrane Fuel Cells (PEMFCs) use hydrogen as a primary fuel source and oxygen as an oxidizing agent. To meet a specific need, oxygen might be delivered in a purified or no-purified form. While protons go via the PEM from anode to the cathode, the electrons must be carried by an external circuit in the form of a load to the cathode. The cathode facilitates the combination of oxygen and protons, resulting in the production of water via the use of the load. The fuel cells in which Protons are transferred from anode to cathode through PEM is called the Proton Exchange Membrane Fuel Cell (PEMFC). This type of fuel cells plays a significant role in the renewable energy market. Based on the type of fuel utilized, PEMFCs can be classified into many categories. 1) hydrogen fuel cell 2) direct ethanol fuel cell, and 3) direct methanol fuel cell. The hydrogen fuel cell utilizes hydrogen gas (H_2) as its primary fuel source and has outstanding performance in terms of fuel cell efficiency. Fig. 2 displays the schematic design of the fuel cell. The half-cell processes associated with the hydrogen Proton Exchange Membrane Fuel Cell (PEMFC) are presented as follows [26].

Anode:

$$H_2 \leftrightarrow 2H^+ + 2e^- \qquad \Delta G^o = 0.00$$

Cathode:

$$^1/_2O_2 + 2H^+ + 2e^- \leftrightarrow H_2O \quad \Delta G^o = -237.3\ kJ/mole$$

Overall:

$$H_2 + {}^1/_2O_2 = H_2O \qquad \Delta G^o = -237.3\ kJ/mole$$

In the aforementioned cell, the cathode reaction produces both electrical and thermal energy. The Gibbs free energy of the process is theoretically accessible as electrical energy but a portion of Gibbs free energy, ΔG, is transformed to heat via the loss mechanisms [26].

$$\Delta G = \Delta H - T\Delta S \tag{1}$$

In the context of a reaction, the symbol ΔH denotes the alteration in enthalpy, whereas T signifies the temperature, and ΔS denotes the modification in entropy. Temperature influences both the enthalpy and entropy of the process. It is widely established that there exists a strong correlation between the Gibbs free energy change of a chemical process and the corresponding cell voltage as [26],

$$\Delta G = -nFV_o \tag{2}$$

$$V_o = -(\Delta G/nF) \tag{3}$$

In the given context, the variable 'n' represents the quantity of electrons participating in the reaction. The symbol 'F' denotes the Faraday constant, which has a value of 96485 C/mole. Lastly, 'V_o' signifies the cell voltage at thermodynamic equilibrium when no

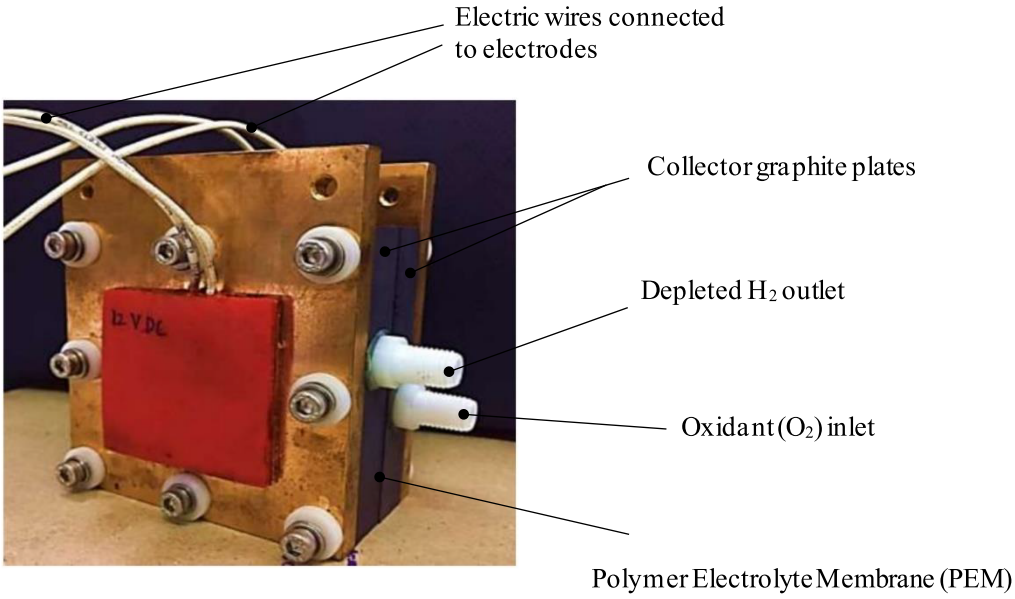


Fig. 3. Photo of fuel cell stack [4].

current is flowing, specifically referring to the circumstances of an open circuit. Substituting the standard conditions values for hydrogen and oxygen into Equations (Eqs. (1) and (3)), gives [26]:

$$V_o = -\frac{-237.3\frac{kJ}{mole}}{2 \times 96485\frac{C}{mole}} = 1.23\ V \tag{4}$$

The electromagnetic field of the equilibrium cell may be defined as the potential difference that exists between the cathode and anode when the system is in a state of equilibrium. Fig. 3 displays the image of the fuel cell.

3.2. PEMFC applications

Various methods are employed in the synthesis of Polymer Electrolyte Membranes (PEMs) for both Direct Methanol Fuel Cell (DMFC) and PEMFC applications such as transportation including light-weight vehicles and busses. These methods include the creation of novel ionic and/or block copolymers, the graft copolymerization of ionic monomers onto hydrophobic polymers, the blending of ionic and non-ionic polar polymers, and the synthesis of Interpenetrating Polymer Networks (IPNs) using ionic/polar polymers. Additionally, composite membranes incorporating a diverse range of fillers are also synthesized.

3.2.1. Transportation

The fast growth of the global automotive industry has brought out a range of concerns, including but not limited to air pollution, climate change resulting from greenhouse gas emissions, and the need for sustainable fuel sources. For the most part, the problems stem from the use of hydrocarbon fuels in traditional engines, such as internal-combustion engines (ICEs). ICEs might be replaced with PEM fuel cells because of their better efficiency and reduced greenhouse gas emissions. Passenger automobiles, utility vehicles, and buses, for example, often utilize electricity between 20 kW and 250 kW. Interest in fuel-cell cars dates back to the late 1970s, but has recently seen a resurgence. Many elements of PEM fuel cells are preferable to ICEs, except for initial costs, according to McNicol et al. [27], Ballard Power Systems provides a fuel-cell technological roadmap in which it identifies numerous key obstacles [28].

3.2.2. Light-weight vehicles

In recent years, General Motors, Honda, and other firms have emerged as prominent leaders in the fuel cell light-weight car sector. Honda has initiated the transportation of its FCX Clarity vehicle to both Southern and Northern California, since both areas have now been outfitted with hydrogen fueling infrastructure. The FCX Clarity is made available to a limited number of consumers via a three-year leasing program, with a monthly cost of $600 specifically for the FCX Clarity model. One way of improving the energy efficiency of PEMFC in lightweight hybrid vehicles is tested by developing a 2 kW air-cooled PEMFC stack model. According to the study, an efficient Convection Heat Transfer (CHT) model using a Computational Fluid Dynamic (CFD) software is

tested. The simulation and physical model testing show a uniform temperature distribution resulting in lower cooling density and hence reduced energy consumption [29].

3.2.3. Buses

The peak seen in 2003 aligns with the introduction of Daimler's fleet of 33 buses for the Australian Sustainable Transport Energy Project (STEP), Ecological City Transport System (ECTOS), and European Clean Urban Transport for Europe (CUTE) initiatives. Each city participating in CUTE has a unique fleet of buses. In Stockholm, every Mercedes-Benz Citaro fuel-cell bus is equipped with two fuel cell stacks, together generating a power output of 250 kW. These buses also store 40 kg of hydrogen at a pressure of 350 bar, which enables them to operate for around 200 kilometers before requiring refueling.

3.2.4. Diverse applications

The Polymer Electrolyte Membranes (PEMs), which serve as the central element of the fuel cell, has a wide range of applications including the elimination of harmful metal ions and the advancement of drug delivery technologies. The commonly used polymer membrane in the Nafion-117 membrane, which has proven to assist in proton conductivity across the membrane [26].

3.3. The PEMFC models

Multiple simulation models have been created throughout the years. The computational scope of the model is generally speaking a good way to characterize these models. One category of models is centered on certain components or aspects of fuel cells, such as the electrode, gas diffusion layer, cathode catalyst layer, or membrane electrode assembly. Another type of model focuses on the whole system of the fuel cells. These models can be quite helpful. Despite this, they are unable to offer a comprehensive image of the fuel cell. Additional categories of models include depictions of individual elements inside a fuel cell, spanning from one-dimensional and single-phase models to three-dimensional and two-phase models [30].

The research work on fuel cells started as early as the last decade of the 20th century. One of the first reports on fuel cells is attributed to Springer et al. [31], who formulated a steady-state one-dimensional isothermal model for a Proton Exchange Membrane Fuel Cell (PEMFC) with a Nafion-117 semi-permeable membrane. The schematic shown in Fig. 4 comprises of mainly the two inlet channels, gas diffusion electrodes, and the Nafion-117 membrane. The model

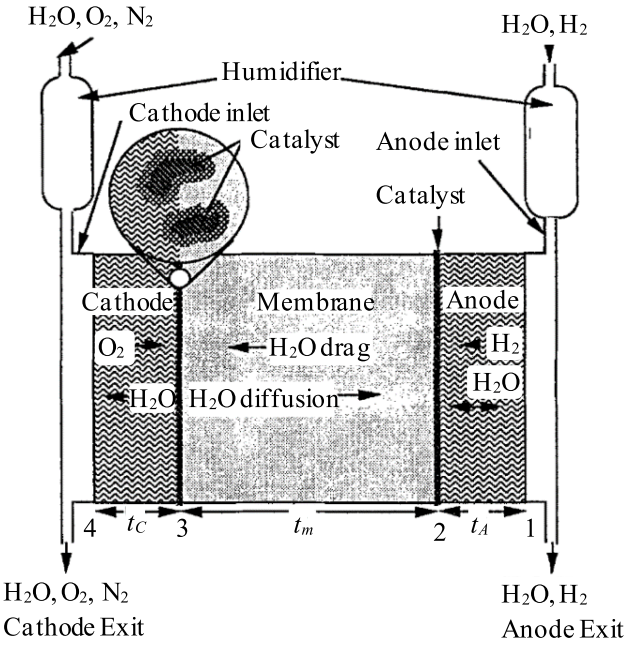


Fig. 4. Fuel cell model schematic [9].

comprised of continuity equation for flow in the inlet channel and diffusion equation for the gas at the electrodes. The continuity equation gave the mole fraction of water at interface 1 as [31].

$$x_{w1} = \frac{\nu_H x^I_{wA} - \alpha\left(1 - x^I_{wA}\right)}{x^I_{wA} - \alpha\left(1 - x^I_{wA}\right) + \nu_H - 1} \tag{5}$$

and diffusion equation resulted in gas flow across anode and cathode as [31]

$$\frac{dx_{wA}}{dz} = \frac{RTI}{P_A D_{wH}}\left[x_{wA}\left(1+\alpha\right) - \alpha\right] \tag{6}$$

$$\frac{dx_O}{dz'} = \frac{RTI}{P_C}\left[\frac{x_O\left(1+\alpha\right) + 0.5x_{wC}}{D_{wO}} + \frac{1 - x_{wC} - x_O}{D_{ON}}\right] \tag{7}$$

$$\frac{dx_{wC}}{dz'} = -\frac{RTI}{P_C}\left[\frac{\left(1-x_{wC}-x_O\right)\left(1+\alpha\right)}{D_{wN}} + \frac{0.5x_{wC}+x_O\left(1+\alpha\right)}{D_{ON}}\right] \tag{8}$$

Integrating (Eq. (6)) with the boundary condition $x_{wA} = x_{w1}$ at $z = 0$, x_{w2} is obtained as [31],

$$x_{w2} = \left(x_{w1} - \frac{\alpha}{1+\alpha}\right) exp\left(\frac{RTIt_A}{P_A D_{wH}}\right) + \frac{\alpha}{1+\alpha}$$

Where, R is molar gas constant, T is temperature, I is molar flux, t_A is thickness of anode, P is pressure, D is diffusion coefficient, α is H_2O flux ratio, x_{wi} is molar fraction of water across the interfaces. Dannenberg et al. [32] used the foundational framework proposed by Springer et al. [31] to construct a two-dimensional mathematical model for heat and mass flow inside a fuel cell, focusing on a single phase. Their model calculated the cell performance in terms of cell voltage vs current density, variation of current and temperature along the gas channel, water contents in the membrane, and ohmic resistance influenced by stoichiometry of fuel cell gases, properties of coolant (air or water), and humidity. The findings of their study confirmed that optimal performance of the Proton Exchange Membrane Fuel Cell (PEMFC) might be achieved by using fuel cell gases that were adequately humidified, maintaining isothermal conditions, employing water coolant, and employing a certain high stoichiometric coefficient value (identified as 2 by the researchers), influenced by the humidity level.

Goudy [33] conducted a study aimed at designing a micro-scale fuel cell and observed that the performance of the fuel cell was influenced by its size. A decrease in the scale of the cell resulted in a decrease in the ohmic losses whereas an increase in the parasitic losses. Also, at microscale, the no-slip condition of gas diffusion within the gas channel no longer remained a valid condition. A study on the momentum transfer in a two-phase model, including gas-phase mass transport and water transport in the ionomer, in an open cathode fuel cell, showed that the conductivity of the ionomer and therefore the output voltage of the cell were influenced by the humidity level [34]. Furthermore, Azimur Rahman et al. [35] proposed an alternative model for a two-phase proton exchange membrane fuel cell (PEMFC) that was non-isothermal and one-dimensional. This model aimed to investigate the transport of gas and liquid within the cell in order to simulate its performance under various operating conditions. These conditions included different relative humidity levels (80% and 90%), varying oxygen concentrations at the cathode (ranging from 1% to 21%), a range of cell voltages (between 0.1 V and 0.3 V), different temperatures (70°C and 80°C), varying pressures (100 kPa_{abs} and 300 kPa_{abs}), and different hydrogen and air flow rates (0.4 NLPM and 2.0 NLPM, respectively). Some more PEMFC models are summarized in Table 1.

3.4. Validation for PEMFC models

The use of experimentation is employed in order to ascertain the performance parameters of the High Temperature Proton Exchange Membrane Fuel Cell (HT-PEMFC). As part of the process to validate the newly constructed model, the findings of the simulation were compared to those of the experiments for a number of the variables.

The dynamic characteristics of a Proton Exchange Membrane (PEM) fuel cell device provide indications of several experimental observations. This study investigates the variations in the dynamic behavior of a single Proton Exchange Membrane (PEM) fuel cell device under varied operational conditions. A comprehensive experimental investigation was carried out by Ziogou et al. [43] in order to explore the behavior of the system under a variety of various settings for its operation. In all conducted tests, the flow rate of reactants was maintained at a consistent level, which was proportional to the greatest projected stoichiometric flow based on the maximum average current density. The definition of the excess flow ratio was as follows [43]:

$$\lambda = \frac{\text{flow applied}}{\text{Stoichiometric flow at mximum current density}} \quad (9)$$

The first operational parameter that underwent testing was the temperature of the fuel cell. This variable was assessed at four different levels: 50°C, 60°C, 65°C, and 70°C, respectively. The hydration temperature was maintained at a constant level of 70°C, the operating pressure of the system was set to the standard value of 0 bar gage, and the surplus flow ratio for the anode flow was 2.3 and the cathode flow was 1.5. The influence of temperature on the fuel cell's performance in relation to voltage and provided power at varying current density is seen in Figs. 5 and 6.

The maker of the membrane said that the minimum acceptable working temperature was 60°C. At the lower temperature of 50°C, a significant decrease in both the maximum power and current density was observed, indicating that the fuel cell was not being fully used. The performance was comparable between 60°C and 65°C up to the maximum amount of power that could be given; however, after that point, the power at the raised temperature dropped at greater current densities. In conclusion, there was not much of a difference between temperatures of 65°C and 70°C. In addition, it is worth noting that although working at elevated temperatures has the potential to provide more power output, a temperature of 65°C was specifically chosen for the experimental setup in order to enhance the longevity of the membrane.

Table 1. Summary of LES models.

Sr. No.	PEMFC Models	Nature of Dimensions	Mode of Analysis	Purpose of Analysis	Observations
1	Two-phase non-isothermal model	Three-dimensional	Numerical simulation	Establish a benchmark for further parameter sensitivity analysis and model validation	The simulation results of local current density distribution, polarization curve, etc. show good agreement with the results available in the literature [36]
2	Steady-state, non-isothermal, multi-component, single-phase (gas) laminar and turbulent flows	Three-dimensional	Simulation software STAR-CCM+	Investigate the thermal, fluid dynamic, and electrochemical behavior of a PEMFC portion	The flow models give reasonable results of fluid dynamic aspect. However, the turbulent flow model shows discrepancy in the electrochemical behavior of the fuel cell especially in the polarization curves [37]
3	Two-fluid five-channel model	Three-dimensional	Commercial CFD software (ANSYS Fluent) through the Used Defined Function (UDF)	Analyze the effect of multi-phase flow in the gas channel on the electrochemical reaction activities and fuel cell functioning	Diminished cell performance at high current densities is observed, which may be attributed to the existence of liquid water inside the gas flow channel [38]
4	Two-phase flow	Three-dimensional	Volume of Fluid (VOF) approach	Comprehensive understanding of the two-phase flow, its constraints, and its consequences	A change in voltage affects the pressure drop and water velocity of the pores. Also, the water coverage ratio is higher for hydrophilic surfaces than for the hydrophobic surfaces [39]
5	Two-phase flow	Three-dimensional	Volume of Fluid (VOF) approach in the interFoam solver of the program OpenFoam 7.0	Investigate the effect of GDL carbon fiber diameter on two-phase flow pattern in the cathode region	Larger fiber diameter allows fluent liquid flow through the CDL that, in turn, floods in the GC [40]
6	steady-state, isothermal, single-phase model	One-dimensional	Experimental and analytical means	Describe the electrode kinetics, mass transport, and ionic and electronic resistances	Optimized quantity of electrolyte in the cathode is much lower than that in anode and any change in the optimized quantity has significant effect on cathode performance [41]
7	Three-in-one flexible micro-server of high temperature electrochemical PEMFC model	Three-dimensional	Experimental means	Real-time analysis of temperature, pressure, and flow distribution	Protection of micro sensor from failure or damage can be ensured using suitable material and process parameters [42]

In the second experimental condition, the hydration temperature of both the anode and cathode electrodes was manipulated, ranging from 65°C to 80°C and subsequently to 90°C. Because a rise in humidity leads to a decrease in internal resistance, the performance of hydrators operating at temperatures up to 80 degrees Celsius was significantly enhanced as a consequence. At temperatures of 90°C, however, flooding occurrences caused a reduction in performance. Because the previous experiment found that an operating temperature of 65°C was optimal, the temperature of the hydrators was decided to be 5°C to 10°C higher. Because of this, flooding was avoided, while at the same time, the membrane received an acceptable amount of humidity [43].

3.5. Performance enhancement

One way of improving the energy efficiency of PEMFC in lightweight hybrid vehicles is tested by developing a 2 kW air-cooled PEMFC stack model. According to the study, an efficient Convection Heat Transfer (CHT) model using a Computational Fluid Dynamic (CFD) software is tested. The simulation and physical model testing show a uniform temperature distribution resulting in lower cooling density and hence reduced energy consumption.

The Proton Exchange Membrane (PEM) plays a crucial role in the functioning of a fuel cell, with its effectiveness being heavily influenced by certain attributes. These attributes include the capacity to

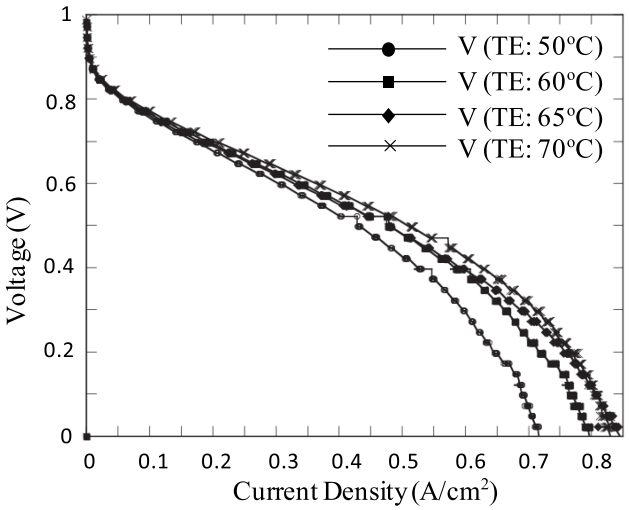


Fig. 5. Effect of temperature on voltage [22].

exhibit strong protonic conductivity at elevated operating temperatures and low relative humidity, as well as demonstrating low methanol permeability. In addition to this, other techniques to ensure temperature, water, and oxygen distribution uniformity, potentially causing improvement the current density are tested by many researchers to enhance PEMFC's energy efficiency, which, in turn, can result in lower energy consumption and longer distances travelled by the transport vehicles. A comparison between the three main categories of material namely Polymeric, Ceramic, and Inorganic-organic composite has shown that some of the desired characteristics are present while others are absent in each of the material categories. The objective of the comparative analysis is to identify a material that is optimal for operating under low relative humidity and high temperature conditions, while exhibiting the highest level of proton conductivity and the lowest degree of methanol permeability. The Nafion®polymer, widely used as a proton exchange membrane (PEM), exhibits diminished proton conductivity in conditions of elevated temperature and reduced relative humidity. Hence, among the several materials under investigation, it is anticipated that altering Nafion®via the augmentation of sulfonic group density on polymer surfaces and the incorporation of chemicals that enhance proton mobility on sulfonic groups might provide favorable outcomes in terms of fuel cell efficiency. Furthermore, composite proton exchange membranes (PEMs) based on Nafion®have shown promising capabilities as a viable alternative to Nafion®. However, enhancement of Proton conductivity needs to be addressed. One potential approach to accomplish this objective involves substituting cobalt and nickel analogues of iron oxyhydroxides (CoOOH and NiOOH) with thermally stable polymers like Teflon and PFA during the synthesis of ferroxane-based composites. Alternatively, reducing the particle size of nanoparticle fillers might also be used. Previous studies have shown that reducing particle size leads to an increase in specific surface area, which subsequently allows for a greater surface area available for proton transport and water adsorption [44]. A coupling of a Longitudinal Vortex Generator (LVG) with cathode channel is one of performance enhancement methods by means of improving the energy, i.e., current density and optimizing the water-thermal management of the fuel cell. It is found that installing the LVG improves the temperature, water, and oxygen distribution uniformity and hence the current density is increased [45]. The geometric model of PEMFC with a representative shape of the LVG is shown in Fig. 7.

The governing equations of the gas flow, mass transport, and temperature distribution are given as [45],

Gas flow field from continuity equation

$$\nabla(\rho u) = 0 \tag{10}$$

Gas flow field from momentum equations

$$\nabla(\rho u \times \ -\mu\nabla u) = -\nabla\left(P + \frac{2}{3}\mu\nabla u\right) + \left[\mu(\nabla u)^T\right] \tag{11}$$

Mass transport equation for species i

$$\nabla\left[-\rho y_i \sum_{j=1}^{N} D_{ij}\frac{M}{M_j}\left(\nabla y_i + y_i\frac{\nabla M}{M}\right) + \rho y_i u\right] = 0 \tag{12}$$

Temperature in energy equation

$$\nabla\left(\rho C_P u T - k\nabla T\right) = 0 \tag{13}$$

Transport in gas diffusion layers

$$\nabla(\rho\varepsilon u) = 0 \tag{14}$$

Momentum equation in gas diffusion layers via Darcy's law

$$u = \frac{k_p}{\mu}\nabla P \tag{15}$$

Mass transport equation in porous media

$$\nabla\left[-\rho\varepsilon y_i\sum_j^N D_{ij}\frac{M}{M_j}\left(\nabla y_j + y_j\frac{\nabla M}{M}\right)+\rho\varepsilon y_i u\right]=0 \tag{16}$$

Diffusivity in porous media using Bruggemann correction formula

$$D_{ij}^{eff}=D_{ij}\times\varepsilon^{1.5} \tag{17}$$

Energy equation in gas diffusion layers

$$\nabla\left(\rho\varepsilon C_P u T-k_{eff}\varepsilon\nabla T\right)=\varepsilon\beta\left(T_{solid}-T\right) \tag{18}$$

Some of the boundary conditions are: inlet reactants temperature (T_{cell}) = 343 K, oxygen mass fraction at the anode inlet ($Y_{O;a}$) = 0, etc. complete account of the boundary conditions can be seen in [45]. Plots of current density vs the distance between the LVG, angle of attack, and number of LVGs are shown in Fig. 8(a-c). The graphs depict that PEMFC best performance with highest current density is achieved with 5 LGVs, angle of attack of 45°, and placed at a distance of 12 mm [45].

Several more numerical models are formulated to investigate the impact of flow patterns, droplet behavior, flow mal-distribution within the Gas Diffusion Layer (GDL), and intake flow channels, as well as input factors like pressure and temperature, on the performance of fuel cells [46, 47]. The findings suggest that the use of hydrophobic gas diffusion layers (GDLs) and hydrophilic channel walls, together with the implementation of narrow communication channels, the incorporation of gas inlet resistance [25], and the operation of the fuel cell at higher input variables [47], contribute to the enhancement of fuel cell

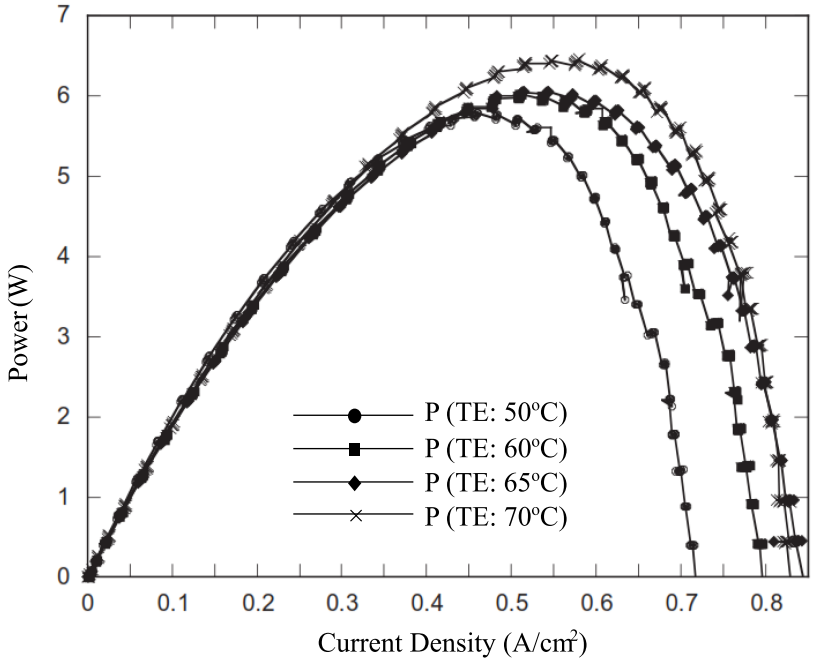


Fig. 6. Effect of temperature on power [22].

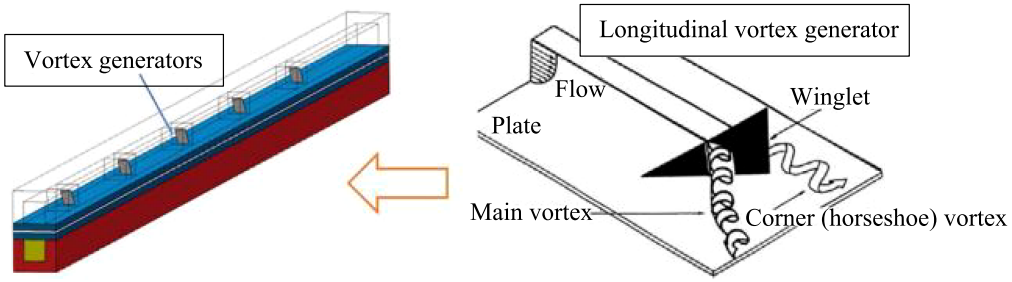
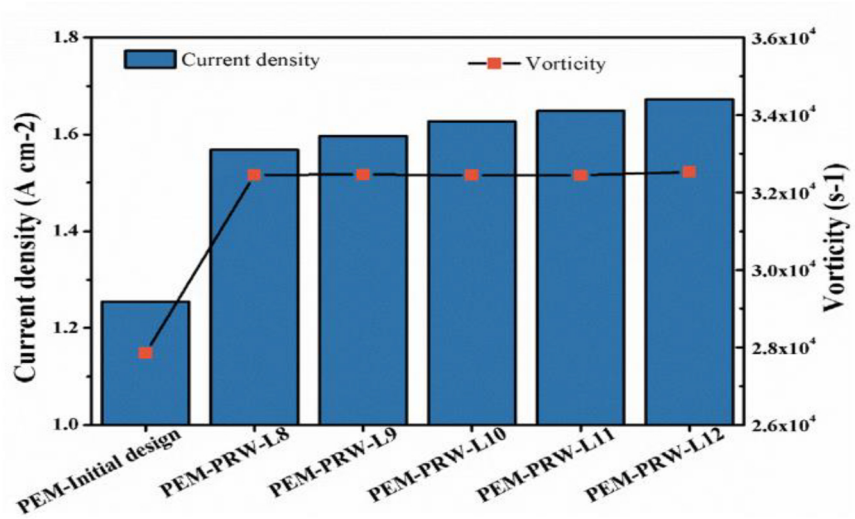
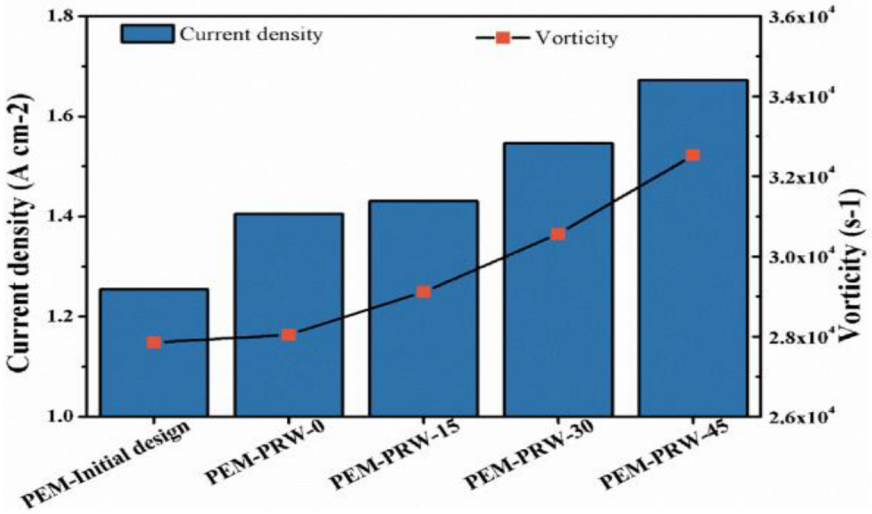


Fig. 7. Cell flow channel and LVG [24].

(a)



(b)



(c)

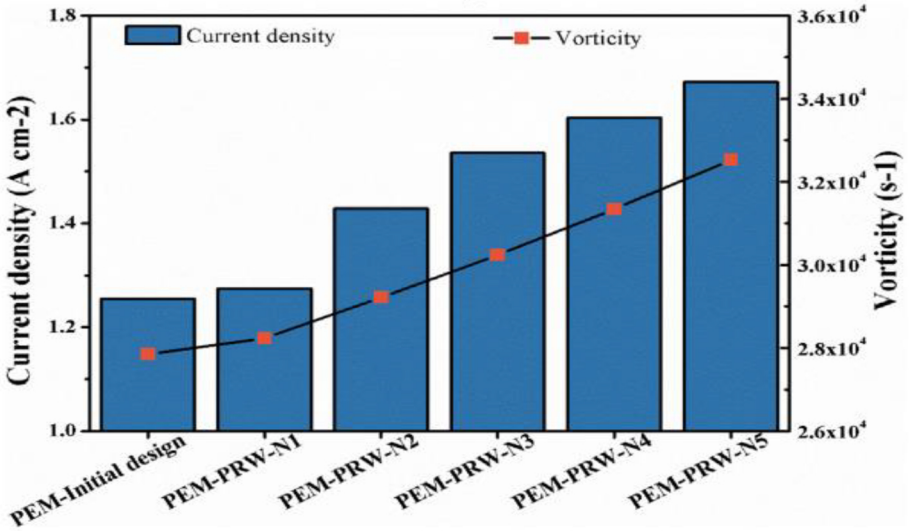


Fig. 8. Current density and vorticity plotted against (a) LVGs separation, (b) attack angle, and (c) number of LVGs [24].

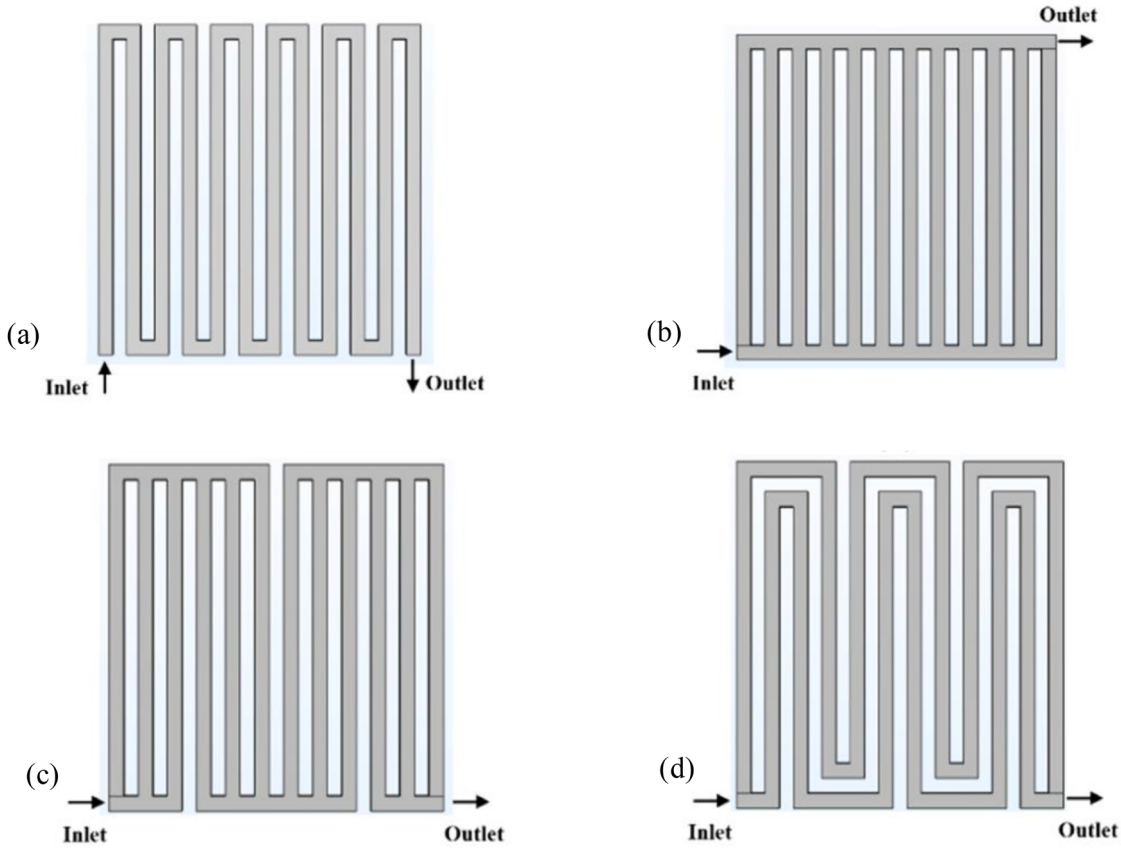


Fig. 9. Anode flow fields tested (a) SFF, (b) PFF, (c) PSFF, and (d) DSFF [28].

performance. There are two distinct two-phase non-isothermal models for Proton Exchange Membrane Fuel Cells (PEMFC) that are developed in order to analyze and evaluate the performance of these fuel cells [48, 49]. The research conducted by Pan et al. [48] was centers on the fuel cell model, with a primary objective of reducing computing expenses while maintaining model precision. This was achieved via the use of analytical order reduction techniques and approximation methodologies. This model when compared with the full one-dimensional model for the polarization curves had a discrepancy of less than 4%. The use of a Reduced Order Model (ROM) may be advantageous in examining the impact of the Membrane Electrode Assembly (MEA) on the performance of fuel cells, hence providing valuable insights into the optimization of the MEA structure. The alternative Direct Methanol Fuel Cell (DMFC) model, as investigated by Hongxiu et al. [49], examines the impact of the anode flow field on many aspects including fuel cell performance, pressure drop, temperature management, fuel management, and byproduct management. The anode flow fields are taken into consideration include the Parallel Flow Field (PFF), Serpentine Flow Field (SFF), Double-channel Serpentine Flow Field (DSFF), and Parallel Serpentine Flow Field (PSFF). The diagrams illustrating the flow fields are shown in Fig. 9.

The anode flow fields undergo testing while maintaining the cathode flow field in a serpentine flow configuration with flow paths of equal size. Theoretical investigation on these anode flow paths reveal that SFF has the highest power density but at the same time high pressure drop resulting in a possible bubble blockage. PFF on the other hand has low pressure drop but the flow in this type of configuration is very low resulting in reduced convection capacity and hence low performance. PSFF has a superior thermal management. However, DSFF has the best overall performance with respect to power density, low pressure drops, excellent byproduct, i.e., CO_2 gas removal capability, and thermal management. So, if only high-power requirement is the concern, then SFF is a good choice but for overall performance of the fuel cell, then DSFF can be the first choice [49].

Among various fuel cell performance enhancement techniques used, a very useful optimization technique is the Genetic Algorithm (GA), which can be employed to indirectly enhance the cell performance by optimizing components geometrical, mechanical, or chemical parameters. A particular non-isothermal

three-dimensional U-shaped serpentine flow field model, characterized by high temperature, is used as a basis for the application of Genetic Algorithm (GA) in order to optimize the Catalyst Layers (CLs) of the anode and cathode. This optimization aims to boost the performance of the fuel cell. The major governing equations of the model can be expressed as [50]

Continuity Equation

$$\varepsilon \frac{\partial \rho}{\partial t} + \nabla . (\varepsilon \rho u) = 0 \tag{19}$$

Momentum Equation

$$\frac{\partial (\varepsilon \rho u)}{\partial t} + \nabla . (\varepsilon \rho u) = -\varepsilon \nabla \rho + \nabla . (\varepsilon \mu \nabla u) \tag{20}$$

The flow velocities of the gases u are zero at the surfaces of the CL. Charge Balance Equation of the Porous layer [50],

$$-\nabla . \left(\sigma_s^{eff} \nabla \Phi_s\right) + S_s = 0 \nabla . \left(\sigma_m^{eff} \nabla \Phi_m\right) + S_m = 0 \tag{21}$$

Energy Equation for the Transfer of Matter [50],

$$\nabla . \left(\rho C_p u T\right) = \nabla . \left(k^{eff} \nabla T\right) + S_T \tag{22}$$

where ϵ = porosity, ρ = density, μ = dynamic viscosity, P = pressure, u = velocity vector, σ_s^{eff} = effective surface tension of conducting solid, σ_m^{eff} = effective surface tension of proton exchange membrane, Φ_s = potential of conducting solid, Φ_m = potential across the proton exchange membrane., T = temperature, C_p = specific heat and constant pressure, k^{eff} = effective heat conductivity of the substance, and S_T = heat source. The optimal thicknesses of the anode and cathode current collector CLs are determined to be 0.0231 mm and 0.0315 mm, respectively. The performance enhancement of 6.8% is obtained using these optimized CL thicknesses [50]. Similarly, other techniques can be utilized to solve the differential equations. For instance, Nassar [51] employed Simpson's 1/3 rule to solve the quadruple integral in order to compute the view factor of rectangular non-aligned surfaces such as PV panels in solar fields.

A comparative analysis of two dynamic models for conventional and air-breathing proton exchange membrane fuel cells (PEMFCs) reveals that the air-breathing PEMFC exhibits notably reduced transient response, particularly in the context of load modifications or large load fluctuations, as compared to the traditional PEMFC. Furthermore, it is shown that the performance of an air-breathing cell may be enhanced by reducing some parameters, including the porosity of the Gas Diffusion Layer (GDL), the thickness of the membrane, and the total electrical resistance. The variation of these parameters does not influence much on the performance of the conventional PEMFC [52].

3.6. Current research on PEMFC

Some very comprehensive review articles have presented research work by the researchers on different aspects of PEMFC related to material and design, fluid transport management, control of operation, types of fuel cells, and different methods to solve the model equations. A review paper was published that provided a comprehensive overview of the technology, applications, and basic research conducted so far on Proton Exchange Membrane Fuel Cells (PEMFC) [28]. Another review paper examined the investigation into the impact of geometric designs of flow channels on the overall performance of a Proton Exchange Membrane Fuel Cell (PEMFC) [24]. Another review paper [53] also presented the research conducted on the material and design of the Gas Diffusion Layer (GDL). The fact that Proton Exchange Membrane (PEM) cannot be completely dry or flooded with liquid since both conditions would disturb gas-fluid two-phase flow distribution resulting in pressure drop, mal-distribution of flow and low cell performance. The Volume of Fluid (VOF) technique, which is widely used, proves to be a valuable approach for simulating the two-phase flow occurring inside a fuel cell. The compilation of such work was presented in a recent review article [54].

A comprehensive collection of related studies on the management of water in gas flow channels and the dynamics of droplets, including factors such as surface wettability, starting liquid water conditions, channel geometry, and operational parameters, can be found in the literature [55]. Numerous researchers have dedicated their efforts to develop physical and data-driven models, using Artificial Intelligence (AI) and other machine learning methods, to facilitate real-time management of Proton Exchange Membrane Fuel Cells (PEMFC) under various operating circumstances, including temperature, pressure, stoichiometric ratio, and humidity [56]. Another class of PEMFC, the air-breathing fuel cell is also studied extensively. A new collection of scholarly research focused on optimizing important factors like the design and material of the current collector, gas diffusion layer (GDL), and catalyst layer (CL), as well as cell orientation and ambient conditions. The impact of these elements on the performance of the cell was also investigated. Furthermore, the collection included

strategies proposed by researchers to alleviate the impacts of harsh circumstances, such as humidity and temperature [57].

3.7. Thermal management

3.7.1. Simulation and modeling

The thermal factor is a crucial determinant of the electric power production and efficiency of the Proton Exchange Membrane Fuel Cell (PEMFC). The electrochemical process produces heat, which must be dissipated in order to maintain the fuel cell within its optimal thermal operating parameters. It is found that the means of cooling also effects the heat dissipation. Two main thermal management modes are usually employed, i.e., active and passive cooling. Active cooling can be accomplished by water circulating the fuel cell or air blown around it. Passive cooling is mainly due to free/natural convection and radiation. It is required to dissipate 90% of the generated heat by active cooling. However, it is found that active cooling has 54% to 67% cooling effectiveness. Also, optimum cooling can be achieved if the water inlet temperature is less than 60°C. on the other hand, passive cooling contributes from 14% to 23% in the cooling process [58]. Thermal analysis involves the heat transfer equations. The theoretical heat generated for the fuel cell stack can be represented by [58],

$$Q_{th} = 1.482\,(1 - \eta_{cell})\,I.n_{cell} \tag{23}$$

where I is stack current in amperes, η_{cell} is the single cell efficiency. The power output is [58],

$$P_{el} = V \times I \tag{24}$$

where V is the electric potential in volts. Single cell efficiency [58],

$$\eta_{cell} = \frac{V_{cell}}{V_{max}} = \frac{V_{cell}}{1.482} \tag{25}$$

Active cooling through water and air circulations can be understood by finding the rate of heat transfer through water and air [58].

$$\dot{Q}_{cw} = \dot{m}_{cw}.C_{p,cw}.\left(T_{cw,e} - T_{cw,i}\right) \tag{26}$$

$$\dot{Q}_{a} = \dot{m}_{a}.C_{p,a}.\left(T_{a,e} - T_{a,i}\right) \tag{27}$$

where the subscripts '*cw*' and '*a*' represent water and air, respectively while the subscripts 'e' and 'i' represent exit and inlet, respectively. The net heat in the fuel stack over a certain period of time is [58],

$$\dot{Q}_{stack} = \frac{m_{stack}.C_{stack}.\Delta T_{stack}}{\Delta t} \tag{28}$$

Passive cooling accomplished through free convection and radiation is represented by [58],

$$Q_{nc} = h.A_{surface}\left(T_{surface} - T_{ambient}\right) \tag{29}$$

$$Q_{r} = \varepsilon.\sum A_{s}.\sigma.\left(T_{s}^{4} - T_{ambient}^{4}\right) \tag{30}$$

$$Q_{passive} = \sum Q_{nc} + Q_{r} \tag{31}$$

where σ is Stefan-Boltzmann constant [58]. Fig. 10 shows the cooling mode contributions at various thermal power values.

The experimental setup is shown in Fig. 11, illustrating the schematic of the system. The active cooling process is achieved by the combined circulation of water and air. The experimental results show that free convection contributes more than radiation in the fuel cell cooling. The provided graphic also demonstrates that although the temperature of the fuel cell stack increases over time, the impact of passive cooling remains relatively constant. Finally, the contributions of both active and passive cooling modes are compared depicting the significant contribution of active cooling of the fuel cell. The experimental findings indicate that the use of active cooling in fuel cells leads to improved cell performance in terms of power production.

Similar work of employing active cooling through forced convection of air shows effective temperature distribution in the PEMFC. A three-dimensional numerical model, validated by experimental results, is established incorporating the mass, momentum, and energy conservation equations [59].

$$\nabla.(\rho\mathbf{u}) = 0 \tag{32}$$

$$\rho\mathbf{u}.\nabla\mathbf{u} = -\nabla p + \mu\nabla^{2}\mathbf{u} \tag{33}$$

$$\rho c_{p}\mathbf{u}.\nabla T_{f} = \nabla.\left(k\nabla T_{f}\right) \tag{34}$$

The diagram illustrating the structure of the model is shown in Fig. 12.

COMSOL is a powerful simulation tool to run such simulations. The computational domain encompasses

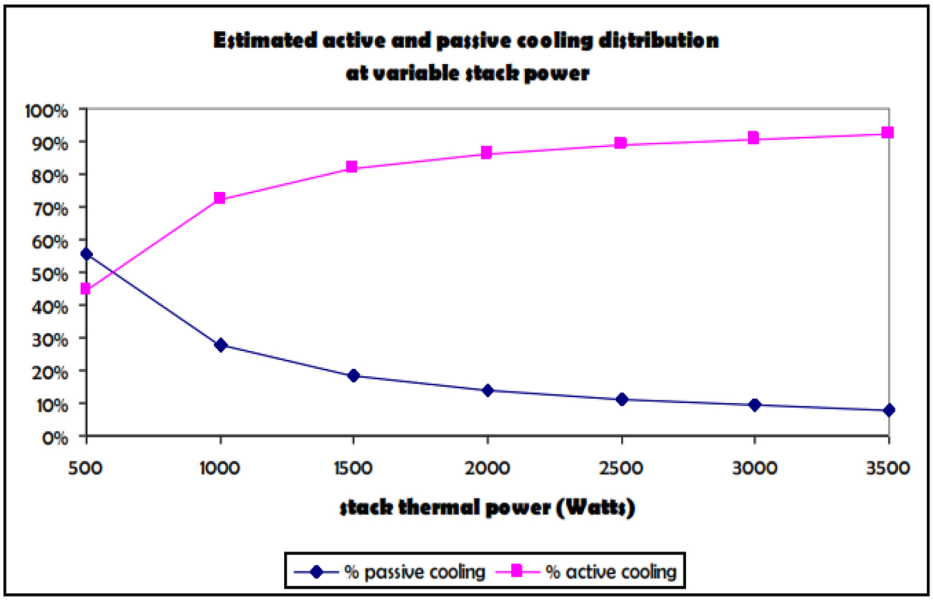


Fig. 10. Cooling mode contributions with varying fuel cell thermal power [36].

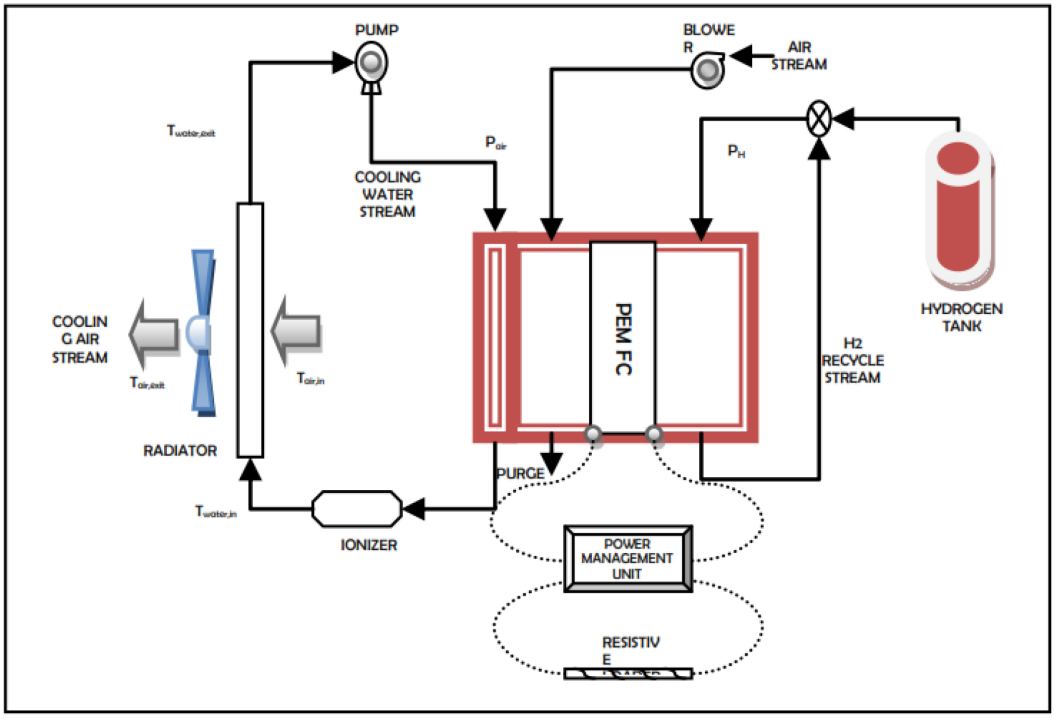


Fig. 11. Schematic of experimental setup [36].

one half of the two-dimensional cathode channel next to the symmetry plane. Fig. 13 shows the temperature distribution on various virtual planes along the cathode channel [59]. Additionally, it is shown that the air velocity and thermal conductivity of the bipolar plate are significantly influenced by the maximum temperature of such plate. The maximum temperature of the bipolar plate decreases as the thermal conductivity and the channel air velocity increase.

Another study focused on examining the impact of temperature on the performance and deterioration of the Proton Exchange Membrane inside PEMFC. As a matter of fact, the normal operation temperature ceiling of the fuel cell was found to be 120°C. It was also found that the temperature impacted the relative

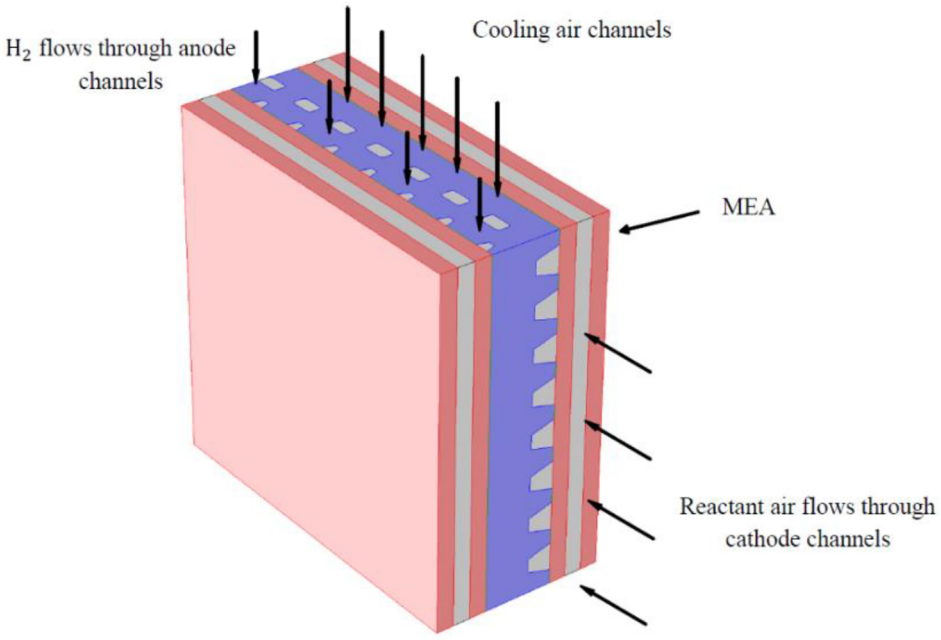


Fig. 12. Schematic of 3-D numerical model [37].

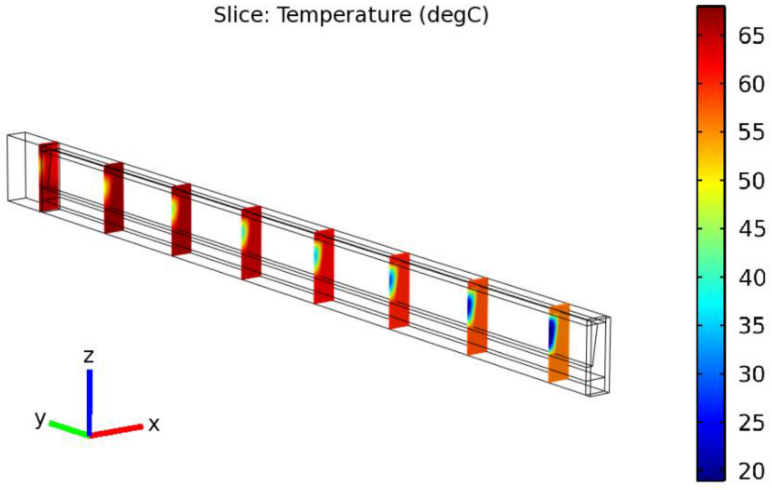


Fig. 13. Temperature distribution contours in the cathode channel at different intermediate locations [37].

humidity and partial pressure of the fluids present in the fuel cell. Dehydrated or excessively humid fluids inside the fuel cell increased the ohmic resistance and hence reduced the performance. On the contrary, an elevation in the partial pressure of the reactants had a favorable influence on the efficiency of the fuel cell. Nevertheless, it was shown that a rise in temperature led to a decrease in the partial pressure of the reactants, but not to a substantial extent [60].

An investigation of considerable use pertains to the influence of separator thickness on the spatial distribution of temperature over the reaction surface inside a solitary Proton Exchange Membrane Fuel Cell (PEMFC) operating at a temperature of 100°C. This temperature distribution represented by the standard deviation of T_{react} -T_{ini} affects the cell performance. In this context, T_{react} represents the temperature distribution on the response surface, whereas T_{ini} denotes the beginning temperature of the cell. The schematic of the one-dimensional multi-plate theoretical heat transfer model is shown in Fig. 14. The reaction plate in each channel is divided into segments. The heat flux relations for the rib (rib), channels (chan) and reaction plate (react) are given as [61].

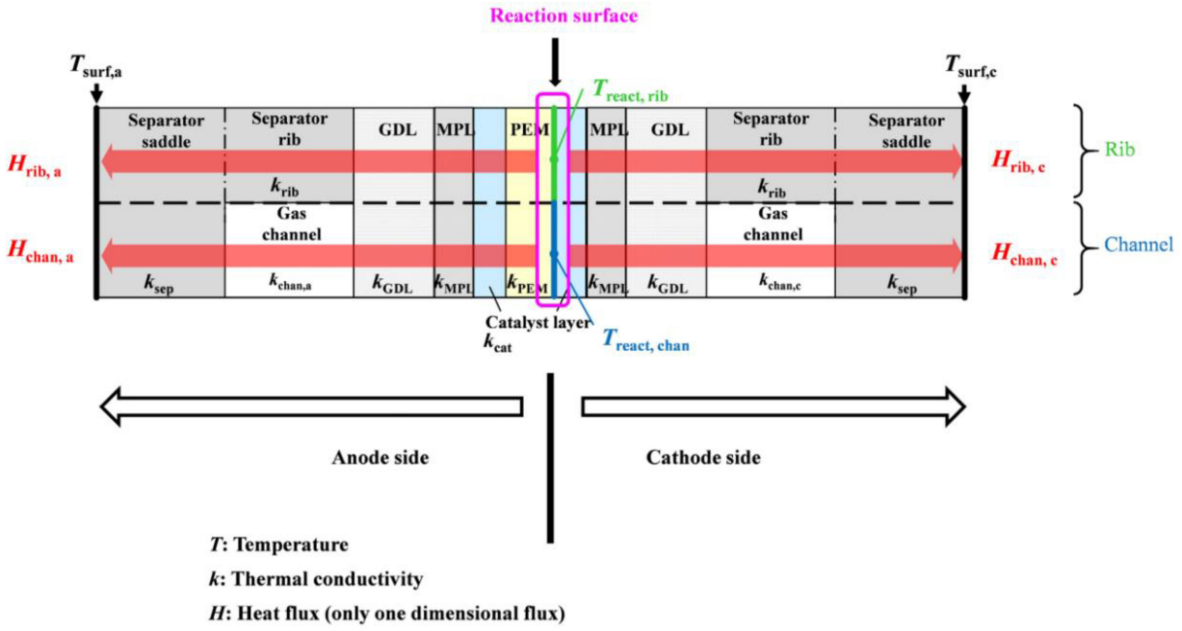


Fig. 14. Model schematic of the fuel cell comprising of the reaction surface, PEM, MPL, GDL, and separator at both anode and cathode sides [39].

$$H_{rib,c} = K_{rib,c}A\left(T_{react,rib} - T_{surf,c}\right)/2 \tag{35}$$

$$H_{chan,c} = K_{chan,c}A\left(T_{react,chan} - T_{surf,c}\right)/2 \tag{36}$$

$$H_{rib,a} = K_{rib,a}A\left(T_{react,rib} - T_{surf,a}\right)/2 \tag{37}$$

$$H_{chan,a} = K_{chan,a}A\left(T_{react,chan} - T_{surf,a}\right)/2 \tag{38}$$

$$H_{react} = H_{rib,c} + H_{chan,c} + H_{rib,a} + H_{chan,a} \tag{39}$$

The prevention of hotspots in the fuel cell stack via the achievement of a consistent temperature distribution is crucial in order to mitigate any harm to the structural components and expedite the degradation rate of the membrane. A low temperature gradient across the high temperature PEMFC stack also leads to a higher mean temperature and current density resulting in better performance. All this can be achieved by employing a more efficient heating and cooling mechanism. It is found that all of the above desired features inside the high fuel cell can be achieved with the help of a heat pipe, which is employed in high temperature PEMFC and theoretically analyzed. This device helps in maintaining the uniform temperature in the cell stack (around 160°C), lower temperature gradient (0.054 °C/cell), higher current density (519.3 mA/cm^2), and facilitating in the desired heat dissipation. This improvement is 79.2% and 14% better in temperature gradient and current density, respectively, as compared to the corresponding parameters obtained through heat pads and conventional forced air-cooling [62]. Similar observation was reported by using a passive cooling through a Phase Change Material (PCM) at the outlet of the PEMFC cooling channel. PCM was found to facilitate in uniform distribution of the reactants and temperature in the fuel cell. The use of phase change material (PCM) in a non-isothermal three-dimensional numerical model yielded simulation results indicating a 4.6% increase in peak current density and a 5.14% increase in peak power density when compared to the utilization of the Air Cooling Channel (ACC). Furthermore, the findings from the simulation indicated that the presence of 2/3 phase change material (PCM) at the outlet of the cooling channel led to an increase of 2.67% and 2.94% in peak current and power densities, respectively, compared to cases where the PCM was completely filled [63]. Hence it can be stated that employing the thermal management systems such as heat pipes and PCM are better than the conventional forced air-cooling in the PEMFC.

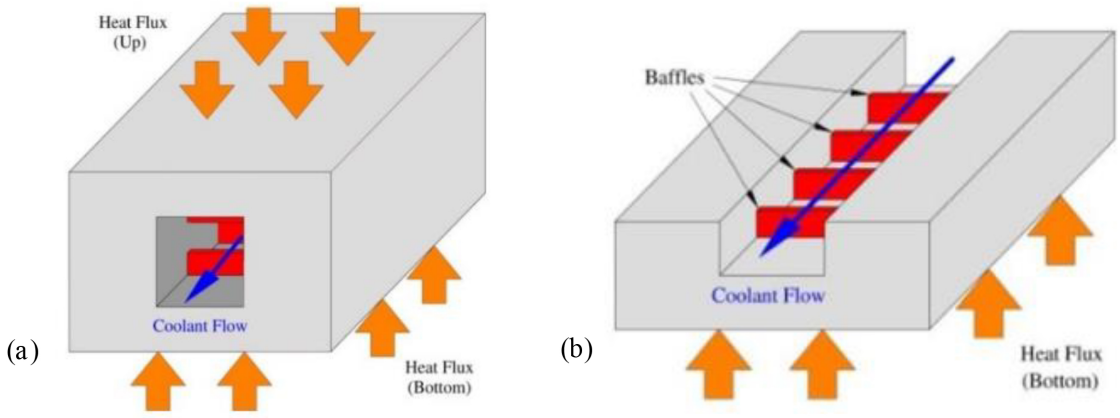


Fig. 15. Baffle installed cooling channel showing (a) complete cooling channel and (b) split cooling channel about the symmetry plane [43].

3.7.2. Performance enhancement

It is a known fact that proper thermal management enhances the fuel cell performance. Temperature control within prescribed limits is very crucial for a fuel cell. The temperature dependent system, i.e., exchange current density, has a positive effect due to increased temperature with lower activation barrier but at the same time, this elevated temperature can lower the electrochemical reaction in the cathode layer due to dehydration. An effective way of controlling the temperature is by using a Proportional Integral (PI) controller, which is tested experimentally and theoretically [64].

An additional endeavor to optimize the efficiency of the fuel cell via effective thermal management involves the use of baffles inside the cooling channel. These baffles help in improving the temperature uniformity in the cooling plates and reducing the maximum operating temperature of the cell. However, there must be an optimum geometry, i.e., height, thickness, and number of the baffles. The parametric optimization is conducted by solving a three-dimensional numerical model using the finite volume method (FVM). The schematic diagram of the numerical model is shown in Fig. 15. It is also known that introducing baffles would cause enhanced pressure drop in the cooling channel. According to the results, the height and thickness of 0.5 mm each produces the best temperature related results. Furthermore, the use of baffles enables the attainment of an optimal balance between the fuel cell's maximum temperature control, uniform temperature distribution throughout the cooling plates, and the pressure drop along the cooling channel [65].

Related to the geometry optimization of the flow channel of cooling plates, it is found through the numerical solution of a three-dimensional model using FVM that a non-uniform cross-section of the flow channel enhances the thermal performance of the flowing water especially at the downstream end of the cooling channel resulting in better temperature distribution, lower operating temperature, and lower temperature gradient in PEMFC, which is desired for improved performance of the cell. Four different non-uniform heights and widths of the channel tested give an insight into the thermal management being a function of the channel geometry [66].

Improving the fuel cell performance via efficient thermal management inside the cell is extensively studied. These studies include proper water and heat management to ensure sufficient membrane hydration [67], mapping the optimum operating temperature with the PEMFC power output through experimental work [68], numerical-based designing of cathode flow field to enhance heat removal and avoid excessive dehydration of the reactant gases in a passive air-cooled PEMFC [69], experimentally investigating the effect of the thermal conductivity of GDL on the distribution of reactant gases and drainage of liquid water produced in the Catalyst Layer (CL) [70], appropriate designing of GDL by incorporating optimum percentage (40%) of Polytetrafluoroethylene (PTFE) in GDL for effective water management (water retaining capability of air-cooled fuel cell) and uniform distribution of current density in the Cathode Catalyst layer (CCL) [71], and in a high-temperature PEMFC investigating the effect of cooling surface temperature difference on the peak power density, uniformity of current density on the working surfaces, and the stress on Polymer Electrolyte membrane (PEM) [72].

In a recent scholarly investigation [73], the impact of flow velocity and cooling medium temperature on the dissipation of heat and the uniformity of temperature distribution inside the fuel cell was examined. The investigation employed three distinct cooling

media, namely hydrogen, air, and water, inside a one-dimensional model. The energy relation x-direction is given as [73],

$$\frac{\partial\left(\rho_{fc}c_{p,fc}T_{fc}\right)}{\partial t}=\frac{\partial}{\partial x}\left(k_x\frac{\partial T_{fc}}{\partial x}\right)+\dot{q}'_{gen} \tag{40}$$

where T_{fc} is the temperature of the fuel cell, $c_{p,fc}$ is the specific heat of PEMFC at constant pressure, ρ_{fc} is the PEMFC density, t is the time, $q^{\cdot}{}'_{gen}$ is the overall heat generation rate per unit area of PEMFC, and k_x is the thermal conductivity of the cell in x-direction. $\dot{q}_{gen}$ is represented by [73],

$$\dot{q}_{gen}=\dot{q}_{rev}+\dot{q}_{irrev}+\left(\dot{q}_{ohm(H^+)}+\dot{q}_{ohm(e^-)}\right)+\dot{q}_{pc,H_2O} \tag{41}$$

The heat generation rate per unit area of the cell, denoted as $\dot{q}_{rev}$, is [73],

$$\dot{q}_{rev}=jT_{fc}\frac{dE_{rev}}{dT_{fc}} \tag{42}$$

The rate of irreversible heat production associated with the electrochemical processes in the catalytic layers, denoted as $\dot{irrev}_{irrev}$, is [73],

$$\dot{q}_{irrev}=j_a\eta_a+j_c\eta_c \tag{43}$$

The heat generation rate of vaporization or condensation of water $\dot{q}_{pc,H_2O}$ is [73],

$$\dot{q}_{pc,H_2O}=J_{H_2O}h_{fg,H_2O} \tag{44}$$

The detailed theoretical model equations related to coolant channel can be found in [73]. The investigation of cooling mediums flowing in the cooling channels of bipolar plates at varying temperatures and flow velocities demonstrated that hydrogen was capable of sustaining the fuel cell's optimal operating temperature range of 69°C to 75°C, as well as maintaining a consistent temperature difference. This was observed when hydrogen was allowed to flow through the bipolar plate cooling channels at a temperature of 35°C and a flow velocity of 0.02 m/sec.

3.7.3. Advances in thermal management strategies for PEMFC systems

There are several review papers available that specifically focus on the temperature impacts on the performance of Proton Exchange Membrane Fuel Cells (PEMFCs). One of the review articles examined the research conducted on the impact of operating temperature on performance and efficiency, humidity, power generation, mass cross-over, leakage current, voltage, catalyst tolerance, and durability. The chemical reaction occurring were represented as [74],

$$2H_2+O_2\rightarrow 2H_2O+energy$$

Anode half reaction:

$$2H_2\rightarrow 4H^++4e^-$$

Cathode half reaction:

$$O_2+4H^++4e^-\rightarrow 2H_2O$$

These are the same chemical reactions as mentioned by Reddy et al. (2021) [26].

The primary categorization of the Proton Exchange Membrane Fuel Cell (PEMFC) is based on the operational temperatures, which may be classified as Low-Temperature PEMFC and High-Temperature PEMFC. Low-Temperature PEMFC is characterized by high gas permeability resistance and cost effective technology. On the other hand, High-Temperature PEMFC is characterized by durability in high CO condition, efficient heat releasing system, and non-dependency on humidification [74]. A very comprehensive review paper focused on the thermal management and Waste Heat Recovery (WHR) in Proton Exchange Membrane Fuel Cells (PEMFCs). It provided an overview of various cooling methods employed in PEMFCs, including active and passive air-cooling, heat spreaders, liquid cooling, and phase change cooling. Additionally, the paper explored the utilization of waste heat generated during the chemical reaction within the fuel cell, which could be used for various applications, such as preheating reactants and releasing hydrogen from Metal Hydrides (MH) tanks, providing heat in Combined Heat and Power (CHP) systems, driving chillers in Combined Cooling and Power (CCP) systems, and generating power through power thermodynamic cycles and heat to power technology. The paper also discussed the advantages and shortcomings of both thermal management and WHR [75]. In relation to thermal management, a separate review study examined the empirical, analytical, and computational investigations pertaining to cold start and water/thermal management. The layout of the flow field for water thermal management was determined by several factors, including the geometry of the cooling channels, the number of cooling units, the employment of metal foam as a flow distributor, and the intake flow characteristics, such as humidity and flow rate. The paper also discussed different ways to improve the cold start including passive and active cold starts [76]. The review paper focused on the High-Temperature Proton Exchange

Membrane Fuel Cell (HT-PEMFC) and its simplified cooling channel design, highlighting the associated benefits. HT-PEMFC at high operating temperatures (100˚C – 200˚C) contain water in only one phase, i.e., gas, which allows its easier transport in membrane, catalytic layers, and GDLs. Furthermore, it should be noted that the reactant and product gases exhibit elevated rates of diffusion. Additionally, the absence of liquid water prevents any obstruction of the electrochemically active surface area, hence facilitating increased reaction rates [77].

Fuel cell technology is an emerging technology for the future energy needs. Production of electrical energy from chemical energy as a result of electrochemical process can replace, to a great extent, the conventional energy sources [78]. The performance and efficiency of the fuel cell can be enhanced by selecting the right polymer material and coupling LVG with cathode channel for enhanced proton mobility through the electrolyte membrane, efficient anode flow fields, optimizing geometrical, mechanical, and chemical parameters, and controlling the porosity of GDL, thickness of the membrane, total electrical resistance, and temperature. PEMFC and HT-PEMFC can be operated under different temperature conditions. In view of the recent research and development on fuel cell, it has strong potential to be a good source of future energy.

4. Conclusion

This review underscores the critical role of multiphase flow modeling in understanding and optimizing Proton Exchange Membrane Fuel Cells (PEMFCs). This unique review study creates a thorough inventory of research findings to highlight crucial gaps in this subject. Key findings are as follow:

- Efficacy of Mathematical Modeling: The deployment of sophisticated mathematical models proves instrumental in accurately capturing both transient and steady-state behaviors of PEMFCs, thereby enabling precise prediction of voltage-current (V-I) characteristics across diverse operational conditions.
- Operational Parameter Optimization: Systematic optimization of temperature and input parameters demonstrates a significant reduction in voltage losses, which directly correlates with enhanced overall fuel cell efficiency and performance.
- Insights into Molar Flow and Pressure Dynamics: Detailed modeling of molar flow rates and pressure variations within anode and cathode channels provides critical insights into flow distribution and system performance, facilitating targeted improvements in design and operation.

Despite these advancements, notable research gaps remain. Current models often simplify complex phenomena such as electrochemical kinetics, water management, and thermal effects, limiting their predictive accuracy. Furthermore, integration of these models into comprehensive dynamic control systems is still in early stages, restricting real-time operational optimization.

Present study also has some limitations which include reliance on simplified models that may not fully capture complex electrochemical kinetics, water management, and thermal phenomena, potentially affecting predictive accuracy. Additionally, the integration of these models into real-time control systems remains underdeveloped, limiting practical application. Further research is needed to develop comprehensive multi-scale models and advanced control frameworks to enhance system performance and reliability. The future research should focus on developing more comprehensive, multi-scale models that incorporate detailed electrochemical, thermal, and water transport processes. Enhancing model integration into adaptive control frameworks will facilitate real-time system management and efficiency maximization. Ultimately, such advancements will accelerate the deployment of PEMFC technology as a viable and sustainable energy source.

Conflicts of interest

There are no conflicts of interest regarding the publication of this paper.

Author contribution

Elaf N. Mahrous was involved in Conceptualization, writing the original manuscript, visualization, and formal analysis. **Ahmad Jamal** involved in Data Curation, investigation, reviewed and editing. **Muhammad Saleem** supervised the work, formal analysis, and validation.

Data availability

The authors confirm that the data used in this paper is available and can be provided on request.

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