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Review

Current Advancements in the Behavior Analysis of EPDM Elastomers in Peripheral Applications of the Cathodic Side of PEMFC Systems

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Abstract

This review examines the latest developments in the study of how Ethylene Propylene Diene Monomer (EPDM) elastomers behave in peripheral applications of Proton Exchange Membrane Fuel Cells (PEMFCs), specifically on the cathodic side. The review highlights the crucial role of EPDM in maintaining the integrity and efficiency of PEMFCs in challenging conditions characterized by varying temperatures, humidity, and acidic environments. The study examines the impact of various additives and vulcanization procedures on EPDM's mechanical and chemical properties, demonstrating enhancements in tensile strength, thermal stability, and chemical resistance. The study also investigates the compounding methods and selection of fillers, such as silica and carbon black, to optimize the performance of EPDM. Additionally, the effects of prolonged operational circumstances on EPDM's mechanical integrity and aging resistance in PEMFCs are being examined. This research emphasizes EPDM's suitability for long-term use in fuel cell systems. This review aims to guide the design of more durable and efficient PEMFC systems by optimizing the use of EPDM elastomers.

Keywords
EPDM elastomers; PEMFC systems; cathodic side applications; mechanical properties; chemical resistance; vulcanization methods; fuel cell durability

1. Introduction

The first successful demonstration of chemical energy transformed into electrical energy in a rudimentary fuel cell was made more than 160 years ago [1]. Building on the fundamental background of PEMFCs, notable progress was achieved in the mid-20th century. Pioneering work in the 1950s by Francis T. Bacon produced the alkaline fuel cell (AFC), essential for NASA's space missions. This era signified a change from theoretical research to pragmatic uses, most famously in the Gemini and Apollo missions, where fuel cells supplied water and necessary power. Concurrently, utilizing ion-exchange membranes, General Electric created the first PEMFC for the Gemini spacecraft of the United States Navy in 1960. These early systems laid the path for future technical developments and use in terrestrial and aeronautical power systems by proving the feasibility of fuel cells under challenging conditions [2, 3].

Driven by environmental issues and the search for renewable energy sources, PEMFC development was revived in the 1990s. Material science advances, especially DuPont's invention of Nafion® membranes, have revolutionized PEMFC performance by improving proton conductivity and durability. During this time, significant advances in catalysts, electrode design, and fuel cell stack engineering also helped to produce more commercially feasible PEMFC systems. These developments enabled PEMFC to use PEMFC outside of aerospace in the automotive, stationary, and portable power sectors. Driven by constant research and development meant to lower costs, increase performance, and widen the spectrum of applications, PEMFC technology is still developing today. Still, translating the early research experiments into commercial products with a realistic market price has proved difficult, even with fuel-cell technology's attractive system efficiency and environmental benefits [4].

PEMFCs' unique qualities- high power density, ruggedness, and fast start-up times- have found a broad spectrum of uses. The automobile sector is one of the PEMFCs most often used applications. PEMFCs run buses and electric cars (EVs), offering a green substitute for internal combustion engines. Since water vapor is the sole result of these zero-emission fuel cells, they are a pleasing way to help lower urban air pollution. Commercially available and aggressively pushed as part of a sustainable transportation plan, major automakers, including Toyota and Honda, have created fuel cell vehicles (FCVs) like the Mirai and Clarity, respectively. In the logistics industry, PEMFCs also run forklifts and other material-handling tools, particularly in refrigerated warehouses where their capacity to run well in sub-zero temperatures is a significant benefit [5-7].

Another vital use of PEMFCs is stationary power generation. Backup power sources for data centers, telecommunications towers, and other vital infrastructure needing consistent power sources use these systems. PEMFCs are perfect for places where pollution and noise are significant issues since they offer continuous power with low environmental effects. For these uses, companies including Plug Power and Ballard Power Systems have commercialized PEMFCs, providing systems ranging from small-scale units for home use to large-scale installations for industrial usage.

Moreover, PEMFCs are included in combined heat and power (CHP) systems, which supply both useful heat for buildings and electricity, improving the general energy economy. Driven by continuous material and system design to lower costs and enhance performance, PEMFC technology's adaptability keeps widening its application range [2, 3, 6-9].

Ethylene propylene diene monomer (EPDM) has emerged as a key material for sealing applications in PEMFCs due to its favorable mechanical and chemical properties, particularly its thermal and oxidative degradation resistance. EPDM's unique chemical structure combines diene functionality with a saturated backbone, which allows it to resist the demanding operating conditions expected on the cathodic side of PEMFC systems, where high humidity and acidic environments are common [5]. EPDM can thus show notable degradation even in opposition to thermo-oxidative aging when mechanical stress and chemical reactions with reactive species are present in the fuel cell environment [10]. The reliability and lifetime of PEMFC components rely on knowledge of the long-term behavior of EPDM under these circumstances.

Research has shown that EPDM undergoes less severe degradation in hydrogen-rich environments than in oxygen-rich environments, as hydrogen does not promote oxidation reactions that typically lead to chain scission and material embrittlement [11]. This characteristic makes EPDM a promising candidate for use in the cathodic side of PEMFCs, where it is often exposed to high pressures and variable temperatures. Nonetheless, EPDM’s performance can still be compromised by factors such as rapid gas decompression (RGD) and acidic by-products formed during the electrochemical reactions within the fuel cell [12, 13]. The use of fillers and additives in EPDM formulations has been investigated to reduce these problems and increase its mechanical stability under cyclic loading circumstances [14], enhancing its resistance to chemical aging. Better general performance of PEMFC gaskets resulting from these improvements should help EPDM to be more widely adopted in fuel cell technologies.

This work aims to investigate and evaluate the recent developments in the performance and durability of EPDM elastomers utilized as sealing materials in the cathodic side of PEMFCs. It emphasizes the mechanical and chemical characteristics of EPDM under the demanding conditions of temperature, humidity, and acidic environments typical of PEMFCs by means of the influence of many additives, curing processes, and environmental variables. This review intends to assist in the development of enhanced EPDM formulations and curing techniques to increase the long-term dependability and efficiency of PEMFC components by assessing current research findings and highlighting primary areas for optimization.

2. PEMFC Operational Conditions

2.1 PEMFC Working Principle

Proton Exchange Membrane Fuel Cells (PEMFCs) are increasingly being adopted in personal vehicles due to their efficiency and environmental benefits. Understanding their working principle is essential for grasping how they function as car power sources.

The basic operation of a PEMFC (Figure 1) involves a series of electrochemical processes that convert hydrogen fuel into electrical energy. The process begins with hydrogen gas being supplied to the anode (negative electrode). At the anode, hydrogen molecules (H_2) are catalytically split into protons (H^+) and electrons (e^-) using a platinum-based catalyst. The proton exchange membrane, a key fuel cell component, allows only the protons to pass through to the cathode (positive electrode).

Meanwhile, the electrons are directed through an external circuit, generating an electric current that can be used to power electrical devices.

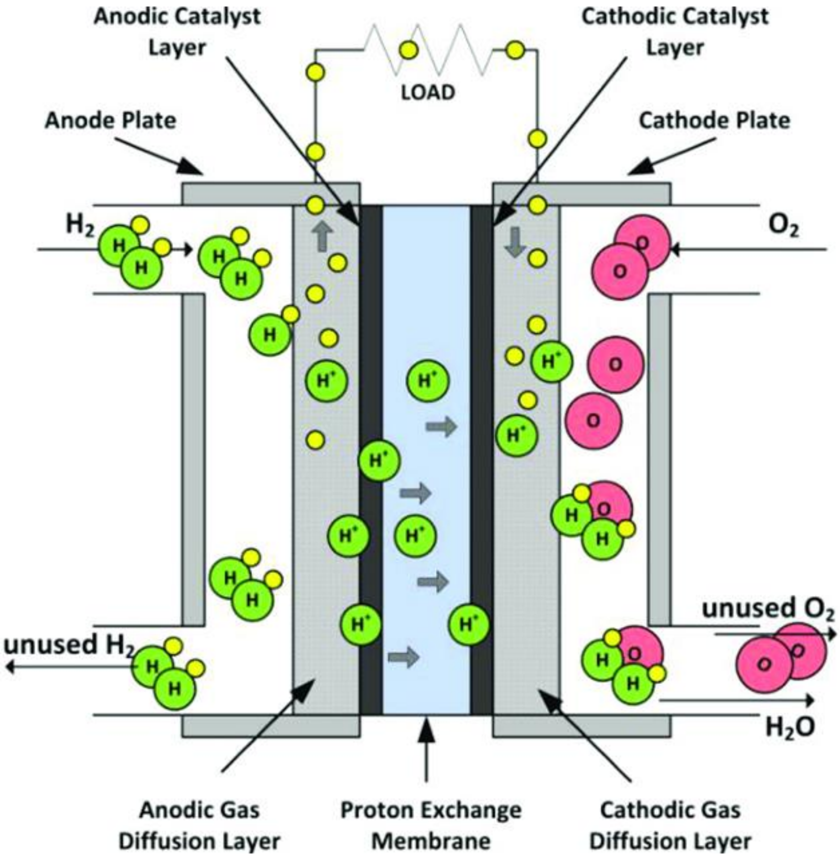

Figure 1 Proton Exchange Membrane Fuel Cell Schematic representation, taken from [15].

At the cathode, oxygen is typically sourced from the ambient combined with the protons that have diffused through the membrane and the electrons arriving via the external circuit. This results in the formation of water (H_2O) and releases heat as a byproducts of the electrochemical reaction. The overall chemical equation for the reaction is:

$$\mathrm{H_2} + \frac{1}{2}\mathrm{O_2} \rightarrow \mathrm{H_2O} + \text{electricity} + \text{heat}$$

This electrochemical process allows PEMFCs to directly convert chemical energy into electrical energy without combustion, resulting in higher efficiencies, often exceeding 60%, compared to the typical 20-30% efficiency achieved by conventional internal combustion engines. This high efficiency, combined with zero harmful emissions other than water, makes PEMFCs an attractive solution for both stationary and automotive energy applications.

2.2 Working Temperature

Proton Exchange Membrane Fuel Cells (PEMFCs) depend critically on their operating temperature, greatly affecting their lifetime, performance, and efficiency. The research on the effects of temperature and humidity indicates that PEMFCs usually run within 25-80°C. The chosen temperature range strikes a compromise between membrane hydration and reaction kinetics. Higher temperatures, toward the maximum limit of 80°C, usually improve the reaction kinetics, increasing the total fuel cell efficiency [16]. Excessive temperatures can hurt membrane performance, causing dehydration and reducing proton conductivity. This can also increase the likelihood of membrane degradation [16]. In addition, it is important to control the temperature to prevent performance degradation, as higher temperatures can lead to increased carbon corrosion rates [17, 18].

Temperature is crucial in deleting the Membrane Electrode Assembly (MEA) in PEMFCs. The research findings emphasize the impact of temperature and backpressure on the degradation rate of MEA. It is observed that operating temperatures within the range of 40-80°C have a significant influence on MEA degradation [19]. When exposed to higher temperatures, the catalyst and membrane material in the fuel cell deteriorate more quickly, resulting in a shorter lifespan for the fuel cell. For example, it was discovered that the electrochemical surface area of the catalyst layer decreased more rapidly at 80°C compared to 40°C, suggesting that catalyst degradation occurs more quickly at higher temperatures [19, 20]. In addition, temperature changes can lead to stress on the cell components, worsening performance. Therefore, it is crucial to ensure that the operating temperature of PEMFCs is maintained at an optimal and stable level to maximize their durability and efficiency [21, 22].

In addition, the impact of temperature on PEMFC performance is also noticeable when considering ambient and low-pressure environments, as summarized in Table 1. A study done by Werner et al. in 2015 investigating the operation of PEMFC under these conditions discovered that changes in operating temperature could impact the fuel cell's humidification. Proper humidification is essential for maintaining membrane hydration and promoting efficient proton conduction. Working with lower temperatures may necessitate extra humidification to avoid membrane drying. In contrast, higher temperatures can intensify the difficulties in managing water, potentially causing flooding or dehydration of the membrane [19].

Table 1 PEMFC Operating Temperature Data [18-21, 23].

Temperature (°C)	Proton Conductivity (S/cm)	Performance Degradation Rate (unitless)	Catalyst Degradation Rate (unitless)	Humidity Requirement (%)	Impact of Contaminants (performance loss %)
25	0.05	0.1	0.12	90	5
40	0.07	0.08	0.1	80	4
50	0.1	0.06	0.08	70	3
60	0.15	0.04	0.06	60	2
70	0.13	0.05	0.09	65	3
80	0.12	0.07	0.11	75	4

It was also found that the performance of PEMFCs can be influenced by contaminants, which are dependent on temperature. For example, the higher temperatures can cause increased reaction rates and the formation of harmful by-products, which can have a more pronounced detrimental effect on cell performance when NO_x and SO_x are present at ppm levels. Thus, it is crucial to effectively regulate the operating temperature and control humidity in order to maximize the performance and lifespan of PEMFCs in different environmental conditions [22, 24].

2.3 PEMFC Humidity

Maintaining the ideal performance and lifetime of Proton Exchange Membrane Fuel Cells (PEMFCs) depends on control of humidity. Usually during PEMFC operation, humidity levels fall between 50-90% relative humidity (RH). High proton conductivity and effective fuel cell operation depend on a sufficiently hydrated proton exchange membrane; hence, proper humidity conditions guarantee this. For instance, the proton conductivity of the membrane raised dramatically at 80% RH when compared to lower humidity levels, improving the fuel cell's general efficiency. On the other hand, too high humidity might induce water flooding inside the cell, obstructing the flow channels and gas diffusion layers, lowering the cell's efficiency and possibly damaging the membrane physically. On the other hand, low humidity can contribute to membrane dryness, raising resistance and lowering proton conductivity [20].

The research on the effects of temperature and humidity on PEMFCs emphasizes that ideal cell performance and durability depend on keeping a balanced humidity level. The membrane stays well-hydrated at increased humidity, which increases proton conduction and raises general cell efficiency. This has to be closely regulated to avoid water flooding, which can significantly compromise cell performance. For example, operating at a relative humidity of about 80% offered a decent balance, preserving membrane hydration and lowering the flood danger. Furthermore, the interplay between temperature and humidity is quite important. While at higher temperatures, the need for exact humidity control became even more important to prevent dehydration, the cell performance was optimal between 60°C and 80% RH (Figure 2). Further complicating water management inside the cell, too high humidity at lower temperatures-e.g., 25°C-can cause condensation and water pooling [20, 23, 25, 26].

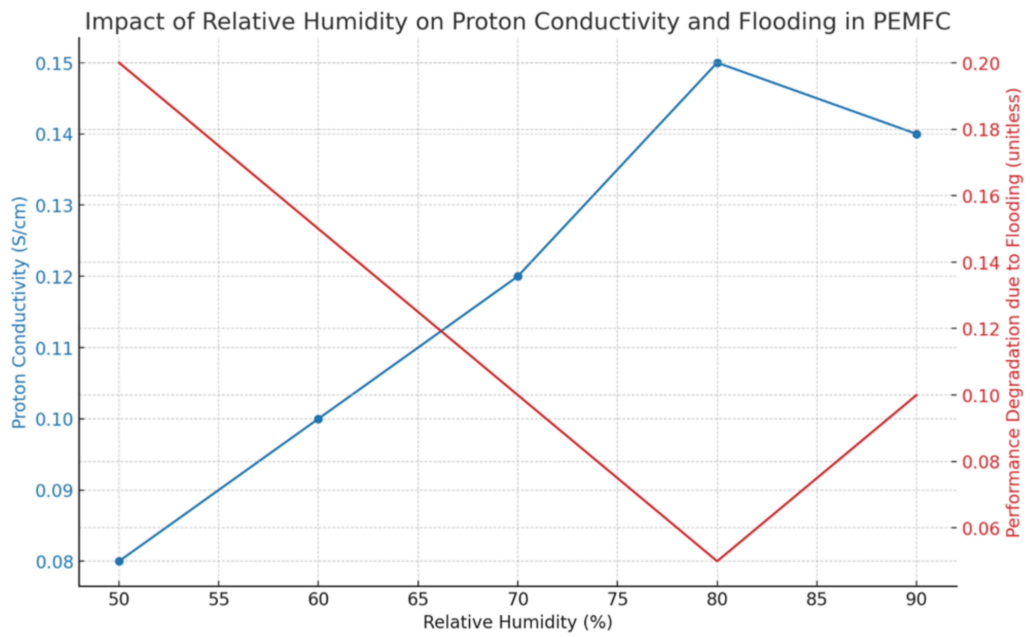

Figure 2 Impact of Relative Humidity on Proton Conductivity and Flooding in PEMFC [20, 23-24].

Moreover, the PEMFC's operational environment, which consists of external humidity conditions, can influence the internal humidity levels and cell performance. Variations in external humidity levels could affect internal humidification and general cell efficiency, according to the investigation on PEMFC operation in ambient and low-pressure conditions. Maintaining enough humidification becomes more difficult in low-pressure situations (e.g., 0.2-1 bar), for which improved water management techniques are necessary to guarantee the membrane stays hydrated. Under such circumstances, the internal humidity must be actively regulated to avoid membrane dehydration-observed to develop more quickly at lower pressures [23].

Preventing the adverse effects of airborne pollutants, such as NO_x and SO_x, which could aggravate membrane deterioration under different humidity levels, also depends on effective humidity control. To underline the complicated interaction between humidity and contaminant impacts, it was discovered, for instance, that pollutants at levels of 10 ppm had a more marked detrimental influence on cell performance at 60% RH compared to 80% RH. Thus, obtaining optimal performance and guaranteeing the lifetime of the fuel cell depends on controlling humidity inside the PEMFC in concert with other operating factors [24].

2.4 Hydrogen and Acidic Water Exposure in PEMFC

The materials utilized in PEMFCs are affected by hydrogen and acidic water exposure. Hydrogen and stress impacts on the electrochemical and passivation behavior of 304 stainless steel were investigated by Wang et al. 2019; levels of hydrogen exposure between 100 and 1000 ppm can significantly affect the electrochemical characteristics of the material. Under these circumstances, particularly under mechanical and thermal loads, the sensitivity of 304 stainless steel to corrosion rises. This result emphasizes the need to control hydrogen exposure to preserve the integrity of PEMFC components [27].

Materials like low-carbon steel have far higher rates of corrosion in acidic conditions. Studies on the corrosion behavior of coated low-carbon steel in simulated PEMFC systems found that the acidic conditions normal to PEMFC operation aggravate the corrosion process.

Avram et al. 2023 underlined how urgently suitable coatings are needed to guard against the consequences of hydrogen and acidic water contact. Without such precautions, the PEMFC's performance and lifetime may be seriously impaired [17].

Fluoride ions present in acidic surroundings hamper stainless steel corrosion resistance even more. Even low quantities of fluoride ions (0.1-10 ppm) could impair the surface of SS304, hence lowering its corrosion resistance, according to a study examining how fluoride ions affect the corrosion performance and surface attributes of SS304. This degradation seriously threatens PEMFC systems' long-term viability since the acidic water generated during fuel cell running frequently includes fluoride ions [16].

Another critical problem aggravated by hydrogen-rich PEMFC environments is carbon corrosion. Hydrogen exposure promotes the degradation of carbon-based components, which are essential for the structural integrity and efficiency of PEMFCs, according to a review done by Zhao et al. 2021 on carbon corrosion causes and mitigating techniques. The study underlined the requirement for efficient hydrogen management techniques to reduce carbon corrosion and increase the lifetime of fuel cell components [18].

The vulnerability of certain materials used in Proton Exchange Membrane Fuel Cells (PEMFCs) to hydrogen and acidic water corrosion is shown in Figure 3. Low Carbon Steel, SS304 in Fluoride Environment (UNS S30400), Graphite (Poco® Graphite), Carbon Cloth (Sigracet® 28BC), Carbon Paper (TGP-H-060), Titanium Grade 2 (UNS R50400), and Nickel Alloy 625 (UNS N0 6625). 304 Stainless Steel (UNS S30400) With impact values of 0.9, the graph shows that 304 Stainless Steel and Nickel Alloy 625 show the most excellent sensitivity to hydrogen exposure. Graphite, with an effect value of 0.75, demonstrates the lowest sensitivity to hydrogen instead. With a corrosion impact value of 0.9, acidic water corrosion affects Low Carbon Steel; Carbon Paper is the least impacted. The dual bar graph emphasizes choosing materials with low sensitivity to hydrogen exposure and acidic water corrosion to maximize PEMFC durability and efficiency.

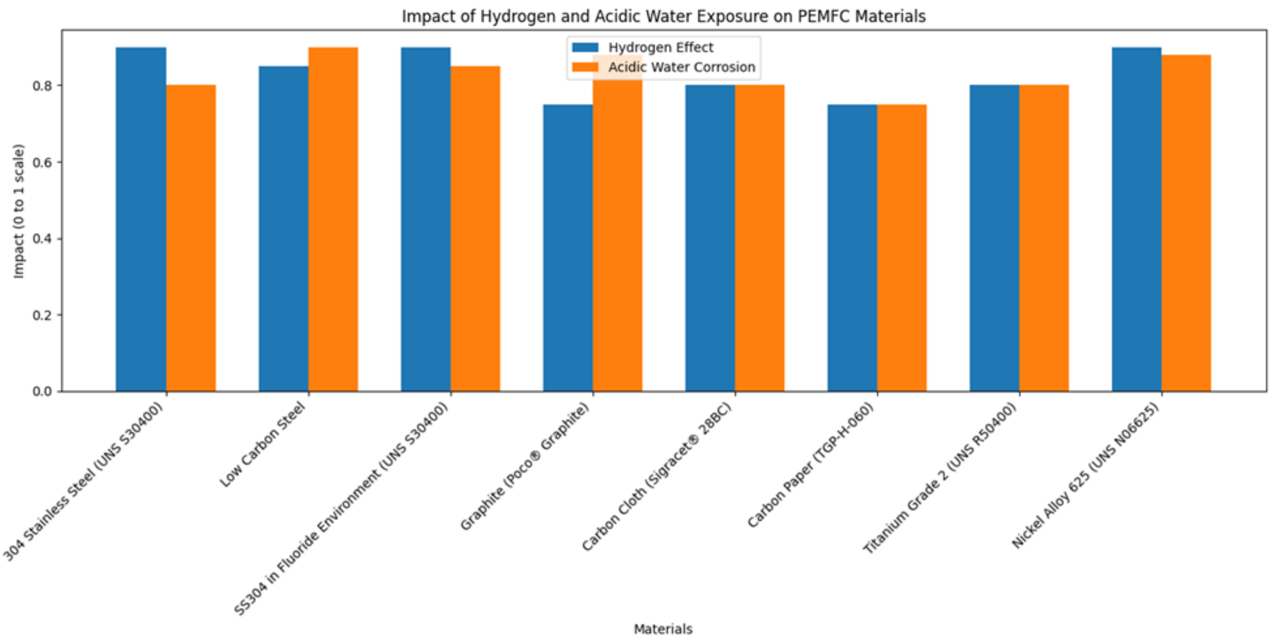

Figure 3 Impact of Hydrogen and Acidic Water Exposure on PEMFC Materials [16-18, 27, 28].

Operating factors like hydrogen exposure and acidic environments can hasten the corrosion of metallic bipolar plates and fundamental PEMFC components. Studies on the corrosion of metallic bipolar plates under simulated PEMFC cathode settings showed that these demanding circumstances could significantly raise the corrosion rates, therefore causing early failure of the plates [28-32].

2.5 Impact of Pressure and Humidification on PEMFC Performance

P EMFCs have different performance and lifetimes depending on the system's operational pressure and degree of humidification. PEMFCs usually operate in low-pressure settings, more precisely between 0.2 and 1 bar (absolute pressure). These pressure fluctuations are important since they directly influence the flow and distribution of reactant gases inside the fuel cell. Reduced diffusion rates of hydrogen and oxygen resulting from lower pressures could limit the general reaction rates and, hence, lower the fuel cell's power output [23]. On the other hand, higher pressures boost the electrochemical reaction rates and gas diffusion, but system components that resist the higher mechanical stresses are also needed [19].

Studies have revealed that when operating PEMFCs at lower pressures, such as 0.2 bar, careful humidification management is necessary to prevent membrane dryness. This can call for techniques to regulate the water vapor content, including outside humidifiers or changing the running temperature. Maintaining a somewhat higher temperature for the fuel cell, for instance, can aid in improving water vapor saturation and minimize membrane drying out [22]. However, This must be weighed against the possibility of overheating, which can cause membrane breakdown and lower fuel cell lifetime [26, 33].

On the other hand, running at greater pressures, like one bar, usually offers more freedom in preserving ideal humidity levels. Higher pressure keeps More water vapor inside the fuel cell, lowering the risk of dehydration. This does not, however, completely rule out the requirement of cautious water management as, with too high humidification levels, flooding remains a possibility. Effective water removal from the cell depends on advanced water management strategies, including hydrophobic treatments on gas diffusion layers and design optimization of flow fields, which preserve enough hydration for proton conduction [4]. Under different pressure and humidification settings, these steps enable PEMFCs to perform steadily and increase their operational lifetime.

The main conclusions of several experiments on the effect of pressure and humidity on PEMFC performance are compiled in Table 2. It offers comprehensive numerical data on pressure ranges (absolute pressure), ideal humidity levels, performance impact, and % performance decline. This data emphasizes the need to control pressure and humidity to maximize PEMFC lifetime and performance. For example, operating PEMFCs at lower pressures (0.2-1 bar) calls for ideal humidity to prevent dehydration; without it, the potential performance deterioration ranges from 10-15%. On the other hand, while it raises mechanical stress on components, increasing backpressure (0.5-3 bar) can enhance reaction rates by 5-10%. Maintaining performance and avoiding problems like floods or dehydration, which can cause performance deterioration ranging from 5-20% depending on the conditions, relies on efficient water management strategies comprising balanced humidification (50-80%) and improved materials.

Table 2 Detailed Findings on Pressure and Humidification in PEMFCs.

Paper	Pressure Range (bar)	Optimal Humidity (%)	Key Findings	Performance Degradation (%)
Characteristics of PEMFC operation in ambient- and low-pressure environments considering the fuel cell humidification [23]	0.2-1	60-80	Low pressures require careful humidification to prevent dehydration.	10-15% at low pressure without optimal humidification
Effects of temperature and backpressure on the performance degradation of MEA in PEMFC [19]	0.5-3	50-70	Higher backpressure improves reaction rates but increases mechanical stress.	5-10% improvement with increased backpressure

Effects of humidity and temperature on a proton exchange membrane fuel cell (PEMFC) stack [20]	0.5-2	50-80	Optimal membrane hydration is crucial to prevent flooding or dehydration.	15-20% due to improper humidity levels
Recent developments of proton exchange membranes for PEMFC: A review [25]	0.2-1	60-80	Proton conductivity is dependent on balanced humidification.	10-15% with balanced humidification
Investigation of the performance parameters for a PEMFC by thermodynamic analyses: Effects of operating temperature and pressure [22]	0.5-2	50-70	Operating temperature and pressure impact membrane hydration.	Varies based on temperature and pressure adjustments
PEMFC aging modeling for prognostics and health assessment [26]	0.2-1	60-80	Effective water management is critical for performance and longevity.	10-15% without effective water management
Materials for fuel-cell technologies [4]	0.5-3	50-70	Hydrophobic treatments help manage water and prevent flooding.	5-10% improvement with advanced materials

2.5.1 Backpressure in PEMFC Systems

In Proton Exchange Membrane Fuel Cells, backpressure is the pressure maintained at the fuel cell outlet-usually on the cathode side. Valves and other control devices are used to limit the exhaust gas flow. This pressure above the ambient atmospheric pressure is obtained, raising the pressure within the fuel cell system. Raising the partial pressure of the reactant gases operating the fuel cell at greater backpressures-usually within the range of 0.5 to 3 bar-absolute pressure dramatically improves the electrochemical reaction rates [23]. Higher power production and better fuel cell performance follow this reaction kinetics development. For instance, raising the backpressure to 2 bar has been demonstrated to improve the general efficiency by up to 10% since improved diffusion of hydrogen and oxygen into the catalyst layers [19] depends on greater pressure.

However, this advantage comes with a trade-off in additional mechanical stress on the cell components, which calls for more robust materials and designs to resist these circumstances [22]. If improperly controlled, the higher pressure might cause the Membrane Electrode Assembly (MEA) and other structural components to degrade faster. Furthermore, the rising backpressure calls for effective water management techniques to stop flooding since higher pressure can result in higher water output and buildup inside the cell [26, 33]. Excess water can cut the active area for electrochemical reactions and block the flow of reactant gases, lowering the fuel cell's performance. Maximizing PEMFC effectiveness under high backpressure circumstances requires careful balancing of the advantages of enhanced reaction rates with the difficulties of mechanical stress and water management [4].

Figure 4 shows how backpressure relates to general PEMFC performance. The graph shows that, with the peak efficiency noted at about 2 bars, raising backpressure usually increases general efficiency up to a point. More especially, the general efficiency rises from 85% at 0.5 bar to 93% at 2 bars. Beyond this, further increases in backpressure cause a modest decrease in efficiency; values drop to 92% at 2.5 bars and 91% at 3 bars. The rising mechanical stress and possible flooding problems related to higher backpressure (6) most certainly contribute to this drop.

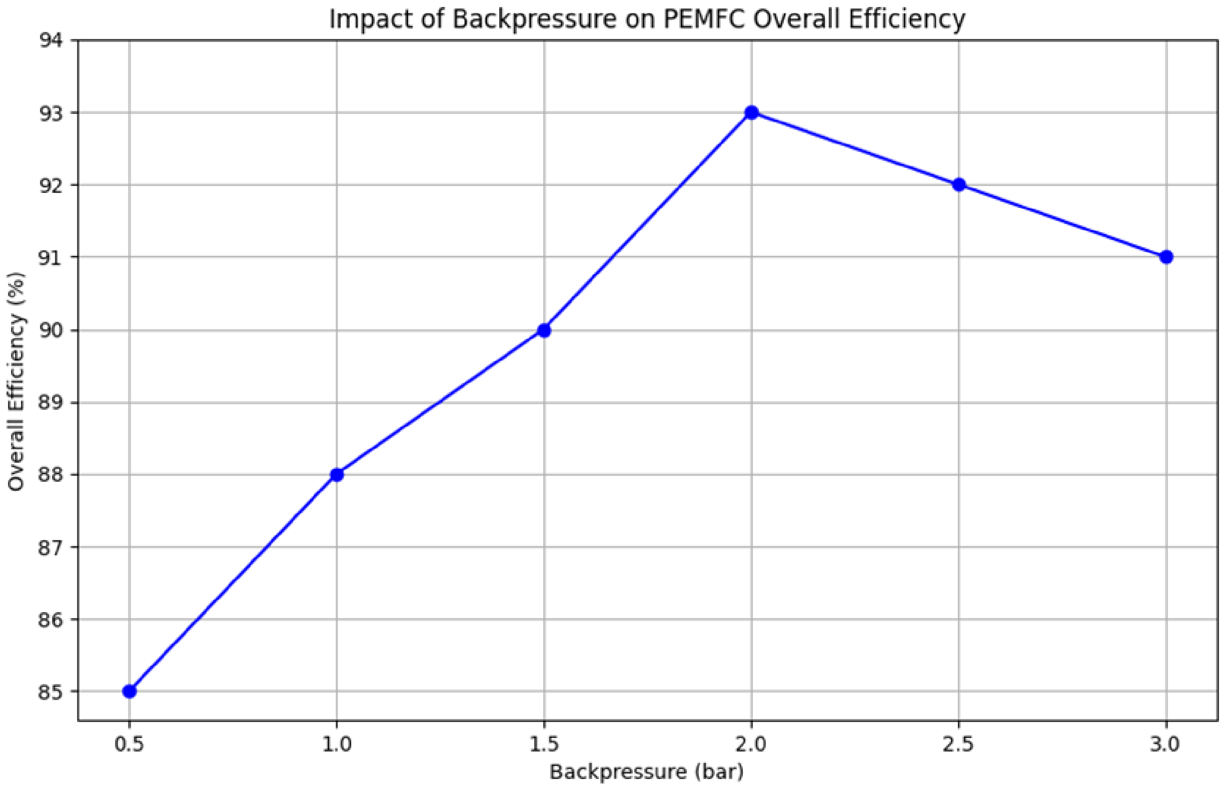

Figure 4 Backpressure vs Overall PEMFC Efficiency [19, 22, 23].

This information emphasizes the need to maximize backpressure to achieve optimal performance in PEMFCs. Although increasing backpressure can increase efficiency and reaction rates, controlling related mechanical and water management issues is necessary to stop performance degradation. The long life and effectiveness of PEMFC systems depend on the harmony between several elements.

Understanding and controlling the limitations of the PEMFC application, such as pressure, humidification, and material durability, will help extend the fuel cell's operational life and ensure performance. These limitations are evident on the cathodic side of the PEMFC, where the surroundings are rather reactive and prone to severe occurrences. Working under certain pressure and humidity that can cause mechanical stress and possibly material corrosion, the cathodic side, in charge of reducing oxygen levels and generating water, works.

Choosing suitable materials for auxiliary components, such as seals and gaskets, will help solve these problems. Excellent resistance to heat, oxidation, and chemical degradation makes ethylene propylene diene monomer (EPDM) rubber generally used for cathodic side sealing needs. The integrity of the fuel cell is mainly dependent on EPDM seals, which prevent leaks and guarantee that the created reactive gases and water never exit the system. This is especially crucial in the high-pressure and humid environment of the cathode since robust sealing solutions to withstand the operational pressures determine the dependability of the long-term functionality of the PEMFC. PEMFC technology will obtain ideal efficiency and durability by educating the user about the behavior and performance of EPDM under particular conditions.

3. Cathode Side Application Requirements

Although the overall criteria for maximizing PEMFC performance center mainly on the whole fuel cell stack - addressing issues including temperature management, humidification, pressure control, and material durability - the cathodic side presents its own special set of problems and conditions that require particular attention. Under conditions intrinsically more reactive and prone to specific issues, including water management, gas diffusion, and chemical stability, the cathode environment, responsible for reducing oxygen and generating water, operates. Although the anode side broadly addresses hydrogen oxidation, the cathode side must efficiently manage oxygen reduction while limiting the negative repercussions of water creation and preservation of appropriate humidity and pH levels. These various demands for materials and operating situations call for a tailored solution to ensure the dependability and efficiency of the cathode, therefore supporting the general performance and longevity of the PEMFC system.

The cathodic side of PEMFCs is operated in particular circumstances necessary for longevity and optimal performance. Maintaining the temperature within the 70-80°C range is essential for effective electrochemical reactions; this also helps to prevent overheating, thus avoiding damage to the membrane and other components. Running at appropriate temperatures provides favorable reaction kinetics, increasing the general efficiency of the fuel cell [34-36].

Another crucial factor is the control of humidity. Enough hydration guarantees high proton conductivity of the proton exchange membrane. Usually between 50 and 80%, ideal humidity levels help prevent the membrane from drying out, thus preventing ohmic resistance; they also help to decrease water flooding, reducing active catalytic sites. Effective water management methods define stable operation and balance of different humidity levels [34, 37, 38].

The pressure the compressor generates on the cathodic side determines the improvement in gas diffusion and reaction speeds. Usually, the running pressures lie between 0.2 and 3 bars. Higher pressures raise oxygen diffusion into the catalyst layer, increasing the reaction rates and general power generation. Therefore, strong materials are required to withstand these conditions, resulting in increased mechanical stress on the components of the components of the system [35, 39, 40].

Maintaining the pH of the water produced at the cathode is also essential. The perfect pH range covers four to seven. Maintaining the pH in this range guarantees the lifetime and durability of the PEMFC since it helps limit the corrosion and deterioration of cathode materials. This requires careful monitoring and control of the chemical environment inside the cell to avoid extreme acidic or basic conditions that can accelerate material degradation [3, 37]. The main requirements for the cathodic side of a PEMFC can be found in Table 3.

Table 3 Cathodic Side Requirements [34-39].

Requirement	Optimal Range/Values	Effects on Performance
Temperature	70-80°C	Optimal temperature ensures efficient electrochemical reactions and prevents overheating.
Humidity	50-80%	Balanced humidity prevents membrane dehydration and water flooding, ensuring stable proton conductivity.
Pressure	0.2-3 bar	Appropriate pressure improves gas diffusion and reaction rates but requires robust materials to withstand stress.
Water pH	4-7	Maintaining pH levels prevents corrosion and degradation of cathode materials, ensuring longevity.

Optimizing the lifetime and overall performance of Proton Exchange Membrane Fuel Cells (PEMFCs) depends on complete awareness of general operational needs, including pressure, humidification, and material selection. Effective electrochemical reactions and preservation of structural integrity under different operational situations depend on these elements, which are of great importance. High reactivity and continual water production define the cathodic environment, which calls for materials and designs that can resist increased mechanical stress and possible corrosive environments. This specific fuel cell section requires firm answers to stop leaks, control water output, and maintain constant performance under changing pressure and humidity levels. Examining the requirements of the cathode side, we concentrate on the critical function of Ethylene Propylene Diene Monomer (EPDM) rubber, a material known for its resistance to heat, oxidation, and chemical degradation, making it ideal for sealing uses in this demanding environment.

4. EPDMs for the Cathodic Side of PEMFC

Ethylene propylene diene monomer (EPDM) rubber is a very flexible elastomer with excellent resistance to heat, oxidation, and various chemical exposures. Especially on the cathodic side, where the environment is highly reactive and prone to harsh conditions, these characteristics make EPDM the ideal material for sealing needs in Proton Exchange Membrane Fuel Cells (PEMFCs). Materials that can withstand high temperatures, variable humidity levels, and acidic surroundings are quite important as PEMFCs' cathodic side oversees generating water and reducing oxygen levels. The specific criteria of this environment need the use of advanced EPDM formulations capable of ensuring dependability, performance, and durability.

Combining the base polymer with many additives compounding EPDM helps to enhance its mechanical, chemical, and physical properties. To effectively address their responsibilities, this chapter investigates the critical components of EPDM compounding fillers, vulcanizing agents, plasticizers, and nanofillers. It also investigates EPDM performance using several curing techniques and optimizing approaches. By means of analysis of recent research and developments in EPDM compounding, this chapter aims to provide a thorough knowledge of how tailored EPDM formulations can meet the demanding standards of the cathodic side in PEMFCs, thereby contributing to the general efficiency and longevity of the fuel cell systems.

Compared to other elastomeric materials that could be a viable solution in PEMFC, the impact of PEMFC operating conditions on the properties of EPDM differs from the impact on FKM and NBR (Figure 5). The tensile strength of EPDM showed a moderate decrease of around 15% under PEMFC conditions, while FKM and NBR experienced higher reductions of 30% and 25%, respectively. This indicates that EPDM is more resistant to mechanical property degradation than the other materials studied [11]. Additionally, the compression set, which measures the material's ability to recover its original shape after compression, increased by 10% for EPDM, while FKM and NBR exhibited increases of 25% and 20%, respectively [10]. Furthermore, volume swelling due to hydrogen absorption and permeation was relatively lower for EPDM (5%) compared to FKM (15%) and NBR (10%), suggesting that EPDM has better resistance to hydrogen-induced swelling and mechanical degradation [12].

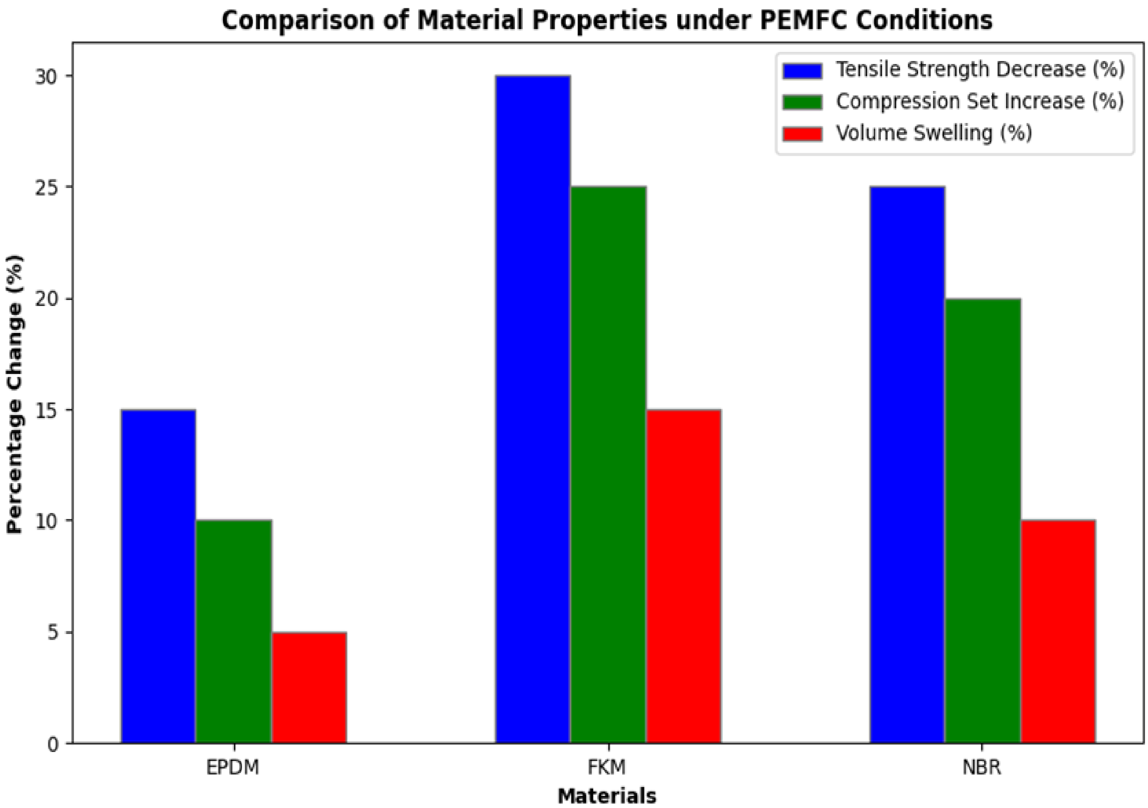

Figure 5 Comparison of the effect of PEMFC conditions on EPDM, FKM and NBR.

4.1 EPDM Compounding

4.1.1 Base Polymer

The base polymer of EPDM consists of ethylene, propylene, and a diene monomer that provides locations for cross-linking. The selection of specific diene monomers, such as ethylidene norbornene (ENB), dicyclopentadiene (DCPD), and 1,4-hexadiene, significantly impacts the overall properties of the EPDM molecule. While propylene units contribute to flexibility and low-temperature performance, a higher ethylene content in the polymer enhances tensile strength and weather resistance [41]. Research has shown that using ENB as a diene monomer enhances EPDM's overall robustness and resilience in challenging environments [42].

4.1.2 Fillers and Additives

Modifying the properties of EPDM for specific applications relies on the incorporation of fillers and additives. Carbon black is frequently utilized as a filler in EPDM formulations due to its ability to enhance strength, abrasion resistance, and electrical conductivity. Typically, the optimal carbon black level is around 65 parts per hundred rubber (phr), which significantly improves the mechanical properties and allows for achieving tensile strengths of up to 14 MPa [43]. Furthermore, studies have demonstrated that adding carbon black to EPDM can enhance its ability to withstand high temperatures, making it suitable for applications requiring elevated heat resistance. An example of a V-ribbed belt design with 65 parts per hundred of carbon black and 5 parts per hundred of nylon fiber demonstrated improved tensile strength and thermal stability [44].

Another important additive is silica, which reduces the permeability of gases and liquids while enhancing tear resistance and tensile strength. Silica-filled EPDM is a material that has improved mechanical properties and is specifically designed for sealing applications where it is important to prevent the passage of gas and liquid. Studies have demonstrated that using silica fillers in EPDM formulations significantly reduces gas permeability, enhancing the material's suitability for applications in PEMFCs where maintaining gas tightness is crucial [45]. In addition, clays and talc are used as fillers to provide additional mechanical reinforcement and improve processing characteristics. This contributes to the overall durability and performance of the EPDM compound [46].

When used in EPDM formulations, plasticizers enhance the ease of processing and the material's flexibility. Paraffinic and naphthenic oils are commonly employed plasticizers to enhance EPDM's low-temperature performance and elongation. Furthermore, phthalates and esters are utilized to improve flexibility and facilitate processing. For example, the intentional selection and fine-tuning of plasticizers to maintain flexibility and performance in extremely low temperatures contributes to the production of EPDM with exceptional resilience to cold. Studies on EPDM compounds with optimal plasticizer content indicate that they exhibit significantly improved cold resistance, consequently maintaining their mechanical integrity and flexibility even at temperatures as low as -40°C [47].

Antioxidants and antiozonants are necessary additives that protect the EPDM component against oxidative and ozone damage, prolonging the seal's lifespan. In challenging environmental circumstances, these additives maintain the structural integrity of the EPDM material and prevent the formation of cracks. Through the utilization of advanced techniques such as Fourier-transform infrared spectroscopy (FT-IR), these additives can be comprehensively analyzed, ensuring optimal formulation. FT-IR analysis allows for the examination of chemical interactions and stability of antioxidants and antiozonants inside the EPDM matrix. This information can guide the formulation process to achieve the best protection against oxidative and ozone-induced degradation [48].

Figure 6 displays the mechanical properties of EPDM with different compounding. EPDM is commonly used as the benchmark for comparison, typically exhibiting moderate mechanical properties. The material demonstrates a tensile strength of around 10 megapascals (MPa), elongation at the point of fracture of about 300%, and a hardness of 50 Shore A. These attributes make it suitable for a broad range of uses. Nevertheless, it is crucial to make enhancements in order to fulfill the demands of more demanding scenarios, such as the cathodic side of PEMFCs. Adding 65 parts per hundred rubber (phr) of carbon black significantly improves the mechanical properties of EPDM. Carbon black is a frequently used additive highly recognized for its ability to enhance strength, durability, and electrical conductivity. The tensile strength of standard EPDM exhibits a significant enhancement, increasing from 10 MPa to 14 MPa, yielding a notable 40% improvement. The enhancement is attributed to the reinforcing influence of carbon black, which bolsters the strength of the polymer matrix. Furthermore, the elongation at break significantly rises to 350%, indicating superior flexibility. The material's hardness also increases to 60 Shore A, indicating that it is more resilient and better suited for high-stress applications [41, 43, 44].

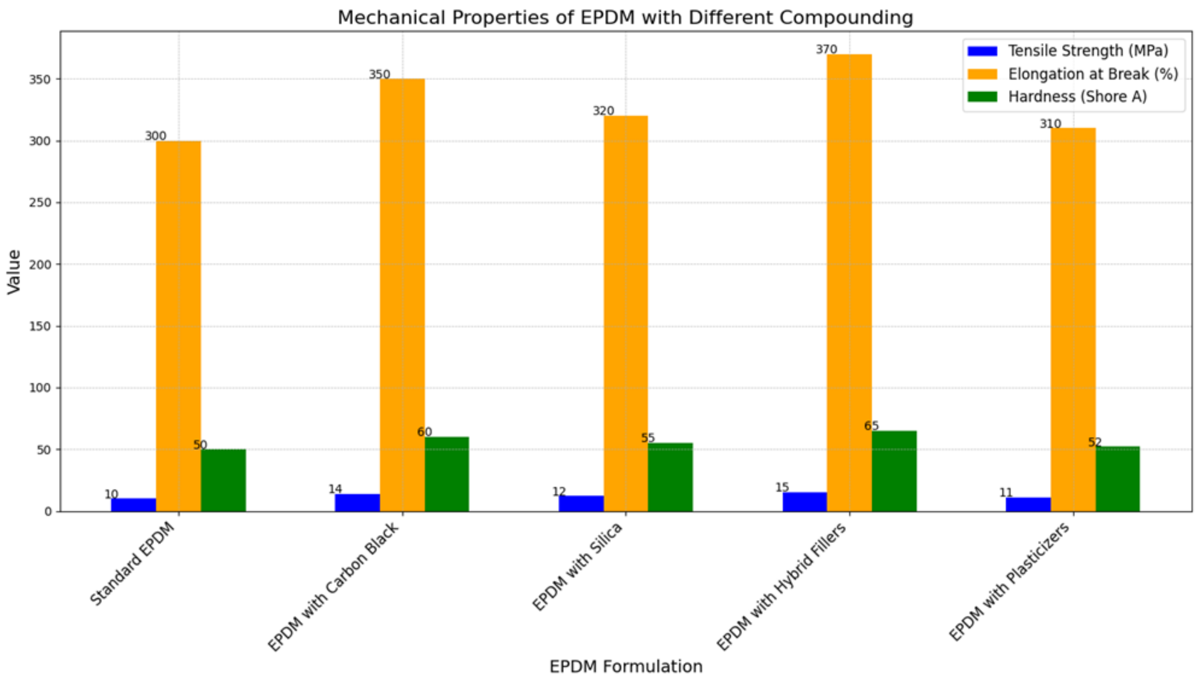

Figure 6 Mechanical Properties of EPDM with different Compounding.

Silica is a notable addition that improves the ability of a material to withstand tearing and stretching while reducing its permeability to gases and liquids. EPDM exhibits a tensile strength of 12 MPa when silica is added, representing a 20% enhancement compared to standard EPDM. The elongation at the point of fracture rises to 320%, while the hardness level increases to 55 Shore A. Silica-filled EPDM exhibits properties that make it very suitable for applications requiring a blend of robustness and flexibility. In addition, it has the benefit of reduced gas permeability, a crucial factor for effectively sealing applications in PEMFCs [45, 46].

Combining carbon black and carbon nanotubes in hybrid fillers exhibits a synergistic effect, enhancing EPDM's physical and mechanical properties. When hybrid fillers are added to the EPDM material, it shows a remarkable tensile strength of 15 MPa, which is 50% greater than that of standard EPDM. The material has excellent flexibility, as evidenced by its elongation at a break of 370%. Furthermore, the material's hardness surpasses that of the other tested formulations, measuring 65 Shore A. Hybrid-filled EPDM is an ideal choice for demanding applications that necessitate both durability and flexibility due to its distinctive combination of characteristics [44].

Paraffinic and naphthenic oils, commonly used as plasticizers, improve elongation and boost performance in cold conditions. When coupled with plasticizers, EPDM demonstrates a significant improvement in tensile strength, reaching 11 MPa, and elongation at break, reaching 310%. The hardness demonstrates a slight elevation to 52 Shore A. These characteristics indicate that plasticizers enhance flexibility and facilitate processing, but they have a limited effect on tensile strength and hardness compared to other fillers like carbon black or silica [47, 49, 50].

4.1.3 EPDMs Specifically Designed for Use in Proton Exchange Membrane Fuel Cells (PEMFC)

To create EPDM formulations designed explicitly for PEMFC applications, it is necessary to enhance the base polymer and additive combinations to meet the stringent requirements of the cathodic environment. In order to maintain both flexibility and performance at extremely low temperatures, EPDM compounds designed for high resistance to cold temperatures incorporate certain additives and plasticizers. Research has shown that certain EPDM formulations have exceptional cold resistance, enhancing temperature resilience measures. EPDM compounds formulated with optimal plasticizer content and specific cross-linking agents maintained mechanical integrity and flexibility even at temperatures as low as -40°C [12, 51-54].

Additionally, it is crucial to focus on advancing EPDM compounds that can withstand chemical degradation in acidic environments. Studies have demonstrated that the chemical resistance of EPDM is greatly affected by its cross-linked structure. To enhance the material's resistance to acidic environments commonly seen on the cathodic side of PEMFCs, one can improve its durability by optimizing the cross-link density and selecting an appropriate cross-linking agent. Research has demonstrated that using peroxide as a vulcanizing agent enhances EPDM's mechanical properties and chemical durability, making it better suited for acidic environments. Peroxide-cured EPDM compounds showed exceptional chemical degradation resistance and maintained their mechanical integrity even after prolonged exposure to an acidic environment [55]. This topic will be covered more broadly in the next sub-chapter.

Typically, combining EPDM for PEMFC requires a deep understanding of the interplay between various components and the operating environment. The dependability and effectiveness of PEMFC systems are ensured using new compounding procedures and compositions to develop EPDM materials with remarkable performance and durability. The continuous research and development of EPDM compounding provides a means to achieve the required quality and performance characteristics for the challenging conditions of PEMFC applications.

4.2 Vulcanization Methods for EPDM

Vulcanization is a crucial process in producing EPDM rubber, as it significantly enhances the material's mechanical properties, chemical resistance, and durability. Two types of vulcanization methods are primarily used for EPDM: sulfur vulcanization and peroxide vulcanization. Each method has distinct advantages and is selected based on the specific application requirements.

4.2.1 Sulfur Vulcanization

Sulfur vulcanization is the most used method for cross-linking EPDM. It involves the addition of sulfur and accelerators to the EPDM compound, which then forms cross-links between the polymer chains during the curing process. This method produces EPDM with excellent mechanical properties, such as high tensile strength and elasticity. The process is typically carried out at temperatures between 140°C and 160°C. A study involving the kinetic finite element model showed that optimizing the sulfur vulcanization process could significantly enhance the performance of EPDM weather strips, leading to improved durability and mechanical properties [41, 56]. However, sulfur vulcanization may not be suitable for applications requiring high-temperature stability, as the sulfur cross-links can degrade at elevated temperatures.

4.2.2 Peroxide Vulcanization

Peroxide vulcanization is an alternative method that involves the use of organic peroxides as cross-linking agents. This method produces EPDM with superior thermal stability and resistance to oxidative degradation compared to sulfur vulcanization. Peroxide-cured EPDM is preferred for applications that require high-temperature performance and excellent chemical resistance. The process typically involves curing at temperatures between 150°C and 180°C. Research has shown that peroxide vulcanization enhances EPDM's chemical stability and mechanical properties, making it suitable for acidic environments commonly found on the cathodic side of PEMFCs [42, 57]. However, peroxide vulcanization can result in lower elongation at break compared to sulfur-cured EPDM, which may be a consideration for applications requiring high flexibility.

Figure 7 compares the mechanical and chemical characteristics of EPDM that have been vulcanized using sulfur and peroxide. EPDM, which has undergone sulfur vulcanization, is well-suited for applications that require strong and flexible materials since it exhibits superior tensile strength (14 MPa) and elongation at break (350%). However, its chemical resistance is only moderate, and its thermal stability experiences a slight decrease around 160°C. At a temperature of 180°C, EPDM that has been vulcanized with peroxide exhibits exceptional thermal stability and greater chemical resistance, categorized as high. Due to its superior thermal and chemical characteristics, this material is highly suitable for applications that demand resistance to elevated temperatures and corrosive surroundings, although having lower tensile strength (12 MPa) and elongation at break (300%).

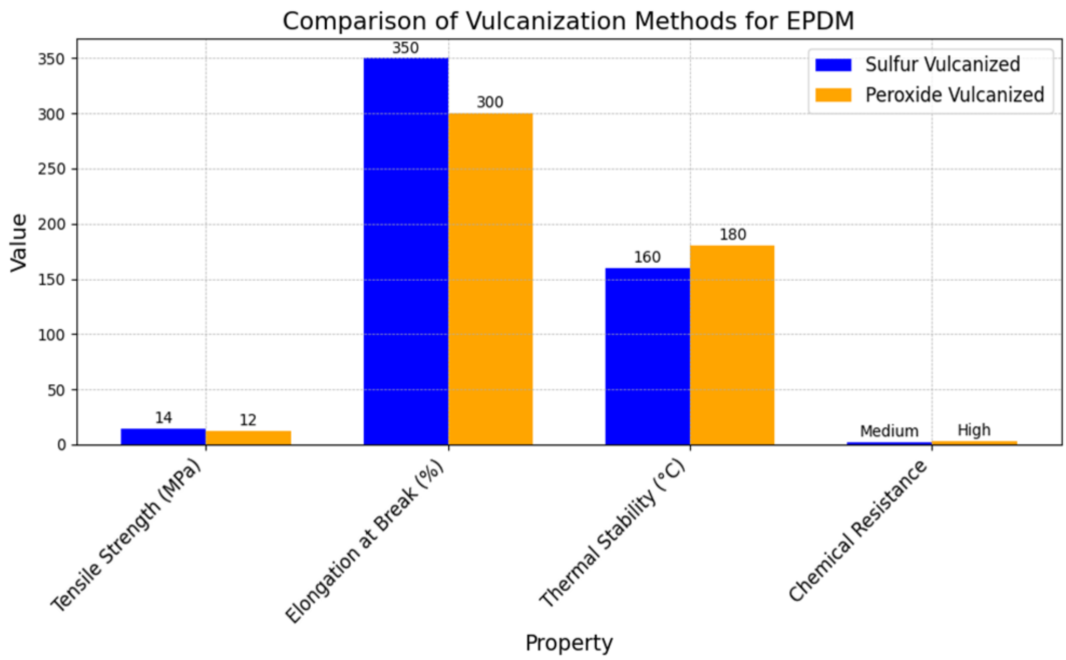

Figure 7 Comparison of EPDM properties with different vulcanization methods [42, 45, 46, 49, 55-60].

4.3 EPDM Compatibility with PEMFC Generated Media

EPDM is primarily utilized as a gasket material. Gaskets in PEMFCs play a crucial role in maintaining cell integrity by preventing gas leaks and ensuring proper compression. The highly reactive environment within PEMFCs, characterized by elevated temperatures, acidic conditions, and fluctuating humidity levels, poses significant challenges for gasket materials. Ensuring the long-term strength and effectiveness of the fuel cells relies heavily on the compatibility between EPDM and the medium produced by PEMFC.

EPDM's mechanical and chemical stability in simulated PEMFC systems has been extensively investigated. The robustness of EPDM as a gasket material is demonstrated by its ability to withstand slight changes in indentation force and elastic modulus even in challenging settings [61]. Furthermore, EPDM is a highly recommended option for sealing applications due to its superior stability compared to alternative elastomers in acidic conditions commonly seen in PEMFCs [12]. Extended aging investigations have demonstrated that EPDM retains its dynamic mechanical properties, including storage modulus and glass transition temperature (Tg), even after prolonged exposure to PEMFC. The reliability and effectiveness of fuel cells throughout their operational lifespan are contingent upon preserving their inherent attributes. In addition to enhancing EPDM's mechanical properties and durability in high-pressure hydrogen conditions, which are frequently encountered in PEMFC applications, the use of certain additives, such as carbon black (CB), can be beneficial [62].

4.3.1 PEMFC Environment Effect on Mechanical Characteristics of EPDM

<u>Microindentation and dynamic mechanical analysis (DMA) results.</u> The mechanical properties of EPDM gaskets play a crucial role in ensuring the structural integrity and sealing effectiveness of fuel cells in PEMFC systems. Microindentation and Dynamic Mechanical Analysis (DMA) have been utilized in numerous studies to evaluate the mechanical durability of EPDM under simulated conditions resembling those of a PEMFC.

Microindentation tests have demonstrated that EPDM exhibits minimal indentation load and elastic elasticity alterations, even after prolonged exposure to simulated PEMFC conditions. An investigation conducted on EPDM subjected to an Accelerated Durability Test (ADT) solution containing 1M H_2SO_4 and 10 ppm HF at temperatures of 60°C and 80°C demonstrated that EPDM maintained its mechanical integrity with little alterations in indentation load and elastic modulus [61, 63]. This outcome demonstrates that EPDM can withstand the acidic conditions often found on the cathodic side of PEMFCs without significant mechanical degradation. In addition, EPDM exhibited superior stability compared to other elastomers, such as fluoroelastomers, which showed more pronounced deterioration under identical conditions [61].

DMA provides further insight into the dynamic mechanical behavior of EPDM. In one study, EPDM samples were subjected to aging in a simulated PEMFC environment. The investigation involved recording the samples' storage modulus (E') and loss modulus (E'') over time. The investigations demonstrated that EPDM retained its storage modulus and exhibited a steady glass transition temperature (Tg), which is essential for maintaining flexibility and robustness in fuel cell applications. The stable loss modulus, which indicates the dissipation of energy inside the material, further suggests that EPDM can effectively absorb and dissipate mechanical loads without producing significant structural alteration. The stability of dynamic mechanical properties is crucial for ensuring the gaskets' effective functioning throughout the working lifetime of the PEMFC [51, 64-66].

Study on the process of aging and the ability to withstand wear and tear. The comprehension of the reliability and durability of EPDM gaskets in PEMFC systems relies on extensive research on long-term aging. Research has shown that EPDM maintains its mechanical properties for extended periods, even in the challenging circumstances of PEMFC environments. EPDM samples subjected to thermal aging at a temperature of 80°C for 63 weeks exhibited very slight alterations in their dynamic mechanical properties, such as storage modulus and glass transition temperature (Tg). This demonstrates that EPDM is suitable for prolonged PEMFC use [65]. Another study shows the preservation of mechanical properties, such as tensile strength and elongation at break, under prolonged circumstances of PEMFC, thereby reinforcing previous findings.

Furthermore, the influence of different curing processes on the aging resistance of EPDM has been examined. Observations revealed that EPDM cured with peroxide exhibited superior resistance to aging and better preservation of its mechanical properties than EPDM cured with sulfur. The enhanced oxidative degradation and thermal aging resistance in peroxide-cured EPDM were attributed to the development of more robust cross-link networks [14]. The importance of selecting appropriate vulcanization procedures for EPDM utilized in PEMFC applications is emphasized by improved mechanical properties and resistance to chemical aging achieved with effective curing systems.

In addition to temperature and chemical exposure, researchers have also studied the effects of high-pressure hydrogen environments on EPDM. Using smaller particle size carbon black (CB) fillers in EPDM enhanced resistance to high-pressure hydrogen, resulting in reduced volume expansion and mitigating physical property degradation. This development holds particular significance for PEMFC applications, where mechanical integrity and hydrogen permeability are critical factors to consider [62]. In addition, the incorporation of carbon black (CB) into EPDM formulations enhances the ability to withstand repeated pressure cycles, perhaps preventing damage progression in EPDM without fillers [52], thereby improving mechanical strength. Although CB-filled EPDM exhibited superior resilience under the same conditions, research has demonstrated that pressure cycling can induce microcracks and subsequent mechanical breakdown in unfilled EPDM, Figure 8 [67].

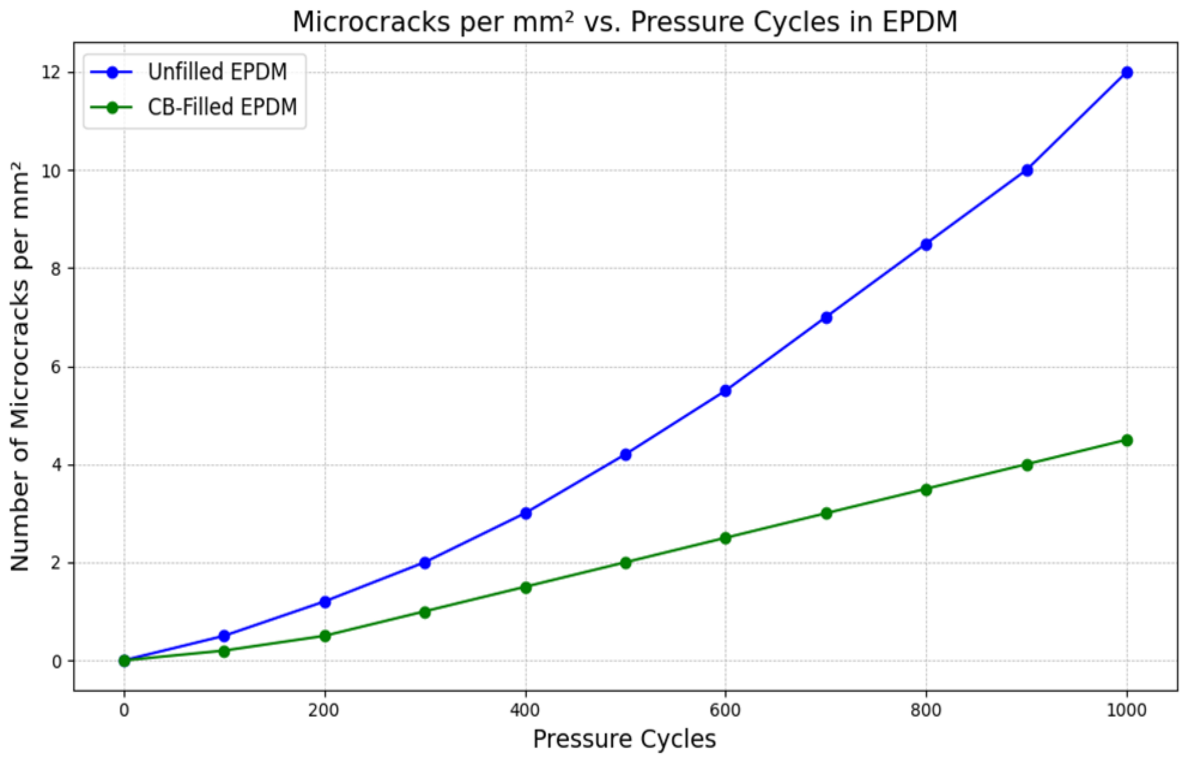

Figure 8 Microcracks per mm^2 vs pressure cycles in EPDM, based on [67].

4.3.2 Chemical Degradation in Acidic Environments

The cathodic side of PEMFCs can undergo substantial chemical deterioration under typical operating conditions, which involves the presence of hydrofluoric acid (HF) and sulfuric acid (H_2SO_4). The durability and lifespan of PEMFC systems are contingent upon the chemical stability of EPDM in such settings.

A detailed investigation of EPDM degradation in simulated PEMFC systems has been conducted. Researchers investigated the chemical resilience of EPDM by subjecting it to an Accelerated Durability Test (ADT) solution containing 1M H_2SO_4 and 10 ppm HF at temperatures of 60°C and 80°C. The findings demonstrated that EPDM exhibited remarkable chemical stability under demanding conditions, as evidenced by minimal fluctuations in its mechanical properties, such as indentation stress and elastic modulus [61, 68]. EPDM demonstrates the ability to sustain its structural integrity and functionality in the acidic environment of PEMFCs.

Subsequent research has demonstrated that various fillers and additives enhance EPDM's chemical stability. The addition of carbon black (CB) fillers has significantly improved the chemical resistance of EPDM. An experiment conducted under identical acidic conditions showed that EPDM including CB fillers, exhibited more excellent stability than EPDM without any fillers. The decreased volume expansion and physical property degradation indicate the presence of CB [62], indicating a reduction in chemical degradation. The advancement can be attributed to the enhancing impact of CB, which enhances the polymer matrix and offers further resistance to acid corrosion.

Moreover, extensive research has been conducted to examine the influence of various curing techniques on the chemical resilience of EPDM. When comparing peroxide-cured EPDM to sulfur-cured EPDM, it has been observed that the former exhibits superior resistance to chemical degradation. EPDM treated with peroxide results in the formation of more stable cross-link networks, leading to enhanced resistance against oxidative degradation and acid corrosion. Studies on peroxide-cured EPDM indicate that, when exposed to acidic conditions for an extended duration, it retains its mechanical qualities more effectively than sulfur-cured EPDM [14]. It is essential to use suitable curing processes to enhance the chemical durability of EPDM for its application in PEMFCs.

EPDM exhibits exceptional chemical resistance under the typically acidic conditions seen on the cathodic side of PEMFCs. EPDM is a dependable material for extended use in PEMFC gaskets due to its peroxide curing procedures and the inclusion of carbon black, which enhances its chemical resistance.

4.4 Recycling Strategies for EPDMs Used in PEMFC

Recycling strategies for ethylene-propylene-diene monomer (EPDM) used in proton exchange membrane fuel cells (PEMFCs) are essential for enhancing sustainability and reducing environmental impacts associated with these technologies.

Current Recycling Strategies involve:

4.4.1 Thermo-Mechanical Devulcanization

One effective recycling strategy for ethylene propylene diene monomer (EPDM) is continuous thermo-mechanical devulcanization using a co-rotating twin-screw extruder, which allows for a high degree of devulcanization and retains many of the properties of the original material. The findings from Brunella et al. [69] indicate that increasing both the thermal profile and the screw speed results in a higher percentage of devulcanization, with values reaching up to 93.9% under optimal conditions. However, it was also found that the percentage of random scission-a phenomenon that can negatively impact the mechanical properties-varied depending on process conditions, such as water injection and screw profile. For instance, higher screw speed and thermal profiles tend to reduce the occurrence of random scission, making the recycled EPDM more suitable for reuse in demanding applications such as PEMFC gaskets. The ability to achieve these high devulcanization rates while minimizing the degradation of rubber chains offers significant potential for the circular economy by enabling the material to be reused effectively in its original applications, thereby reducing waste and overall environmental impact.

4.1.2 EPDM Use in Thermoplastic Vulcanizates (TPVs)

Recycling EPDM through thermoplastic vulcanizate (TPV) presents an effective solution for improving performance in fuel cell applications. TPV, consisting of cross-linked EPDM in a polypropylene matrix, showed better mechanical stability than EPDM, with a compression set below 50% after 2000 hours at 120°C, while EPDM experienced a 245% increase. Unlike EPDM, TPV showed minimal oxidation and no carbonyl group formation, maintaining more excellent durability under aging conditions (pH 3, 90°C for 1000 hours). These findings support TPV's enhanced recyclability and suitability as a gasket material in PEMFC applications [70].

5. Conclusions

Under the rigorous circumstances usual of these systems, the thorough investigation of EPDM elastomers in the Proton Exchange Membrane Fuel Cells (PEMFCs) framework has underlined their applicability and performance. EPDM is a useful material for gasket uses because of its strong mechanical stability, chemical resistance, and adaptation to PEMFC operating conditions.

According to the studies under consideration, EPDM shows notable chemical resistance in acidic circumstances that are common on the cathodic side of PEMFCs. Strong C-C bonds in the EPDM polymer matrix resist acid-induced degradation, preserving the material's structural integrity and mechanical qualities even in demanding surroundings. Maintaining the efficiency and dependability of PEMFCs over their running lifetime depends on this chemical stability.

Another important consideration is mechanical stability. EPDM shines in this regard. Tensile strength, elongation at break, resilience to high temperatures, and gas permeability of EPDM have been proven to be much improved using silica and carbon black fillers. With these fillers, optimal compounding formulae guarantee that EPDM gaskets can survive the mechanical stresses and fluctuations in pressure normal of PEMFC operations, improving their general performance. Maintaining the correct compression and sealing inside the fuel cell stack and stopping gas leaks depend on these improvements.

Furthermore, studied is how various curing techniques affect EPDM's chemical aging resistance. Peroxide-cured EPDM shows more resistance against oxidative degradation and acid attack than sulfur-cured EPDM. This is so because more stable cross-link networks developed during the peroxide curing process improve the lifetime and durability of the material in PEMFC surroundings. Such developments in vulcanization techniques emphasize the need to choose suitable curing systems to maximize the performance of EPDM gaskets.

EPDM is a reasonably affordable and dependable material for gasket use in PEMFC systems. Its great mechanical stability, chemical resistance, and adaptation to PEMFCs' particular environmental circumstances make it a recommended choice for guaranteeing the lifetime and efficiency of these fuel cells. Further improving its fit for PEMFC applications is envisaged from continuous research and development activities concentrating on refining EPDM formulations and curing techniques, advancing fuel cell technology and its broader acceptance in many different sectors.

Proposed Areas for Future Research on EPDM Formulations and Curing Techniques:

1. Development of Nano-Composites: Find ways to integrate carbon nanotubes (CNT), graphene, and silica to improve the mechanical and thermal properties and the chemical resistance to the PEMFC working media.
2. Optimization of Curing Systems:
    - Study hybrid curing methods combining sulfur and peroxide to leverage their respective strengths.
    - Investigate new cross-linking agents or co-peroxides to improve EPDM's stability in acidic and low-temperature PEMFC environments.
3. Enhanced Chemical Resistance:
    - Modify cross-link density and structure to improve chemical resistance in PEMFC cathodic conditions.
    - Evaluate using antioxidants, anti-ozonants, and stabilizers to extend the material's operational lifespan.
4. Investigate how additives can minimize rapid gas decompression (RGD) and improve EPDM's overall durability.

Author Contributions

Conceptualization, methodology, formal analysis, investigation, resources, data curation, writing, Daniel Foltut; validation, review and editing, supervision, Viorel-Aurel Serban. All authors have read and agreed to the published version of the manuscript.

Competing Interests

The authors have declared that no competing interests exist.

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