

Review

Water Management Strategies for Proton Exchange Membrane Fuel Cells: A Comprehensive Review

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Abstract

Proton exchange membrane fuel cells (PEMFCs) are a promising clean energy technology due to their zero gas emissions, low operating temperature, and high efficiency. This review synthesizes research from 2015–2025 on (i) materials-level approaches (advanced/modified PFSA membranes and composite membranes) that improve water retention and ionic conduction, (ii) engineered gas diffusion layers and hydrophobic/hydrophilic gradients (including Janus and asymmetric GDL architectures) that facilitate directional water transport and have been shown to increase peak power density in some reports (e.g., from ≈ 1.17 to ≈ 1.89 W·cm⁻² with Janus GDL designs), (iii) flow-field design strategies. This review examines the key aspects of water management in PEMFCs, including their impact on cell performance, the underlying causes of related issues, and the mechanisms of water transport within these cells. Additionally, it discusses the methods and materials used to enhance water management, highlighting recent advancements and potential directions for future research. Topics such as water transport, water flooding, and water control strategies in PEMFCs are also addressed. Both excess water (flooding) and water depletion (dehydration) can negatively influence fuel cell performance and lifespan. Particular attention is given to water dehydration, with a detailed discussion of its effects on the cathode, Anode, gas diffusion layer, catalyst layer, and flow channels.

Keywords: proton-exchange membrane fuel cells; water management; water flooding; membrane drying; catalyst layer



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1. Introduction

Hydrogen energy technology is an environmentally favorable alternative to harmful fossil fuel energy production. An electrochemical device that utilizes hydrogen to generate power is known as a proton exchange membrane fuel cell (PEMFC) [1]. The most widely used fuel cell for mobility applications is the PEMFC in the energy renewable sector, which has demonstrated encouraging performance when used in place of fossil fuel engines [2]. PEMFC commercialization is primarily constrained by challenges related to cost, durability, and water and thermal management [3]. Due to PEMFCs operating at a lower temperature than other fuel cell types (70 °C to 90 °C), the formation of water in both the gas and liquid phases is feasible in the cell under most operating conditions. A mediatorless glucose/oxygen biofuel cell has exhibited steady performance at 20 °C, with an open-circuit voltage of 0.95 V and a maximum power density of 1.0 mW cm⁻² over a duration of

30 days. Furthermore, EFCs are noted for their capacity to operate at ambient temperature, providing advantages such as enhanced fuel conversion efficiency and scalability [4–6].

Many renewable and fossil fuel-based processes produce hydrogen. Steam methane reforming (SMR), which accounts for approximately 70% of the world's hydrogen production, is the most widely used industrial process, despite its high CO₂ emissions: renewable electricity powers water electrolysis, a clean method for producing hydrogen with a minimal carbon footprint [6,7].

Biomass gasification and the currently being developed thermochemical or photocatalytic water-splitting processes are further promising approaches. To create a sustainable hydrogen economy and provide safe distribution and storage infrastructure (such as subterranean hydrogen storage) to satisfy future energy demands, hydrogen production technologies must be diversified [8].

Maintaining the amount of water content in PEMFCs within an acceptable range is a subject deserving of investigation. This review paper examines water transport, faults, and advanced water management techniques in a PEMFC. An overabundance of overflow or insufficient dehydration in a fuel cell may impact its performance and longevity [3]. There are several other issues associated with the cell's water content, such as its effects on the cathode, Anode, gas diffusion layer (GDL), catalyst layer (CL), and flow channel. Identifying whether one of the two scenarios—overflow or dehydration—occurs is best done by actively monitoring the flow and accumulation of water in the PEMFC. Monitoring the direct flow and accumulation of water within the PEMFC is the best course of action to prevent overflow or dehydration [3]. The water transport procedure in fuel cells was efficiently studied using nuclear magnetic resonance, X-ray irradiation, and neutron scanning to investigate and optimize the transport procedure. The literature discusses current PEMFC water management approaches, including modifying hydrophilic materials, optimizing control systems, and improving flow field structure [5–8].

According to the PEMFC's current design, there are three phases involved in acoustic cavitation: nucleation, bubble expansion, and implosion. These phases have several essential impacts on the cell operation conditions: agitation, turbulence, mass transfer, microstreaming, shockwaves, etc. [9]. These are the physical effects, while the chemical effect involves the production of radicals to speed up the chemical separation reaction. Another operating issue is the interaction of pressure waves (ultrasound) with the liquid medium, which causes cavities to form in the liquid. When these cavities come into contact with positive and negative pressure cycles, they experience constant compression and rarefaction [8–10]. This process is maintained until the cavities attain a critical radius, which depends on the ultrasonic frequency. The cavities stop absorbing through-field energy once they reach this proper radius. As a result, it cannot remain stable, and the bubbles burst when the surrounding media intervenes. The implosion of cavities creates a special chemical reaction environment at high temperatures, high pressures, and cooling rates [1].

This paper aims to provide a comprehensive review of water management strategies in proton exchange membrane fuel cells (PEMFCs), emphasizing core principles, contemporary methodologies, diagnostic instruments, and recent research developments. Effective water management is essential for attaining optimal performance, durability, and efficiency in PEMFCs. In bullets, the objectives of this paper are:

- (i) Summarizing the primary methodologies for regulating water transport and distribution within PEMFCs.
- (ii) Identifying the challenges and limitations of both traditional and novel water management techniques.

- (iii) Identifying prospective future strategies for enhancing PEMFC performance under various environmental and load conditions.

The contributions of this review are to provide a comprehensive understanding of water transport phenomena, evaluate water management techniques, assess advanced diagnostic methods, compare modeling and simulation approaches for predicting water transport, and identify research gaps and future perspectives in the context of next-generation PEMFC systems for transportation, stationary, and portable power applications.

To prevent the occurrence of a short circuit, the protons must traverse the membrane from the Anode to the cathode, while electrons are conveyed via an external circuit [11]. The membrane must be impervious to the through-plane passage of the reactant gas, a phenomenon referred to as gas crossover. As the system's output, oxygen reacts with the protons on the cathode side, resulting in the production of heat, electricity, and water [11].

A comprehensive and critical evaluation of existing methods is often lacking, resulting in the presentation of fragmented information without a unifying framework. Furthermore, the limitations and challenges associated with current water management strategies in PEMFCs may not be adequately addressed in specific papers [12]. The lack of a systematic analysis of the strengths and limitations of various methods, along with a synthesized overview, may hinder researchers' and practitioners' ability to comprehend the broader landscape [12]. The objective of this review is to address the limitations of previous research, provide a comprehensive guide for future advancements in the field, and conduct a more in-depth and critical examination of water management strategies in PEMFCs, thereby bridging these gaps. The Faisal group's work makes a unique contribution by methodically analyzing and synthesizing various water management strategies in PEMFCs. It surpasses the typical literature review by providing a critical assessment of current methodologies, highlighting their strengths and weaknesses, and suggesting potential areas for improvement. It addresses vital aspects of the widespread adoption of fuel cell technology in renewable energy applications by identifying challenges and providing insights into optimizing PEMFC performance [12].

The Xinjie group proposes a closed-loop water management system that regulates the water content within the target range, using feedback from stack impedance information, to address deficiencies in previous studies. The system introduces a measurement method based on the phase of single-frequency impedance to accurately characterize the water content and correspond numerically with it [13]. To regulate water content and establish a balance between power loss and time cost, two preferred operating conditions are implemented: air stoichiometry and stack temperature [14].

According to the Massimo group, standard techniques, such as neutron magnetic resonance and neutron imaging, can be used to measure the water membrane content offline directly [15]. However, it is not feasible to directly measure the water membrane content while the cell is operating in a real environment [16,17]. Consequently, virtual sensors or observers that are based on physical models should be implemented. Subsequently, Dickinson and Smith conducted a literature review that revealed that numerous subsequent works had expanded the formulation with distinct regressions [18]. The formation of a four-dimensional map database resulted from numerically solving the model in steady-state operation with parametric boundary conditions [18]. Molecular dynamics simulations were employed to predict the value of an electroosmotic drag coefficient under various operating conditions. This approach demonstrated satisfactory agreement with experimental literature data at a low water membrane content; however, it is not suitable for real-time applications [18].

This work proposes a technique for the lizard-inspired water management strategy, which is more straightforward to implement. The scalability of this technique is examined

up to 100 cm² under the guidance of the nature-inspired chemical engineering methodology. The research process involves observing nature, abstracting nature-inspired concepts, computationally assisted design, prototyping, and application [15].

The organic Rankine cycle (ORC) is the preferred thermodynamic cycle for power generation, as it utilises a low-temperature heat source. The utilisation of an ORC is logical since the PEMFC operates within a modest temperature range of 80 to 100 °C. The ORC directly enters the ORC as its working fluid, serving as the cooling fluid for the fuel cell [16]. For the sake of simplicity, heat and pressure losses for this fluid will be disregarded. The cycle functions similarly to a Rankine cycle; the distinction is in the working fluid [19,20].

A proton-exchange membrane (PEM) is a polymeric semipermeable membrane that can conduct or transfer cations (protons) while simultaneously maintaining the separation of the reactants. The presence of carboxylated or sulfonated groups with a cationic counter ion enables the conduction of protons along the polymeric backbone. The ion's mobility typically increases as water absorption increases. Typically, the permselectivity decreases as the water expansion increases [16–18]. Consequently, a compromise must be established between mechanical and chemical stability, selectivity, and conductivity to ensure long-term use in the presence of oxidising species. The primary characteristics that these ion exchange membranes must possess for an electrochemical process include a high permselectivity for the anions and nonionized molecules, as well as a suitable electrical resistance (which can be adjusted by adjusting the ion exchange capacity), water content, and thickness [18].

The ideal relative humidity (RH) is 100% (in other words, entirely saturated gases). The membrane is entirely hydrated, and proton conductivity is optimised under these circumstances. High-performance systems frequently aim to operate at 100% relative humidity, despite the challenges associated with water management to prevent inundation. The conductivity of a substance increases as the temperature rises, as a result of the increased mobility of molecules. Nafion demonstrates remarkable chemical and mechanical stability, elevated proton conductivity, and compatibility with standard PEMFC operating conditions. The properties arise from its perfluorinated polymer structure, which contains sulfonic acid functional groups that facilitate efficient proton transport routes. Nevertheless, the operational temperature of Nafion is constrained by its water retention capacity. The water within the membrane rapidly dissipates at ambient pressure when the temperature exceeds 80–90 °C, leading to a catastrophic decrease in conductivity and rapid dehydration [17–20].

Due to their high power density, low operating temperature (usually between 60 and 80 °C), and quick startup time, PEMFCs are regarded as exceptional. They are especially well-suited for portable power and transportation applications [21,22]. Furthermore, PEMFCs have zero carbon emissions at the point of use, low noise levels, and high energy conversion efficiency (up to 60%), all of which are critical for clean and sustainable energy systems [23].

The integration of PEMFCs into vehicles and small-scale distributed power systems is made possible by their compact design, lightweight components, and rapid responsiveness to load changes, which set them apart from SOFCs and PAFCs [24]. Additionally, compared to liquid-electrolyte fuel cells, the use of a solid polymer electrolyte (such as Nafion) avoids leakage issues and permits simpler system design [24].

2. PEMFC Structure and Operation

Figure 1 illustrates the essential structure of a proton-exchange membrane fuel cell (PEMFC), consisting of a membrane electrode assembly (MEA) located between gas diffusion layers (GDLs) and bipolar plates. The membrane electrode assembly includes a proton exchange membrane (PEM) placed between dual catalyst layers. Hydrogen fuel

is transported to the Anode, where it works under an oxidation process into protons and electrons. The generated protons are sent through the PEM system, which selectively allows proton passage while blocking electron crossover [2]. The electrons are forced to cross an external circuit, generating useful electrical power before arriving at the cathode. Concurrently, oxygen delivered to the cathode interacts with incoming electrons and protons to produce water. Along with Energy, water and heat are formed as byproducts. Effective control of this water is crucial to prevent membrane dehydration or electrode flooding, both of which reduce fuel cell efficiency. Consequently, Figure 1 serves as a structural reference for comprehending the mechanisms of gas transport, heat distribution, and water generation—essential components of the water management systems examined in this research [2].

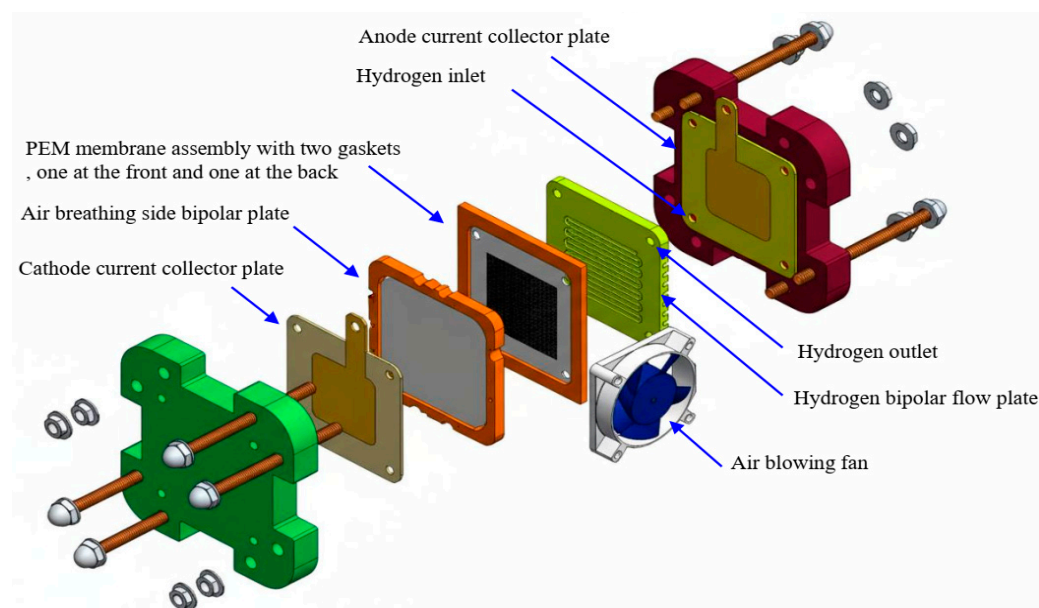


Figure 1. Proton exchange membrane fuel cell structure [2].

2.1. Important Elements of PEMFC

The membrane structure design of PEMFCs is crucial to their proton exchange efficiency and transportation performance. Typically, the cell membrane utilizes a perfluoro-sulfonic acid polymer with robust proton conductivity and chemical kinetic stability, such as the Nafion membrane. The membrane's primary role is to block electrons and reactant gases while allowing protons (H^+) to pass through, ensuring the separation process that facilitates the desired electrochemical reactions [1–3], as illustrated in Figure 2.

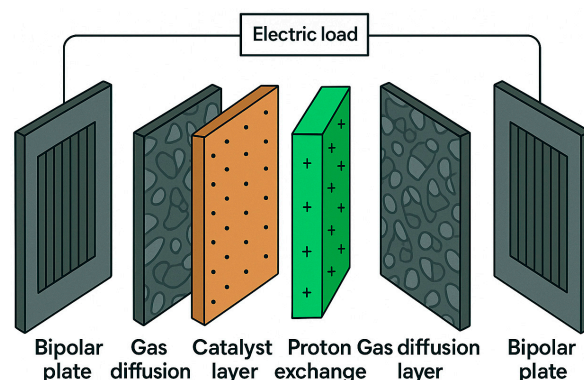


Figure 2. List of PEMFC elements and layers.

A PEMFC consists of several key layers that work together to convert hydrogen and oxygen into electricity. The outermost components are the bipolar plates, which contain flow channels that evenly distribute the gases, remove excess water, collect current, and provide mechanical strength to the stack. Between the bipolar plates and the reaction sites are the gas diffusion layers (GDLs)—porous carbon sheets that help spread hydrogen and oxygen uniformly across the catalyst surface, conduct electrons, and balance moisture within the cell, as shown in Figure 2 [2–6]. The catalyst layers, typically coated with platinum, are where the electrochemical reactions occur: hydrogen is split into protons and electrons at the Anode, and oxygen reacts with these protons and electrons at the cathode to form water. At the core lies the proton exchange membrane, a thin polymer film that allows only protons to pass through while blocking electrons, forcing them to travel through the external circuit and generate an electric current. Together, these layers enable efficient energy conversion, water management, and stable operation of the fuel cell [7].

2.1.1. Anode and Cathode Electrodes

Both electrodes (cathode and Anode) are generally manufactured of porous carbon substances treated with catalysts based on platinum. The electrode structures of the system are located on either side of the proton exchange membrane PEM cell. Although the cathode decreases oxygen in water, the anode structure enhances hydrogen oxidation, producing electrons and protons [2].

2.1.2. Gas Diffusion Layers

The location of these design layers is attached to the working electrodes. These layers are typically composed of porous carbon-based paper or carbon cloth, which facilitates the even distribution of reactant gases in the catalyst layers. They contribute to water management by removing the excess water generated during the electrochemical reaction [2,3].

2.1.3. Bipolar Plates

Bipolar plates have several uses, including removing heat produced during operation, conducting electricity between neighboring cells, distributing reactant gases through flow channels, and providing mechanical support. These plates are frequently composed of coated metal or graphite for durability and conductivity [4].

2.1.4. Catalyst Layers

Platinum-based catalysts are applied to the cathode and Anode in thin layers to efficiently convert Energy by accelerating the electrochemical reaction rate. For reactions involving hydrogen oxidation and oxygen reduction, platinum's high catalytic activity is essential [5].

2.1.5. Principle of Operation

Hydrogen gas molecules are provided to the cell anode of a PEMFC, where the catalyst separates them into electrons and protons. The electrons are directed into an external circuit to generate electricity as an electric current, while the protons transfer to the cathode through the membrane. At the same time, the cathode receives oxygen gas, which interacts with the incoming protons and electrons to produce the sole waste, water [1–5].

The functional role of each component of PEMFC in water production, retention, and removal, while incorporating essential engineering parameters that influence hydration and flooding dynamics. Current pertinent design variables, including PTFE loading in gas diffusion layers (usually 5–30 wt%), ionomer content in catalyst layers (20–35 wt%), and membrane thickness ranges (10–50 μm), together with their effects on back-diffusion, capillarity, and vapour transport [24,25].

In a proton exchange membrane fuel cell (PEMFC), hydrogen is transported to the Anode, where it undergoes oxidation to generate protons and electrons as per the following reaction:



Anode reaction described as follows:



Protons penetrate the proton exchange membrane to the cathode, while electrons circulate via the external circuit, producing an electric current. At the cathode, oxygen interacts with the incoming protons and electrons to produce water.

Cathode reaction:



The overall cell reaction:



where H_2 , O_2 , and H_2O are hydrogen, oxygen, and water, respectively [1–3].

2.2. PEMFC Manufacturing and the Negative Effects of Excessive Water Content

The composition of a perfluorosulfonic acid polymer in PEMFCs, such as Nafion, is essential for proton conduction, which directly affects PEMFC performance and the balance of water content within the membrane [7,8]. Since both excessive and insufficient water content can damage the system, water management is essential for the effective operation of PEMFCs. Water is a byproduct of the electrochemical process that occurs at the cathode during operation [9]. As a result, the electrochemical reaction's active area is reduced, which in turn lowers the power output [10,11].

On the other hand, insufficient water content may cause membrane dehydration, which, over time, can lead to damage to the membrane structure and increased resistance to proton transport. These circumstances highlight the importance of precise water management techniques, including the application of advanced water management technologies, such as flow field designs and water-absorbing materials, as well as the optimization of cell design and operating conditions [25]. Water management is one of the challenges in PEMFC. Today, to overcome this problem, PEMFCs are used at elevated temperatures (between 120 °C and 200 °C). In this case, water molecules evaporate faster (easier water management). Nowadays, there are PEMs that, unlike Nafion, do not need humidity for proton conduction because their proton transport mechanism is different [25–27].

In PEMFCs, water accumulation promotes deterioration and reduces performance, lowering the fuel cell's lifespan. Isolated hot spots may form due to the unbalanced current distribution caused by flooding, placing strain on the membrane and catalyst layers [26]. Dehydration, on the other hand, may result in the membrane shrinking or cracking, further jeopardizing its structural integrity. These problems underscore the need for sophisticated diagnostics and control systems to monitor and adjust water content in real-time while PEMFCs are operating [26–28]. In conclusion, although PEMFCs have considerable potential for use in sustainable energy applications, the challenges associated with water management must be carefully considered. To improve the efficiency and longevity of these fuel cells and lessen the negative impacts of excessive water content, advances in material science and system engineering are crucial. PEMFC technology is expected to become more widely used and commercialized with the support of ongoing research in this field [27–29]. Performance deterioration can result from excessive water buildup, or “flooding,” in the Anode, which might interfere with gas transport channels [30].

An uneven reactant distribution and a decrease in electrochemical reaction rates result from the Anode's water concentration rising over acceptable limits, which hinders hydrogen's ability to reach the catalyst layer [31,32]. On the other hand, membrane dryness resulting from a low water content can reduce ionic conductivity and lead to voltage losses. Thus, maintaining the proper water balance depends on efficient fuel cell functioning [33].

Improper water content causes a variety of harm to the Anode. Static water in the porous anode structure during overhydration can cause localized decreases in hydrogen availability, which is known as hydrogen famine [34]. Furthermore, this condition reduces fuel cell performance and accelerates the degradation process at the anode catalyst, finally worsening operational inefficiencies. Moreover, the membrane materials and the Anode may endure mechanical stress due to repeated water saturation and dehydration cycles, potentially resulting in structural fatigue and eventual failure [35–37]. Efficient water management techniques are crucial for reducing these dangers and increasing PEMFC longevity. These include the use of sophisticated gas diffusion layers and optimized flow field designs [36]. The difficulties with the Anode's water content highlight how crucial it is to use cutting-edge diagnostic methods to track and manage water distribution. For example, real-time monitoring with neutron imaging provides essential information on water dynamics in the Anode, enabling the development of plans to address floods and dehydration [37].

Additionally, designing more robust fuel cell systems can benefit from computer modeling of water transport processes. These methods enhance the overall dependability and effectiveness of PEMFCs in real-world applications by tackling the twin hazards of dehydration and overhydration [38]. The water within the membrane rapidly dissipates at ambient pressure when the temperature exceeds 80–90 °C, leading to a catastrophic decrease in conductivity and rapid dehydration [36–38].

3. Water Transportation

3.1. Flow Channel Issues with Water

A crucial component of cell efficiency is the balance between maintaining membrane hydration and avoiding water accumulation in the flow channels. To sustain the membrane's proton conductivity, it needs to possess a sufficient quantity of water [39]. Insufficient water can lead to diminished power output, increased resistance, and membrane desiccation. On the other hand, flooding may occur from an overabundance of water, which blocks the flow channels and gas diffusion layers, preventing reactants from reaching the catalyst sites [39]. Flooding of a PEMFC's flow channels reduces the effective area available for gas flow, which results in an uneven distribution of current and a decline in performance. The electrochemical reactions require hydrogen and oxygen gases, but the liquid water blocks their passageways [40,41]. The pressure drop throughout the flow field may also increase as a result of this occurrence, requiring more pumping power and decreasing the system's overall efficiency. In severe situations, continuous flooding can hasten the corrosion of metallic parts and the deterioration of the catalyst layer, reducing the fuel cell's useful life [42].

Furthermore, variables such as cell operating temperature, pressure, and relative humidity influence the accumulation of water in the flow channels. Water generated as a byproduct of the electrochemical reaction is more prone to condense at lower temperatures, exacerbating flooding problems. In water management, flow channel design is also fundamental [43–45]. Ineffectively built channels can result in stagnant liquid zones by preventing efficient water disposal. These negative impacts can be mitigated by employing methods such as improving flow field geometries, utilizing hydrophobic coatings, and applying advanced water removal techniques [45]. Table 1, which methodically compares

different mechanisms according to their advantages, disadvantages, operating principles, and significance to flow-field design.

Table 1. Comparison between under-rib convection vs. shear-driven removal vs. uniformity/low Δp .

Mechanism	Transport Principle	Typical Flow Field Designs	Advantages	Limitations	Operating Conditions
Under-Rib Convection	Pressure-driven flow forces liquid water from the gas diffusion layer beneath the rib towards the channel under differential pressure.	Serpentine flow fields with narrow ribs; interdigitated configurations	Strong water removal; prevents flooding under ribs; improves oxygen access	High pumping losses; risk of local dehydration; uneven current density	High current density; moderate–high stoichiometry
Shear-Driven Removal	Gas velocity exerts shear stress that detaches droplets from channel walls	Parallel or serpentine flow fields with moderate velocities	Promotes continuous droplet detachment; low structural complexity; stable operation	Less effective under low gas flow rates; sensitive to surface wettability	Mid-range flow rates; moderate humidity
Uniformity/Low Δp Design	Improves flow distribution uniformity across the active area with minimal pressure drop	Parallel, multi-pass, or bio-inspired flow fields	Low energy consumption; improved hydration stability; easier scaling	Less effective in severe flooding; limited forced convection effect	Low–medium current density; optimized water balance needed

3.2. Water Transport Mechanisms

Optimizing the performance, durability, and efficiency of PEMFCs involves appreciating the water transport mechanisms. In a PEMFC, the primary routes of water transport are electroosmotic drag, capillary action, back diffusion, and condensation [46]. The drag is induced by electroosmosis as water molecules migrate with protons across the proton exchange membrane from the Anode to the cathode. This phenomenon is known as electroosmotic drag [46]. The conductivity and functionality of the membrane are impacted by each proton tugging water molecules, which helps to hydrate the cathode but may cause dehydration at the Anode [46]. Research indicates that the electroosmotic drag coefficient, generally ranging from one to three water molecules per proton, fluctuates according to temperature, relative humidity, and membrane type [47]. Back diffusion refers to the reverse movement of water molecules from the cathode to the Anode due to a concentration gradient. This mechanism helps balance the distribution of water in the cell, particularly in low-humidity working conditions. The effectiveness of back diffusion depends on the size of the concentration gradient and the membrane's water permeability [47].

Condensation and Evaporation: Water produced at the cathode as a result of the oxygen reduction process may condense into liquid if not properly managed. Similarly, water that has been vaporized can likewise evaporate [47]. These phase changes affect the distribution of water, particularly in porous structures such as the GDL. Appropriate water management is necessary to avoid dry-out conditions or floods (an excess of liquid water) [48]. Moreover, capillary action regulates the flow of liquid water via the microchannels and porous medium of the GDL. The interplay of hydrophilic and hydrophobic surfaces within these structures facilitates water removal or retention, ensuring perfect equilibrium between gas diffusion and liquid water evacuation [48,49]. To prevent flooding, which blocks reactant gas pathways, and dry-out, which reduces membrane conductivity, effective water management is required. Advanced materials, such as hydrophilic-hydrophobic gradient GDLs and enhanced flow field designs, are widely employed to optimize water transport and distribution [49]. Table 2: compare EOD coefficient vs. T & RH for Nafion-like PEMs; include how membrane thickness and EW shift balances; show a through-plane schematic with flux arrows and relative magnitudes at low vs. high current [46–49].

Table 2. EOD coefficient vs. T & RH; include how membrane thickness and EW shift balances; show a through-plane schematic with flux arrows and relative magnitudes at low vs. high current.

Parameter	Condition	Nafion 117 (Thick, EW 1100)	Nafion 212 (Thin, EW 1100)	Impact on Water Balance
Electro-osmotic drag coefficient (nd)	30 °C, 100% RH	0.9–1.2 H ₂ O/H ⁺	1.1–1.4 H ₂ O/H ⁺	Drives water from anode → cathode
Electro-osmotic drag coefficient (nd)	80 °C, 50% RH	1.6–2.0 H ₂ O/H ⁺	2.1–2.5 H ₂ O/H ⁺	Increases with temperature
Back diffusion coefficient (Dw)	30 °C, 50% RH	1.5×10^{-10} m ² /s	2.0×10^{-10} m ² /s	Opposes EOD; higher in thinner membranes
Membrane thickness	—	178 µm	50 µm	Thinner membranes → faster equilibration
Hydration level (λ)	Cathode	14–22	12–20	Depends on RH and current load
Dominant flux at low current	0.1 A/cm ²	Back diffusion	Balanced	Cathode drying risk
Dominant flux at high current	≥1 A/cm ²	EOD	Strong EOD	Cathode flooding risk

3.3. Effects of Dehydration and Harsh Operating Conditions on PEMFCs

Proton exchange membranes generally have high energy production efficiency and a low environmental footprint. Nevertheless, their energy performance and endurance are significantly affected by operating parameters, primarily hydration levels and exposure to harsh environments [50]. Both dehydration and concentrated operational conditions can substantially weaken their efficiency, reducing durability, productivity, and necessitating more maintenance procedures [51]. The proton-conducting polymer membrane, which requires sufficient hydration to maintain ionic conductivity, is the primary component of PEMFCs that is affected by dehydration. The membrane's proton conductivity drops when it dries out, increasing the cell's ohmic resistance [52]. This phenomenon lowers the total power production and may contribute to mechanical strains that lead to membrane tears or cracks. In addition to reducing the cell's efficiency, these mechanical flaws may also permit reactant gases to pass through, which could result in additional performance deterioration and safety issues [51–53]. The catalyst layer structure includes carbon-coated platinum powder on both sides of the membrane, with pore sizes smaller than those of the gas diffusion layer. This issue may arise in PEMs (Nafion), as their performance is dependent upon humidity levels. Nonetheless, other membranes, such as polybenzimidazole and ionic liquid-based membranes, can function at elevated temperatures in anhydrous environments. The membrane's proton conductivity drops when it dries out, increasing the cell's ohmic resistance [50–53].

Thus, among all the components, the water transfer that occurs in CL is the most intricate. The way water is transported in CL is comparable to how it is transported in delicate pores [53]. Thus, the mechanisms underlying CL and GDL are comparable. Since CL contains smaller pores and a smaller distance between them than GDL, the Knudsen number can be used to characterize the state of water transport in CL. PEMFC problems are exacerbated by dehydration and other severe operating conditions, such as high temperatures, high current densities, and erratic load cycles [53]. While high current densities can cause mechanical and thermal strains, high temperatures can hasten the breakdown of the catalyst layers and the polymer electrolyte membrane. Moreover, variable loads result in localized drying or flooding and uneven water distribution, both of which impair ideal cell performance [53]. These circumstances reduce the operational lifespan of PEMFC systems by accelerating the chemical and mechanical deterioration of essential components, such as the catalyst layer, gas diffusion layers, and sealing materials. Careful system design and operating methods are necessary to mitigate the impacts of extreme environments and dehydration [54]. Developing membrane materials with enhanced thermal stability and water retention capabilities is crucial. Advanced water management technologies, such as water recovery units or humidifiers, can also aid hydration balance. Adaptive control systems that track and optimize operational parameters can also decrease fuel cell stress under varying load circumstances [55]. Resolving these issues is crucial for enhancing PEMFC durability and performance, particularly in demanding applications

such as portable power systems and automobiles. Studies and development of fuel cell current in materials composition, operational controls, and cell design are crucial for overcoming operational challenges and ensuring the development and application of PEMFC technology in sustainable energy solutions [53–55].

Water management influences the longevity and efficiency of proton exchange membrane fuel cells (PEMFCs). This process relies on the GDL, which ensures efficient transport of reactant gases and electrons while facilitating water flow. The GDL is often made of carbon-based porous materials, such as carbon cloth or carbon paper, and is frequently coated with hydrophobic compounds, such as polytetrafluoroethylene (PTFE), to optimize its water management properties [56–59]. Water in a PEMFC can be divided into phases: vapor or liquid. It flows through the GDL with various transport mechanisms, including vapor diffusion, capillary action, and liquid penetration. Draining liquid water away from the catalyst layer and directed to the flow channels in the hydrophobic pores of the GDL, where capillary-driven transport is predominant, facilitated by surface tension forces. This method is crucial in preventing water buildup at the catalyst layer, which could obstruct reactant gas access and impair the electrochemical reaction [59–62].

Diffusion is the process by which water vapor travels from areas of higher concentration close to the catalyst layer to areas of lower concentration in the flow channels, resulting in vapor-phase transport [61]. The temperature differential across the fuel cell affects this process because higher temperatures encourage evaporation and the flow of water vapor. To keep the fuel cell balanced and prevent flooding and dehydration, the interaction between liquid and vapor transport is essential [62,63]. The GDL's composition and characteristics have a significant impact on water transport. The porosity and pore size distribution determine the paths accessible for the transport of liquid water and gas, whereas the hydrophobicity affects how easily water can be removed. Furthermore, the GDL's pore structure and transport characteristics may change due to compression during assembly. Improving PEMFC performance requires an understanding of and commitment to adjusting these factors [63–67].

Additionally, recent research has emphasized how microstructural engineering might enhance water management in the GDL. To increase drainage efficiency and generate preferential water paths, methods including dual-layer GDL designs and laser perforation have been investigated [68]. With sufficient membrane hydration for proton conductivity, these developments aim to mitigate flooding, particularly in situations with high current densities [69–71]. High power density and long-term stability in PEMFCs depend on efficient water movement in the GDL. Further investigation into the basic workings and creative designs of GDLs will aid in the creation of fuel cell systems that are more robust and efficient [72–74]. Table 3 covers electrochemical performance metrics, including voltage decay rate, ohmic resistance growth, and catalyst degradation, which are affected by water imbalance, high current density, and temperature transients.

Table 3. Durability impacts of Water management and operating stress in PEMFCs.

Stress Factor/Condition	Water Management Impact	Durability Mechanism	Observed Effect	Relevance to Load Cycling
Membrane dehydration (low RH, insufficient humidification)	Reduced membrane water content	Increase in ohmic resistance (ΔR_{ohmic}), polymer chain scission	Voltage decay, membrane thinning	Repeated dry/wet cycles lead to mechanical fatigue
Cyclic dry-out and rehydration	Osmotic stress in the membrane	Crack formation, pinhole initiation	Gas crossover, reduced OCV	Strongly linked to duty cycling in automotive PEMFCs
Cathode flooding (excess water in GDL/flow channels)	Water accumulation blocks O ₂ transport	Mass transport loss in ORR	Voltage loss at high current	Starts during dynamic load shifts + inadequate water removal

Table 3. Cont.

Stress Factor/Condition	Water Management Impact	Durability Mechanism	Observed Effect	Relevance to Load Cycling
High current density ($>1.2 \text{ A cm}^{-2}$)	Increased water production	Local thermal stress and dehydration at the inlet	Hot spots, carbon support corrosion	Accelerated by transient high power demand
High temperature operation ($>80 \text{ }^{\circ}\text{C}$)	Faster dehydration and membrane shrinkage	Radical attack ($\bullet\text{OH}$), chemical degradation	Loss of proton conductivity	Thermal cycling increases stress on the membrane
Potential cycling (start-stop/load cycling)	Water imbalance in the catalyst layer	Pt dissolution, agglomeration, carbon corrosion	ECSA loss, voltage decay	Major factor in automotive PEMFC durability
Low-pressure operation	Poor liquid water removal	Flooding-induced transport limitation	Efficiency reduction	Load cycling worsens transient water control

3.4. Water Movement in the Catalyst Layer

The efficiency and longevity of PEMFCs are significantly influenced by water movement in the catalyst layer. Ionomer, catalyst particles, and void spaces facilitate gas movement within the thin, porous CL. Water is a byproduct of the electrochemical reactions that are facilitated by this layer: hydrogen oxidation at the Anode and oxygen reduction at the cathode [75,76]. Optimizing performance, avoiding flooding, and preventing severe membrane dehydration all depend on an understanding of and ability to control water movement within the CL. There are two types of water in the catalyst layer: generated water and water carried by electroosmotic drag. Water is produced at the cathode by the oxygen reduction process (ORR) [77–79]. Electroosmotic drag brought on by proton migration simultaneously moves water from the Anode toward the cathode across the membrane. To prevent performance degradation, the PEMFC's water distribution may become significantly unbalanced due to this method of water transport. Capillary-driven liquid water transport is introduced by the catalyst layer's porous structure [80]. Water's interaction with the porous media and the hydrophobic or hydrophilic characteristics of the catalyst layer materials produces capillary forces. A crucial part of the CL, the ionomer is hydrophilic, meaning it absorbs water and promotes proton transmission. Excessive water buildup in the pores, however, can obstruct reactant gas routes, limiting mass movement and decreasing efficiency [80]. Water diffusion, which is fueled by variations in the concentration of water vapor, is another important mechanism. This diffusion occurs through the ionomer phase and within the CL's empty regions. The relative rates of diffusion, capillary transport, and electroosmotic drag determine the total distribution and buildup of water in the catalyst layer. To maximize the fuel cell's performance and accomplish ideal water management, these processes must be balanced [81].

Extensive models and experimental studies have been used to study water mobility in the catalyst layer. Techniques such as X-ray computed tomography and neutron imaging provide detailed information regarding the distribution of water in the CL [81]. To simulate water transport and inform methods for improved design and operation, mathematical models that incorporate multiphase flow, capillary effects, and ionomer hydration dynamics are also employed. The microstructure of the catalyst layer is optimized, the ionomer characteristics are modified, and additives are used to control hydrophobicity and porosity, aiming to enhance water management. According to the study, ionomer coverage within flow channels under high current densities may be encouraged by increased local capillary pressure and decreased effective pore connectivity caused by higher ionomer coverage. While maintaining adequate hydration for proton conduction, these strategies aim to prevent flooding [79–82]. Better water management is a crucial area of research and development, as it prolongs the lifespan of PEMFCs and enhances their performance [80–82].

3.5. PEMFC Simulation of Water Transport in Catalyst Layers

The effective control of water transport inside the CL is a crucial component of PEMFC performance. This layer serves two purposes: it facilitates electrochemical reactions and allows for the movement of water and reactants. Understanding how water content, ionic conductivity, and oxygen diffusion interact to maximize cell durability and efficiency requires simulating water transport in the CL [83,84]. The catalyst particles, ionomer, and void spaces that make up the CL in a PEMFC combine to form a complex porous structure. During the oxygen reduction reaction, water is generated at the cathode and can accumulate inside the CL. Poor hydration reduces proton conductivity, while excessive water can obstruct oxygen pathways, resulting in mass transfer losses. Effective water management techniques are therefore essential to preserving ideal hydration levels without causing flooding [85].

Multi-physics models that combine mass transport, charge transfer, and phase-change dynamics are commonly used in simulations of water transport. These models take into account several variables, including diffusion, electroosmotic drag, and capillary pressure inside the CL [86]. For example, Fick's law is frequently used in numerical simulations to model diffusion processes, and the Darcy–Brinkman equation is used to represent fluid flow in porous media. To comprehend the dynamics of liquid water under various operating situations, phase-change processes such as condensation and evaporation are also considered [86,87]. The microstructural characteristics of the CL, including ionomer thickness and pore size distribution, are also considered using sophisticated modeling techniques. These elements affect the flow of liquid water driven by capillaries and the availability of oxygen at catalytic sites. The accuracy of these models is increased when simulation tools are combined with microstructural characterisation methods, including X-ray computed tomography [88]. In addition to water saturation constraints at the gas diffusion layer–catalyst layer interface, typical inlet gas humidification levels (e.g., 60–100% RH), temperature ranges (60–80 °C), and pressure conditions (1–3 bar) are frequently employed in model boundary conditions [87–89].

Correlation coefficients (R^2), absolute percentage error (MAPE), and root mean square error (RMSE). For instance, we now state that, when compared to neutron radiography data, multiphase flow models based on the Darcy–Brinkman approach usually achieve RMSE values of 0.02–0.05 for liquid saturation predictions, while mist-flow models exhibit average current density prediction errors of 5–10% under dynamic load conditions [88–90]. Realistic depictions of the CL's porous structure are crucial for improving the accuracy of water transport behavior predictions, according to recent studies [88]. The design of PEMFC components, such as hydrophobic treatments and optimum ionomer loadings, is informed by simulations of water movement in the CL. For PEMFC systems, these developments result in increased performance, longer operational lifetimes, and lower material costs. To address long-term performance difficulties, future research paths will involve combining degradation mechanisms with water transport models [88–90].

3.6. PEMFC Principle of Judging Water Failure Through Pressure Drop

Analyzing pressure drops in the system, which serve as markers of water behavior and potential issues, is a crucial step in diagnosing water-related failures in PEMFCs. The flow field design, gas channel geometry, reactant gas flow rates, and the buildup or removal of water within the channels are some of the variables that affect the pressure drop in a PEMFC system. During operation, the electrochemical reaction at the cathode produces water as a byproduct [91]. Excess water must be effectively drained to prevent floods, which can block gas pathways and reduce the active surface area available for reactions. However, membrane dryness resulting from insufficient hydration can impair performance and

proton conductivity. Engineers can identify irregularities indicative of water management issues by tracking pressure dips across the gas flow channels. For instance, an abrupt rise in pressure drop could indicate flooding due to an excessive buildup of water. In contrast, a fall in pressure drop might suggest membrane dehydration or inadequate humidification of reactant gases [92]. Operational characteristics, including temperature, current density, and reactant gas humidity levels, further complicate the link between pressure drop and water dynamics [92].

Unusual PD alterations are typically present when the PEMFC's water content is aberrant. It is possible to compare the estimated PD value with the actual measured PD. It is possible to determine whether the PEMFC has an abnormal water content issue when the difference between the two surpasses a specific threshold [93]. One can determine whether a pressure decrease has occurred by examining the deviation rate. A process for PEMFC water management [93]. When the battery is in good condition, this model can detect a decrease in battery pressure. The measured pressure drop curve will differ from this predicted curve if the battery fails. A water fault happens when there is a divergence. Using this technique, one may determine the consistency and reliability of the results. To precisely identify water-related failures, advanced diagnostic methods combine experimental analysis, computational fluid dynamics (CFD) models, and pressure drop data. Liquid water accumulation in the gas diffusion layer (GDL) and channels increases two-phase frictional losses, while inert single-phase losses remain essentially constant under steady operating conditions [93]. The water blockage factor (Φ) presents empirical threshold values reported in PEMFC diagnostics literature (typically $\Phi > 0.2$ indicating early flooding and $\Phi > 0.4$ signifying severe mass transport limitation) and provides the standard equation used to compute Φ from baseline dry gas pressure measurements. Additionally, ΔP monitoring is working as a real-time feedback diagnostic signal within fuel cell control systems—specifically showing how variations in Φ are used to adjust parameters such as cathode stoichiometry, humidification, stack temperature, or backpressure to mitigate flooding while minimizing efficiency penalties flowchart illustrating (i) acquisition of differential pressure signal, (ii) computation of Φ , (iii) comparison to baseline thresholds, and (iv) control decision actions (Flowchart 1) [91–94].

The durability and effectiveness of PEMFCs are enhanced by these techniques, which help optimize flow field designs and operating conditions to ensure efficient water management as described by the Flowchart in Figure 3. Frequent pressure drop monitoring also reduces maintenance expenses and downtime by facilitating the early identification of possible problems [93,94].

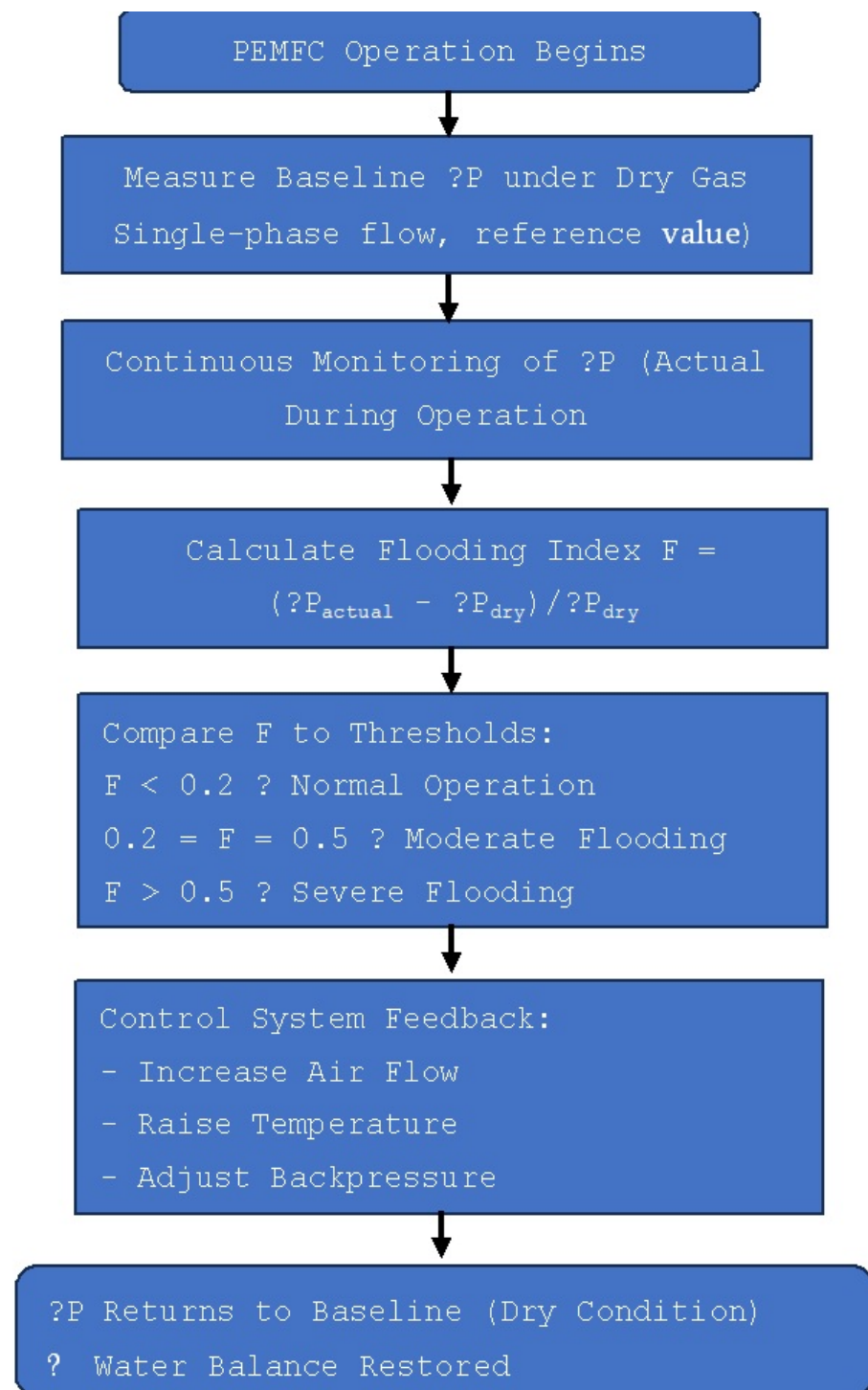


Figure 3. Principle of judging water failure through pressure drop in PEMFC.

4. Modeling Approaches for PEMFC Water Management

PEMFC water management involves various modeling approaches, including zero-dimensional (0D) models, one-dimensional and multi-dimensional models, two-phase flow models, and advanced techniques. Zero-dimensional models simplify PEMFC structure, while two-phase flow models enhance water movement and design strategies [95]. Advanced techniques include EIS-based water control, CFD and multiphase flow modeling, macro-homogeneous and patterned wettability models, one-dimensional physics-based stack models, and porous electrode two-phase flow modeling [95–100]. These techniques

enable real-time adjustments to air stoichiometry and stack temperature, balancing hydration and performance as follows:

4.1. Zero-Dimensional Models

Zero-dimensional (0D) models expect that the parameters are lumped together and that the cell is identical everywhere. These models do not account for internal gradients, but they can still illustrate how water content, current density, and temperature change over time. Because they can do math quickly, they are often utilized in system-level simulations, fuel cell control systems, and built-in diagnostics [95]. Although they do not consider geographical variables, 0D models offer a dynamic description of fuel cell behavior that varies over time. The Culubret research group created a 0D electrochemical model for water transport in the membrane-electrode assembly (MEA), which was combined with higher-dimensional physical submodels [95]. These models are especially well-suited for system-level simulations and real-time control, requiring minimal processing resources [95]. An example of a Zero dimension is advancements in lumped modeling of membrane water content for real-time prognostics and control of PEMFC [1000] [95].

4.2. One-Dimensional and Multi-Dimensional Models

One-dimensional models simplify PEMFC structure along a single spatial axis, making them computationally efficient for system-level simulations and control design. They solve mass, momentum, Energy, and charge conservation equations, assuming homogeneous properties across the plane [96]. Early models focused on membrane hydration and electroosmotic drag. Researchers have created 1D and multi-dimensional models to represent spatial variations [97–101]. A pseudo-3D channel model and a 2D model for the GDL were built by the Culubret group, together with a 1D model for the membrane [102]. These models, which replicate the movement of gases and liquids between layers, were verified using experimental neutron imaging [101–104]. The Gass group made a noteworthy recent addition by introducing an advanced 1D two-phase isothermal model [102]. This enhancement improves overvoltage prediction in PEMFCs by introducing a new parameter, referred to as the limit liquid water saturation coefficient. This coefficient accounts for excess water saturation in the catalyst layers, which has a significant impact on the electrochemical performance. With its finite-difference approach, the model is beneficial for low-cost control techniques and real-time diagnostics. It provides spatial insight into through-plane behaviour while adhering to zero-dimensional simplifications [104]. The error remains low for current densities below $1.3 \text{ A}\cdot\text{cm}^{-2}$, with $\Delta U_{\text{max}} = 1.5\%$ within this range, but increases significantly for higher current densities. An example of a 1D-dimension is an advanced 1D physics-based model for PEM hydrogen fuel cells with enhanced overvoltage prediction, demonstrating improved overvoltage prediction [102–104].

Key equations used in these models include the following:

1. The capillary pressure equation explains the necessary pressure differential to force liquid water through the hydrophobic GDL:

$$P_{cap} = \frac{2\gamma\cos\theta}{R_{pore}} \quad (5)$$

where γ is the surface tension of water; θ is the contact angle; and R_{pore} is the pore radius [95].

This equation presupposes quasi-static capillary transport and an isotropic pore structure within the GDL. Validation studies demonstrate concordance within $\pm 10\text{--}15\%$ for standard GDL porosities (0.6–0.85). It may exhibit diminished accuracy during dynamic two-phase transients or in gas diffusion layers characterised by considerable anisotropy or compression [85–97].

2. Darcy's law-based drainage criterion determines when liquid water drains from the porous medium.

$$P_{liq} - P_{gas} > P_{cap} \quad (6)$$

where P_{liq} is the liquid pressure and P_{gas} is the gas pressure [95].

Darcy's law is applicable at low Reynolds number flow conditions where inertial effects are insignificant. Comparison with pore-network simulations demonstrates an accuracy of $\pm 12\%$ for liquid saturations ranging from 0 to 0.4. Its reliability diminishes at elevated saturations, where channel flooding and film flows prevail, or when non-Darcy (Forchheimer) effects become pronounced [95–97].

3. Evaporation source term models the rate of water phase change from liquid to vapor.

$$S_{vl, evp} = \kappa_{evp} \varepsilon s \frac{\rho_{liq}}{M_{H_2O}} (P_{H_2O} - P_{H_2O}^{sat}) \quad (7)$$

where κ_{evp} is the evaporation coefficient, ε is porosity, s is saturation, and P_{H_2O} is partial pressure [95].

This model presumes local thermodynamic equilibrium and perfect gas characteristics. Validation against in situ neutron imaging data demonstrates satisfactory concordance within $\pm 8\text{--}12\%$ at normal PEMFC operation temperatures ($50\text{--}80^\circ\text{C}$). It may underestimate evaporation at elevated current densities where temperature gradients are strong [95].

4. The condensation source term represents the condensation of vapor into droplets [83].

$$S_{vl, con} = \frac{k_{con} \varepsilon (1 - s) X_{H_2O}}{RT} (P_{H_2O} - P_{sat}^{H_2O}) \quad (8)$$

The condensation model posits that condensation predominantly transpires within the pores and channels of the gas diffusion layer, influenced by variations in temperature and vapour pressure. Agreement generally falls within $\pm 10\%$ relative to experimental observations in humidified settings. The model may exhibit inaccuracies during rapid transient load cycling due to thermal and phase delays [95–98].

5. Water absorption rate simulates the re-humidification of the GDL.

$$S_{abs} = \delta_{w, min} q_{abs} \quad (9)$$

where $\delta_{w, min}$ is the minimum water content and q_{abs} is the absorption rate [95].

The absorption model encapsulates re-humidification induced by capillarity and the coupling of membrane hydration. The accuracy is contingent upon the calibrated material diffusion coefficients and ranges between $\pm 10\text{--}15\%$ for Toray and SGL GDL types. Model efficacy diminishes under circumstances of membrane deterioration or micro-fracturing [95–99].

4.3. Two-Phase Flow Models

Two-phase flow models have been created to clarify and enhance the movement of water in PEMFCs, which can be either vapor or liquid [105]. These models are crucial for enhancing design and control strategies, and they facilitate the prediction of performance loss due to floods [106]. There are three kinds of two-phase flow models: macroscopic (continuum-based) models, two-fluid models, mixture models, pore-scale models, and multiphysics models. Parameter estimation, validation, and computing cost are among the problems that arise when modeling two phases [106]. Recent improvements include the use of machine learning and the design of dynamic flow fields. However, there are

still challenges, including parameter estimation, limited visibility into experiments, and high computational cost. Future endeavors should focus on reconciling the disparity between precision and computational efficiency while advancing experimental validation methodologies [107]. Several research groups used neutron imaging to study in situ water distribution within channels and GDLs [105–107]. The models expanded on this by demonstrating the formation of liquid droplets, gas pressure drops, and evaporation/condensation dynamics using two-phase flow equations. These models are crucial for assessing liquid water and gas coexistence, which is essential to comprehending flooding and dry-out conditions [107–109]. An example of a 1D dimension is the development and experimental validation of a 2D PEM fuel cell model to study the effects of heterogeneities along a large-area cell surface [109].

4.4. Advanced Modeling Techniques

Advanced modeling techniques for water management in PEMFCs include Electrochemical Impedance Spectroscopy (EIS)-based water control, CFD and multiphase flow modeling, macrohomogeneous and patterned wettability models, one-dimensional, physics-based stack models, novel flow-field and flow plate designs via simulation, and porous electrode two-phase flow modeling [107–109]. EIS in PEMFCs assesses system impedance as a function of frequency, examining resistive and capacitive characteristics [98]. High-frequency resistance is related to the amount of water in the membrane, whereas mid-frequency arcs indicate how charge moves and the capacitance in the double layer [110]. Low-frequency responses are associated with issues related to moving bulk due to flooding. EIS can distinguish between floods and dehydration, enabling the initiation of real-time control measures [111,112]. These techniques allow real-time adjustments of air stoichiometry and stack temperature, thereby balancing hydration and performance. Macrohomogeneous models incorporate hydrophilic/hydrophobic patterns to manage water distribution, while one-dimensional, physics-based stack models combine distributed thermal, liquid water, droplet detachment, and gas-phase transport across layered components for real-time control schemes [113]. An example of a 3-D dimension is Computational fluid dynamics modelling of proton exchange membrane fuel cells: Accuracy and time efficiency. However, these exhibit the highest predictive fidelity (local temperature, species, two-phase flows) but are computationally intensive. To reduce run-times while maintaining essential 3D physics, hybrid and neural-accelerated approaches have been proposed [111–113].

Multi-physics models are advantageous because embedding sensors within a cell is impossible, as they expand the available information to facilitate more effective control of PEM fuel cells. Currently, most existing models either offer a highly detailed description of the cell's internal states but require a computationally intensive approach, such as computational fluid dynamics models, or are rapid but provide only summary information about the cell, such as lumped-parameter models [112]. The objective of this research is to identify a more optimal compromise between the rapidity of execution and the accuracy of the results. Consequently, a dynamic, two-dimensional model has been created, and its inert behavior has been verified against experimental data. Several experimental polarisation patterns have been published [113]. This model has a runtime that is two orders of magnitude faster than 1D models from the commercial software Comsol Multiphysics and up to five orders of magnitude faster than 3D models from the literature. It maintains compatibility with embedded applications and techniques (Table 4).

Recent advances combine data-driven models with multiphysics. Thermal, mass transport, and electrochemical effects are combined in multiphysics models. Pourrahmani and Van Herle's research group employed an artificial neural network to forecast the ideal porosity

and permeability for water removal after simulating liquid water creation using a CFD-based 3D model: Optimal porosity = 0.9 and Optimal permeability = $1.481 \times 10^{-11} \text{ m}^2$ [96]

Table 4 provides a comparison of 0D, 1D, 2D/3D, and advanced models in terms of complexity, spatial resolution, computational cost, typical applications, accuracy range, and validation status.

Table 4. Modeling techniques comparison.

Model Type	Complexity	Spatial Detail	Computational Cost	Typical Applications	Accuracy Range	Validation Status
0D	Low	None	Very low	System-level control, energy management	Low–Moderate	Experimental, literature
1D	Moderate	Through-plane	Low–Moderate	MEA hydration, voltage-current prediction	Moderate	Partially validated
2D/3D	High	Full geometry	High	Design studies, performance optimization	High	Validated with experiments
Two-phase	Very High	Multiphase	Very high	Water removal, flooding analysis	High	Validated, CFD comparison
Advanced	Varies	Embedded/learned	Low–Moderate	Real-time prediction, control systems	Moderate–High	Validated, data-driven

4.5. Water Content Adjustment in PEMFC by Changing the Pressure Drop

Changing the cathode air stoichiometry, where the air serves as both an oxidant and a cooling medium, can substantially impact membrane hydration levels and thermal regulation throughout the cell, as demonstrated by a three-dimensional multiphase model of an open-cathode PEMFC with integrated cooling channels [114]. Improved stoichiometric ratios lead to more consistent membrane hydration and better water removal, which stabilizes proton conductivity and lowers ohmic losses. However, especially at high operating currents, this results in larger parasitic losses because of the increased pressure drop over the cooling zones and cathode flow field [115]. Furthermore, pressure drop impacts the balance between liquid water removal and membrane humidification by changing the phase equilibrium of water within the porous media in addition to reactant transport [115]. Water management is made more difficult by temperature variations throughout the GDL. The condensation and evaporation cycles inside the porous structure cause phase-change-induced (PCI) flows, which are generated by these gradients. Recent multiphysics models have demonstrated that localised accumulation of liquid water, especially at the cathode side, is caused by higher temperature gradients. Particularly in the areas along the channel-rib interface, this uneven water distribution may result in localised flooding, which further raises the pressure drop and limits gas access to the catalyst layer [116]. To maximise water transport and preserve performance stability in PEMFCs, especially in dynamic or high-load scenarios, the interaction of temperature gradients, PCI-driven fluxes, and pressure differentials is essential [115,116].

In PEMFCs, pressure drop is crucial for managing water, as it impacts membrane hydration, gas transport, and water removal. Changing the air stoichiometry on the cathode side to adjust the pressure drop facilitates the movement and removal of water, maintains stable proton conductivity, and reduces ohmic losses [114–117]. However, this enhancement results in increased parasitic power losses and can cause the membrane to dry out [118]. A pressure drop also changes the balance of the water phases, which affects the capillary pressure and saturation levels in the catalyst and gas diffusion layers. It also affects flows caused by phase changes inside porous structures, resulting in uneven water saturation across the membrane-electrode assembly [119]. The interplay between temperature changes and pressure drop makes it more difficult for water to move, leading to an increase in pressure drop and a decrease in gas diffusivity. To optimize fuel cell performance, it is

essential to understand how pressure drop impacts temperature, humidity, and flow field design [117–121]. Changing the cathode air stoichiometry, where the air serves as both an oxidant and a cooling medium, can substantially impact membrane hydration levels and thermal regulation throughout the cell, as demonstrated by a three-dimensional multiphase model of an open-cathode PEMFC with integrated cooling channels [120]. Improved stoichiometric ratios lead to more consistent membrane hydration and better water removal, which stabilizes proton conductivity and lowers ohmic losses. However, especially at high operating currents, this results in larger parasitic losses because of the increased pressure drop over the cooling zones and cathode flow field [121]. Furthermore, pressure drop impacts the balance between liquid water removal and membrane humidification by changing the phase equilibrium of water within the porous media in addition to reactant transport [121].

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4.6. Improvement of Flow Channel Shape and Surface Tension Problems

Fuel cell performance and membrane hydration are influenced by water removal and flow stability, which are significantly impacted by several GDL structural features, such as channel–land geometry, the presence of a microporous layer (MPL), and PTFE content [121,122]. It has been shown that flow channel design significantly impacts wetted area ratios and two-phase flow behaviour in PEMFCs, as observed through in situ visualisation of cathode flooding. Because serpentine channels have greater shear forces and improved pressure gradients than other flow field designs, they typically offer more efficient water removal among the popular configurations [121]. Tapered channels enhance local flow velocities by decreasing the cross-sectional area along the flow path, which elevates shear stress at the gas–liquid interface, thus facilitating droplet separation from the channel walls. The shape of tapered channels enhances under-rib convection, facilitating water removal from under the gas diffusion layer via localised pressure gradients and secondary flow effects. The synergistic effects of shear-assisted droplet detachment and enhanced under-rib convection elucidate the greater water removal efficacy of tapered channels relative to uniform designs [121,122].

Water blockages brought on by surface tension can be lessened by hydrophobic treatment of the gas diffusion layer (GDL), usually accomplished using PTFE coating that encourages capillary-driven drainage. Nevertheless, droplet instability and random detachment points at the GDL–channel interface continue to impede consistent water evacuation, and surface tension effects make these issues worse [120–122]. Flooding occurs when too much liquid water builds up inside the GDL due to improperly managed surface tension. As a result, gas transport channels are blocked, pressure losses rise, and voltage dips at the cathode are brought on by oxygen starvation [122].

4.7. Water Management Materials

Inappropriate water management and the improper use of substandard materials can result in cathode flooding, impeding gas transmission, and markedly diminishing fuel cell efficacy. To tackle this issue, specialised advanced materials designed for efficient water regulation have been created and included in many components of PEMFCs, such as membranes, gas diffusion layers (GDLs), microporous layers (MPLs), and catalytic layers (CLs) [123–125]. Instances of membrane materials exhibiting enhanced water retention properties include inorganic fillers, hydrophilic polymer composites, and membranes injected with ionic liquids [126–128]. Gas diffusion layers (GDLs) are typically constructed from carbon fibre paper or cloth that is coated with hydrophobic polytetrafluoroethylene (PTFE), enhancing gas permeability and aiding in the expulsion of liquid water [129]. To enhance the equilibrium between gas diffusion and water transport, engineering methods for pore structure, including gradient porosity gas diffusion layers (GDLs) and dual-layer GDLs, have been devised. The MPL, situated between the GDL and the CL, is essential for regulating capillary pressure and averting the accumulation of liquid water. Recent studies have investigated the integration of functional additives—such as ceramic nanoparticles, graphene, and carbon nanotubes—to concurrently improve electrical conductivity and water management efficiency [128–136]. Notwithstanding these advancements, persistent long-term challenges endure, such as maintaining optimal membrane hydration at elevated current densities without causing cathode flooding, ensuring the longevity of hydrophobic and hydrophilic treatments, and guaranteeing material stability under freeze–thaw and start-stop operational conditions [133].

4.8. Water Performance and Water Buildup in PEMFC by Changing the Pressure Drop

Excessive water collection, or flooding, obstructs reactant movement and markedly diminishes fuel cell efficiency, whereas sufficient membrane hydration is crucial to lower ionic resistance. Regulating and observing the pressure differential across the gas diffusion layers (GDLs) and cathode flow channels is an effective method for evaluating and managing water content within the system [131]. The two-phase pressure drop multiplier (Φ), defined as the ratio of the two-phase pressure drop ($\Delta P_{\text{two-phase}}$) to the single-phase pressure drop ($\Delta P_{\text{single-phase}}$), is a crucial diagnostic tool for assessing flooding severity and quantifying the total liquid water content in a PEMFC [134,135]. According to experimental studies, PEMFCs operate best when this multiplier is kept between 1.2 and 1.5. Values above this range frequently signify substantial water buildup, which lowers fuel cell performance and efficiency due to channel blockage and impaired gas diffusion [134–136]. Capillary pressure, represented as:

$$P_{cap} = P_l - P_g = \frac{2\gamma \cos\theta}{r} \quad (10)$$

where P_c is the capillary pressure, P_l is the liquid pressure, P_g is the gas pressure, and r is the pore radius. [137,138]. This connection highlights the interaction between capillary and hydraulic pressures, determining the crucial conditions for efficient liquid water evacuation and the GDL structure's internal pore radius. This connection highlights the interaction between capillary and hydraulic pressures, which determines the crucial circumstances needed for efficient liquid water evacuation [137,138]. Several experimental and modeling studies have shed light on how the water content in PEMFCs can be efficiently controlled by varying the pressure drop. Operating at higher airflow velocities significantly reduces Φ from values as high as 10 (indicating severe flooding under low velocities) to near unity, representing clear, unobstructed flow channels, as Adroher and Wang (2011) [134] showed through both analytical modelling and experimental validation. With the help of sophisti-

cated 3D multiphysics modeling, this study demonstrated that while increasing cathode air stoichiometry increases pressure drop, which improves water removal and membrane hydration, it also increases parasitic pumping losses, necessitating careful optimization [139]. To dynamically maintain pressure drop multipliers within the ideal range, real-time control systems have been developed that actively utilize pressure drop monitoring to modify airflow rates or inlet pressures. By successfully regulating membrane hydration and preventing channel flooding, these adaptive controls significantly enhance cell longevity and maintain steady performance [125–139]. Furthermore, Mortazavi and Tajiri (2015) [140] provided thorough analyses emphasizing the significant impact that microchannel geometries and GDL structural alterations have on two-phase pressure drop behavior, which informs efficient PEMFC design and operating strategies. Therefore, managing pressure drop becomes a crucial strategy that protects PEMFC longevity and efficiency by striking a balance between capillary-driven water evacuation and ideal hydration conditions. In PEMFCs, steady-state flooding regularly occurs when the accumulation of water in the gas diffusion layer (GDL) and catalyst layer surpasses the local removal capability, resulting in mass transport limits and performance deterioration. Conversely, transitory effects such as droplet nucleation, growth, and detachment are highly dynamic phenomena affected by swift variations in current density, flow rate, and local temperature gradients [140].

4.9. Nuclear Magnetic Resonance Imaging

It can measure the amount of water and its movement in PEMFCs without needing to cut them apart, using magnetic resonance imaging (MRI) and nuclear magnetic resonance (NMR) spectroscopy. NMR directly probes protons in water molecules, which is different from X-ray approaches. This makes it very sensitive to phase, mobility, and the immediate environment [141]. NMR can distinguish between free and bound water in the membrane and catalyst layers. This is important for understanding water back-diffusion and electroosmotic drag. Using NMR, it is possible to visualize the distribution of water in a PEMFC [142]. Tsushima et al. used NMR to visualize PEMFCs and examine how water is distributed in the presence of excess water in PEMFCs [143]. Several practical works employed MRI to vary the current density, resulting in differences between the study groups. The researchers claim that water exhibits a distinct property regarding anti-osmosis, and this difference causes the phenomenon to occur. Based on the studies above [143]. The Tsushima research group employed an MRI scanner to investigate how delivering water directly to the proton exchange membrane in liquid form affected the performance of PEMFC [144]. The experiment showed that the section directly supplying water to the PEMFC was bent because the membrane swelled in that area due to a higher water content. Delivering water straight to the membrane would also raise the voltage of the battery. Using MRI-based flow mapping, researchers have been able to visualize how water moves and accumulates in the plane of the MEA [145]. For example, the Perrin research group used MRI to monitor liquid water in the flow field and GDL while the cells were running, which helped them better understand how channels flood and how water buildup issues arise. The spread of PEMFC dehydration can also be detected via NMR. The experimental results indicate that the dehydration distribution of PEMFC occurs from the air inlet to the outlet. The limits of this technology are comparable to those of neutron scanning [146].

4.10. Methods for X-Ray Irradiation

X-ray computed tomography (X-ray CT) and X-ray radiography offer high-resolution three-dimensional and two-dimensional visualisation of liquid water distribution within the gas diffusion layers (GDLs), flow fields, and catalyst layers of proton exchange mem-

brane fuel cells (PEMFCs) [147]. These methodologies serve as essential instruments for examining water transport dynamics during fuel cell operation. X-ray radiography facilitates real-time observation of water buildup and movement under diverse operational situations. Prior research has established that the thickness of liquid water in PEMFC components may be measured using X-ray irradiation by correlating X-ray attenuation with the water layer thickness. Experimental findings have demonstrated a linear correlation between the reduction in X-ray intensity and water thickness, thus validating the efficacy of this technology for in situ water assessment [147,148]. Moreover, X-ray methodologies can be employed to monitor the advancement of water accumulation throughout cellular function. Mankel and colleagues utilised synchrotron-based X-ray imaging to examine water flow during the start-up of PEMFC. Their findings indicated that liquid water tends to collect at the interface between the microporous layer (MPL) and the flow channels, affecting fuel cell performance and initiation behaviour. These findings illustrate that X-ray imaging techniques are essential for enhancing the comprehension of water management in PEMFCs [146–148].

Furthermore, X-ray radiation is not steady because electrons can easily scatter and absorb X-rays, which is why using X-rays to examine water is not prevalent. Create an alternative bath for the cathode that enables the flow to continue. This new design utilizes radial flow fields instead of typical rectangular flow channels [149]. Experimental results demonstrated that the novel flow field design is capable of transferring more water and mass in dry air flow environments compared to the current standard parallel channels. The Seong research group improved the cathode channel, and the experiment developed a novel method for removing water utilizing the Concus-Finn condition. A new shape for the flow channel was created through simulation [150]. Tests have shown that the new runner does help with water management. John Bachman and others [151] investigated the impact of flow channel length on the difference between standing water and pressure drop by designing a PEMFC capable of adjusting the flow channel length. The experiment compared and evaluated flow pipes of different lengths. The test showed that 25 cm is better than 5 cm. The specific direction for improving performance is the stability of PEMFCs [151]. At the same time, 25 cm also did better in terms of current density and power. There was the most electricity and the least standing water in the 25 cm aisle. There is limited research on how the depth of the flow channel affects drainage; however, in reality, shallower flow channels are typically used because they allow for larger gas flow rates, which facilitate the movement of liquid water. X-ray CT will enable the examination of the structure in close detail, including the levels of porosity and saturation, which allows for the design of the best flow-field geometries [151]. As a summary, Table 5 illustrates information and comparisons about the detection methods.

Table 5. Summary of diagnostic modalities used in PEMFC water management studies.

Modality	Spatial/Temporal Resolution	What It Measures	Operational Constraints	Key PEMFC Water Findings
Neutron Imaging	~10–25 μm spatial; ~1–2 s temporal	Liquid water distribution	Requires access to reactor facility; limited portable use; beam time required.	Reveals initial water accumulation near the GDL–channel interface; shows channel vs. under-rib flooding.
X-ray Computed Tomography (XCT)	~1–5 μm spatial; static imaging	Liquid water saturation, GDL structure	High radiation dose; complex during dynamic PEMFC operation	Shows water transport paths in GDL and MPL; capillary behavior
Magnetic Resonance Imaging (MRI)	50–200 μm spatial; 100–500 ms temporal	Water distribution in porous layers	Magnetic field limits materials; complex setup	Reveals internal membrane hydration dynamics

Table 5. Cont.

Modality	Spatial/Temporal Resolution	What It Measures	Operational Constraints	Key PEMFC Water Findings
Optical Visualization	~1–10 μm spatial; video-rate temporal	Liquid droplets in channels	Requires transparent cell/window; only 2D surface data	Shows droplet growth and detachment regime; channel blockages
Infrared Thermography	~50 μm spatial; ms temporal	Surface temperature $\rightarrow$ water effects indirectly	Limited to surface; emissivity correction needs	Identifies hot spots from dry-out or flooding

4.11. Changing the Material Structure

Modifying the hydrophilicity of the proton exchange membrane to align with the moisture content of the PEMFC is crucial for water management, as it diminishes the risk of overflow. An additional efficient method to optimise water management is to enhance the physical qualities of other components in the PEMFC [152].

Adding silica to the proton exchange membrane can increase its hydrophilicity. The proton exchange membrane retains more water, which enhances its ability to convert water into hydrogen. This not only improves water management but also enhances the performance and durability of PEMFC operation. The Xiaoqian research group developed a novel type of hydrophilic porous carbon plate (HPCP) to improve the balance between humidification and drainage [152]. A porous carbon plate features a hydrophilic silica coating that is electrochemically assisted in self-assembling on its pore surface [153]. This makes HPCP a continuous, hydrophilic pore, making it easier to humidify and drain. The Jung research group examined various materials for the catalyst layer to enhance the performance of the PEMFC, aiming to improve the material's hydrophilic characteristics [152–154]. Researchers have explored the use of a spraying method to incorporate silica into the anode catalytic layer, aiming to improve the water management and performance of PEMFCs at low temperatures [153]. The current study suggests that the hydrophilicity of the Anode's catalyst layer is enhanced with an increased presence of SiO_2 , indicating that its addition can significantly increase the material's hydrophilicity. Another technique to improve water management is to modify the thermal conductivity of the materials exposed to the PEMFC at high temperatures. The poor thermal conductivity prevents other sections from quickly attaining the elevated temperatures present in the PEMFC. This effect results in a more uniform temperature distribution within the PEMFC. P. Manoj Kumar and colleagues proposed utilising low thermal conductivity PEMFC to passively address water management issues in fuel cells [154]. This material, characterised by low thermal conductivity, can be utilised in regions of the battery that are sensitive to elevated temperatures. The peak power density increased by 36%, while the limiting current density grew by 37.5% following the utilisation of this material [154]. Enhancing the flow channel material can facilitate accelerated water drainage from the PEMFC. As the contact angle increases, the flow resistance significantly decreases for hydrophilic flow channels, and the region of diffuse flow diminishes as the contact angle increases [155]. As a result, the wave resistance effect is less intense, which complicates the drainage of water from the flow channel. However, the liquid water in the GDL can still be released in time to stop the GDL from flooding. With these methods, the gas pushes liquid water off the surface of hydrophobic runners. However, it also causes liquid water to flow as a film on the GDL surface. Therefore, the hydrophobic flow channel allows water to exit more easily, but it still causes flooding of the GDL in some instances. The Rouxian research group utilised a volume of fluid method to develop a three-dimensional numerical simulation of liquid water transitioning from the GDL surface to the gas flow channel in a PEMFC [154,155].

The experiment's findings reveal that if the material is hydrophilic, water will not form a film on the cornea. If the flow channel is designed as a U-shaped pipe, the high-velocity gas will disrupt the water on the gas diffusion layer. Furthermore, the Ziang research group developed a cathode with a double-catalyst layer structure, enhancing the gas diffusion layer and microporous layer [156]. The findings indicate that the thin hydrophilic layer, constructed with perfluorosulfonate as a catalyst binder, significantly enhances the air permeability of the fuel cell, thus improving PEMFC water management. To improve PEMFC water management, the Zhiqiang research group designed a bipolar plate with a porous, hydrophilic water transport plate (WTP) [157]. The test results indicate that WTP enhances the humidification and drainage capabilities of fuel cells compared to conventional solid plates. The transfer of water is slightly influenced by hydrogen stoichiometry; nevertheless, reducing air stoichiometry can shift the principal role of WTP from humidification to drainage [158–162]. Modifying the membrane's composition enhances its hydrophilicity, allowing water to attach to and be absorbed by the membrane. This can improve the stability of PEMFCs, optimise their water utilisation, and elevate their performance [162].

Nevertheless, the cost is unacceptable, and the membrane will rapidly degrade. Altering the material to enhance its hydrophilicity will increase the expense of PEMFC. Changing the flow channel and other material components can improve the drainage rate of water; however, this is a complex and costly process [150,151].

4.12. Improvement of Flow Channel Shape in PEMFCs

To improve fuel cell efficiency, water removal, and reactant distribution in PEMFCs, optimising the flow channel geometry is essential. Conventional straight parallel tubes have a low pressure drop (ΔP), but they also have water buildup and poor gas distribution [161]. On the other hand, serpentine channels, distinguished by their lengthy, twisting pathways, enhance water evacuation and mass transport through improved shear flow, albeit at the expense of higher parasitic pumping power and a higher pressure drop (ΔP). In contrast to longer or excessively complex layouts, such as 13-channel vs. 26-channel designs, experimental studies have demonstrated that serpentine designs with optimised pass numbers (e.g., three-pass configurations) provide better membrane hydration and less flooding [161,162]. The influence of geometrical dimensions and pressure drop can be used to describe the serpentine flow field voltage (V), which usually highlights a trade-off between pressure loading and water removal [161]. Interdigitated flow fields (IDFFs) with dead-ended channels drive under-rib convection to move reactants across the gas diffusion layer, greatly enhancing reactant access and water removal at greater current densities. IDFF performs better than serpentine designs in reducing water buildup and improving performance, as indicated by CFD and experimental studies [162,163].

Low ΔP and reasonably uniform flow are provided via modified parallel flow fields, such as tapered, curved, or micro-distributor designs. Positive tapered parallel channels, for example, increase their cross-section towards the outlet, thereby enhancing water evacuation and flow velocity. Power increases of up to 61% under high current densities with positive tapering were shown in a 3D CFD research [156–162]. Similarly, by encouraging capillary-driven water clearance beneath the ribs, zigzag and porous insert-enhanced channels yield performance increases of 17–20% [163].

The following are essential metrics that support these improvements:

1. Pressure drop, represented by Equation (11).

$$\Delta p = f \frac{L}{D_h} \rho v^2 / 2 \quad (11)$$

where D_h is hydraulic diameter, v is flow velocity, and f is a friction factor, modified by bends and channel geometry [158],

2. For multi-U inlet designs, the dimensional uniformity index, which measures reactant distribution across channel arrays, improved from 0.70 to 0.16 [153].
3. Interdigitated or curved channels enhance the under-rib convection effect, facilitating the evacuation of water and oxygen.

In conclusion, optimal flow channel designs must balance efficient water removal with sufficient reactant supply. Each configuration—serpentine, interdigitated, and modified parallel—provides unique benefits. Tapered or curved parallel channels reduce pressure drop while ensuring efficient water removal; interdigitated channels improve convective water transport beneath ribs, and serpentine channels excel due to shear-induced liquid evacuation. Consequently, it is imperative to select and tailor the flow field shape according to particular operating conditions and application specifications to enhance the durability, efficiency, and overall performance of PEMFCs [153–158].

Performance versus Cost Trade-off: Commercial and automotive applications can benefit from low-cost techniques, including flow field optimisation and PTFE-treated GDLs, which provide moderate to high performance gains [159]. On the other hand, sophisticated techniques such as self-humidifying membranes and pore-engineered GDLs exhibit outstanding performance potential but are still costly because of their intricate manufacture (Table 6).

Technology Readiness Level (TRL): Commercial stacks already employ strategies like temperature control and external humidification, which have TRL 9 [160]. Ongoing R&D needs are shown by the fact that membrane engineering and surface modification approaches are still in the research stages (TRL 4–6).

Scalability and Applicability: Automotive and stationary systems benefit greatly from mature approaches (TRL ≥ 8). Although cost and manufacturing complexity prevent widespread implementation, intermediate TRL technologies like Water Transport Plates (WTPs) show promise for next-generation high-power-density fuel cells [161].

Integration Potential: To achieve excellent water balance and prevent membrane dehydration and flooding, the best-performing PEMFC systems frequently include hybrid techniques, such as MPL + optimised flow field + thermal management [162]. Table 6 illustrates the strategies, description, cost, and technology.

Table 6. Water management cost and pressure strategy.

Water Management Strategy	Description	Cost Implication	Performance Impact	Technology Readiness Level (TRL)	Notes
Hydrophobic GDL (PTFE-treated carbon paper)	Enhances liquid water transport and prevents flooding	Low–Medium	Improves water removal and gas diffusion	TRL 9 (Commercial)	Widely used in automotive PEMFC
Microporous Layer (MPL)	Added between GDL and catalyst layer to improve water distribution	Medium	Better water balance, reduced membrane dehydration	TRL 8–9	Common in commercial stacks
Hydrophilic/Hydrophobic Gradient GDLs	Gradient design enhances capillary-driven water transport	Medium–High	Significant flooding control, stable performance	TRL 6–7	Used in advanced research systems
Membrane Humidification (external humidifier)	Humidifies inlet gases to prevent dry-out	Medium–High	Ensures membrane conductivity	TRL 9	Older commercial systems still use this
Self-Humidifying Membranes (Nafion + hygroscopic fillers)	Water generated retained by membrane additives	Medium	Reduces system complexity	TRL 7–8	Used in portable/low-temp PEMFC

Table 6. Cont.

Water Management Strategy	Description	Cost Implication	Performance Impact	Technology Readiness Level (TRL)	Notes
Thermal Management (coolant plates)	Controls cell temperature to manage vapor–liquid balance	Medium–High	Improves stability under transient load	TRL 9	Standard in high-power systems
Wicks/Capillary Structures	Passive water transport via porous wicking layers	Low	Simplifies water control	TRL 4–5	Prototype systems
Electro-Osmotic Drag (EOD) Enhancement	Adjusting membrane chemistry for balanced water transport	Medium–High	Uniform hydration	TRL 3–4	Active research
Two-Phase Flow Control via Back Pressure	Gas flow pressure control aids water removal	Low	Effective, but increases parasitic loss	TRL 8–9	Common method

4.13. Proton Transport Mechanisms (Vehicle and Grotthuss)

Proton transport in polymer electrolyte membranes (PEMs) depends on the Grotthuss (structural/hopping) and vehicle mechanisms. The vehicle mechanism depends on the diffusion of carrier species, such as H_2O^+ , which is influenced by water content and viscosity. Rapid bond transfers via hydrogen-bond networks are associated with proton mobility in the Grotthuss mechanism, which permits net charge movement that surpasses individual molecule displacement [163]. These mechanisms are contingent upon a variety of parameters, including the connectedness of hydrogen-bond networks, temperature, hydration, and membrane chemistry. The internal acid networks of materials like phosphoric-acid-doped polybenzimidazole (PA-PBI) can maintain proton conduction in the presence of reduced humidity, even though Grotthuss transport is facilitated by hydration in conventional PEMs such as Nafion [163,164]. Therefore, the influence of external humidity on Grotthuss-like hopping may be reduced when an internal hydrogen-bonded network is present, even though both methods are affected by moisture in water-swollen ionomers. Conductivity is significantly enhanced in membranes that come into contact with water, such as Nafion, when moisture levels are elevated. Conversely, imidazole and acid-doped PBI systems can function effectively in low-humidity environments [164]. This necessitates a comprehensive understanding of membrane chemistry and proton conductivity. It emphasizes the necessity of circumspect hydration for membranes that depend on vehicle movement, as opposed to those with inherent proton-conducting networks, which can reduce the need for humidification [164–166].

5. Future Challenges in Water Management

Future challenges in water management for PEMFCs involve a complex interplay of transport phenomena, material behavior, and operating conditions. Membrane dehydration and cathode flooding are critical issues that can lead to voltage drops, acceleration of degradation, and limited operating windows [167–169]. Insufficient hydration can lead to high current density, elevated operating temperatures, and inadequate humidification. Cathode flooding can result from inadequate water removal, poor GDL design, and insufficient temperature gradients [170]. Dynamic load and environmental sensitivity can also affect water balance, leading to transient flooding and long-term degradation. Ionomer degradation can also occur due to low hydration, resulting in reduced mechanical integrity and eventual failure [171]. Future directions in PEMFC water management include developing advanced materials for self-humidifying membranes, modifying microstructures in GDLs and MPLs, and integrating real-time water monitoring and control systems. Improved

system design can also enhance water management, including humidifiers, flow fields, and water recovery subsystems [172–174].

Reviewing the syntheses and contrasting divergent findings in the literature and PEMFC production technology improves PEMFC manufacturing. Discrepancies between cell-level and stack-level water transport observations, along with the impact of operating modes and gas diffusion layer (GDL) microstructure, highlight specific research gaps [175]. There is a particular need for integrated multi-scale models that couple two-phase transport, electrochemistry, and degradation; standardized protocols for transient and vehicle-relevant testing; and long-term durability studies under realistic start–stop and cold-start conditions [176–179]. It also outlines prioritized avenues for future investigation, including advanced in situ diagnostics and imaging, data-driven real-time water management strategies, GDL and microporous layer (MPL) microstructure optimization informed by pore-scale modeling, and membrane/catalyst materials capable of withstanding wider hydration fluctuations [180,181].

It is based on these recommendations from recent studies: several reviews and technical papers from 2024–2025 emphasise the transition to system-level control [182]. The necessity for integrated modeling frameworks, foundational research on component and thermal-water interactions, and recent control and diagnostics studies reveals effective real-time stack water management strategies for automotive applications [183]. A brief roadmap subsection has been incorporated, emphasising (1) the advancement and community integration of benchmark transient test protocols, (2) synchronised multi-scale experimental and modelling initiatives to mitigate parameter uncertainties, (3) an increased focus on durability in realistic cycling and cold-start conditions, and (4) the conversion of laboratory-scale advanced diagnostics into field-deployable monitoring instruments—each point supported by specific citations and proposed experimental or modelling tasks [184–187]. The improvements enhance Section 5 from a solitary paragraph to a targeted, evidence-driven, prospective analysis designed to inform researchers and funders; the amended wording delineates which gaps are critical, which are manageable with existing methods, and which necessitate long-term resources [187–190].

6. Conclusions

This review explores the importance of water management in PEMFCs, its impact on performance, and the methods employed to improve water management. The PEMFC's structure, including three phases: nucleation, bubble expansion, and implosion, is crucial for efficient proton exchange and transportation. The membrane structure, made of perfluorosulfonic acid polymer, is essential for efficiency and longevity. Usually, the anode and cathode electrodes are made of porous carbon that has been treated with platinum-based catalysts. Gas diffusion layers assist in getting rid of extra water that forms during the electrochemical reaction. Bipolar plates, on the other hand, get rid of heat and spread reactant gases through flow channels. Too much water in the anode can cause hot spots, shrinkage of the membrane, and dehydration, which can make the performance worse. To lower these dangers and make PEMFCs last longer, it is essential to use good water management methods, like gas diffusion layers and optimised flow field designs.

Flow channel issues with water are also crucial for cell efficiency. Overabundance of water can lead to diminished power output, increased resistance, and membrane desiccation. To improve the movement and distribution of water, people often employ advanced materials like hydrophilic-hydrophobic gradient GDLs and better flow field designs. Harsh working conditions and dehydration can have a significant effect on the energy performance and lifespan of PEMFCs. The system needs to be carefully developed and run to lessen these effects. Managing water is very important for the long life and efficiency of

PEMFCs. The GDL ensures that reactant gas and electron conduction transit occur quickly and easily, while also allowing water to flow. Vapour and liquid allocation are essential to move together to preserve everything in equilibrium and eliminate dehydration and flooding. The mode in which the GDL is built and how it works, such as its porosity, hole width, hydrophobicity, and compressibility when assembled, all have a significant impact on water flow through it. Recent studies have shown how crucial microstructural engineering is for better managing water in the GDL.

Water movement in the catalyst layer is also crucial for the efficiency and longevity of PEMFCs. The thin, porous CL contains generated water and water carried by electroosmotic drag. Effective water transport control within the CL is essential for cell durability and efficiency. Multi-physics models, including diffusion, electroosmotic drag, and capillary pressure, are commonly used in water transport simulations. Zero-dimensional models are useful for system-level simulations, fuel cell control systems, and built-in diagnostics, but do not account for geographical variables. Advanced modeling techniques for water management in PEMFCs include EIS-based water control, CFD, multiphase flow modeling, macrohomogeneous and patterned wettability models, one-dimensional, physics-based stack models, novel flow-field and flow plate designs via simulation, and porous electrode two-phase flow modeling.

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