Journal of Innovations in Business and Industry

Vol. 02, No. 01 (2024) 55-60, doi: 10.61552/JIBI.2024.01.007 - http://jibi.aspur.rs

A REVIEW OF PEM FUEL CELLS USED FOR AUTOMOTIVE APPLICATIONS

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Received 08.11.2023.
Accepted 01.02.2024.

Keywords:

Electrolyte, Fuel cell performance, Catalyst, Energy management, Maximum power point.

A B S T R A C T

Proton Exchange Membrane (PEM) fuel cells have garnered considerable attention as a promising technology for automotive applications due to their potential to revolutionize transportation. This paper comprehensively reviews PEM fuel cells used in automotive applications, exploring their working principles, ad-vantages, and challenges. It examines the current state of PEM fuel cell technology in the automotive industry, including recent advancements and commercial implementations. Additionally, the paper discusses the critical factors influencing the widespread adoption of PEM fuel cells in vehicles and identifies potential future developments.

1. INTRODUCTION

In pursuing a sustainable and eco-friendly future, the automotive industry has witnessed an unprecedented transformation, with a growing emphasis on cleaner and more efficient trans-portation technologies. Among the various alternatives, Proton Exchange Membrane (PEM) fuel cells have emerged as a promising and viable solution, offering a compelling path toward zero-emission mobility. Their unique ability to convert hydrogen and oxygen into electricity with only water as a byproduct has attracted significant attention, positioning them as a critical player in the quest for decarbonizing the transportation sector.

As concerns over greenhouse gas emissions and climate change escalate, conventional internal combustion engine vehicles have become intensely scrutinized due to their significant contri-bution to global carbon emissions. In response, governments, industries, and researchers have intensified their efforts to develop alternative powertrain solutions that align with sustainabil-ity, efficiency, and environmental responsibility principles. In this context, PEM fuel cells have emerged as a front-runner, representing a breakthrough technology with the potential to revolutionize the automotive landscape. The success of PEM fuel cells in automotive applica-tions hinges upon their ability to address the pressing challenges that have impeded the wide-spread adoption of other fuel cell technologies. These challenges include high cost, limited durability, and insufficient power density. Advancements in materials science, engineering, and system design have significantly improved the

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performance and practicality of PEM fuel cells, making them increasingly appealing to automotive manufacturers and consumers alike.
Through this review, we seek to present a comprehensive overview of the progress made thus far in PEM fuel cell development for automotive applications, shedding light on this technology's achievements, limitations, and potential future directions. We hope this paper will serve as a valuable reference for researchers, engineers, policymakers, and automotive stakeholders, inspiring further advancements, and collaborations to expedite the realization of a sustainable and greener automotive future through PEM fuel cell technology.

2. FUNDAMENTALS OF PEM FUEL CELL

The Proton Exchange Membrane Fuel Cell (PEMFC) is an electrochemical energy conversion device that harnesses the chemical energy of hydrogen and oxygen to produce electricity, water, and heat. At the core of this technology lies the proton exchange membrane, also known as a polymer electrolyte membrane, which facilitates the critical process of proton transport within the cell. Understanding the fundamental principles of PEMFC operation is essential for comprehending its potential for automotive applications. This section provides an overview of the critical components and electrochemical processes involved in PEMFC opera-tion.

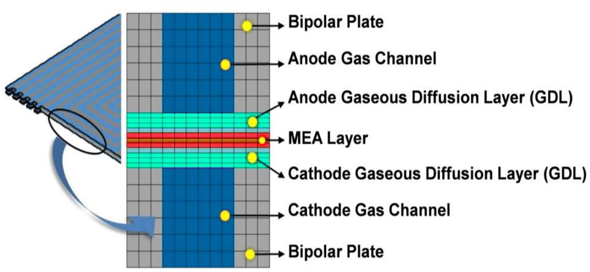

Figure 1. Schematic illustration of a PEM fuel cell domain

The electrochemical reactions within a PEMFC occur at the anode and cathode electrodes. At the anode, hydrogen gas (H_2) is fed, and a catalyst, typically platinum-based, facilitates the splitting of hydrogen molecules into protons and electrons:

Anode Reaction: $H_2 \rightarrow 2H^+ + 2e^-$ (1)

The protons generated during this reaction travel through the proton exchange membrane while the electrons flow through an external circuit, creating an electric current. The electrons reach the cathode, where they combine with oxygen gas (O_2) and protons from the anode reaction to produce water and heat:

Cathode Reaction:

$$1/2O_2 + 2H^+ + 2e^- \rightarrow H_2O \quad (2)$$

The proton exchange membrane, usually made of a perfluorinated sulfonic acid polymer, acts as an electrolyte, facilitating the transfer of protons between the anode and cathode compartments while preventing the passage of electrons. The membrane's selective permeability ensures the fuel cell operates efficiently by maintaining an adequate supply of protons for the electrochemical reactions. The efficient operation of PEMFCs relies heavily on effective ion transport and water management. Protons are conducted through the membrane by proton hopping, enabled by water molecules in the membrane structure. Ensuring an adequate water content in the membrane is vital for maintaining its proton conductivity and avoiding performance degradation.
PEMFCs operate at relatively low temperatures compared to other fuel cell types, typically between 60°C to 80°C (140°F to 176°F). This characteristic offers numerous advantages for automotive applications, including faster startup times, higher power density, and reduced issues related to heat management.
Electrode, electrolyte catalyst, and gases make up a PEM fuel cell, as shown in Fig. 1. Membrane, flow channel plate, catalyst, and gas diffusion layer are made of polytetrafluoroethylene, graphite, platinum, and carbon cloth, respectively. Numerous factors, including the cross-section of the channels, the design of the flow field, and the operating parameters, impact the performance of the fuel cell (Kolavennu, Telotte & Palanki 2009, Offer et al. 2010, Karthikeyan et al. 2013, Muthukumar et al. 2014, Palaniswamy, Marappan & Jothi 2016, Turkmen, Solmaz & Celik 2017, Karthikeyan et al. 2020). At atmospheric pressure and temperature, the serpentine flow field with a square cross-section performs better. The ideal flow field for improved water management is the modified serpentine flow field. The line formed between Power density and Current density is known as the performance curve or P-I curve.
In conclusion, the fundamentals of the Proton Exchange Membrane Fuel Cell encompass the intricate interplay between electrochemical reactions, the proton exchange membrane, and the efficient transport of protons and water within the cell. These principles underpin the promising potential of PEMFCs for automotive applications, where their ability to provide clean, silent, and efficient power offers a compelling solution to address environmental concerns and transform the transportation landscape (Choi et al. 2014, Duy et al. 2015, Vinh & Kim 2016, Duy & Kim 2017, Duy et al. 2021).

3. APPLICATION OF PEM FUEL CELL ON AUTOMOBILE

3.1 Development of the fuel cell electric vehicle (FCEV)

According to research in Ala et al. (2021), electric mobility is required for decarbonization objectives in Europe, where CO2 emissions now account for one-third of all emissions. The authors com-pared the quantity of repurchased FCEVs with ICE-based cars, BEVs, and

HEVs (McNicol, Rand & Williams 2001). They discovered that the FCEVs powered by hydrogen or methanol are the finest solutions to the demands of contemporary transportation. Different European nations have varying EV growth rates. For instance, polls show that the Netherlands, Norway, and the UK are the most EV-ready nations in Europe (Collett et al. 2021). This study concentrated on filling stations, infrastruc-ture, country regulations, and policies, mainly car registrations, in 22 nations. Overall, com-pared to previous years, most of the nations considered in the survey had more developed registration platforms.

Toyota began selling its Mirai model in the USA in 2015, while the ix35 was the first FCEV to be marketed in Europe. With 61 24-kW batteries and 61 100-kW FC systems, Hyundai also started selling the Tucson vehicle in 2014 (Duan et al. 2021). Hybrid hydrogen FCEVs are now being tested even in the aviation industry. Using Li-Po batteries, Emre Ozbek et al. created and as-sessed a hybrid system for an unmanned aerial vehicle (Ozbek et al. 2021). The propulsion tests were con-ducted using experimental data. According to reports, the technology has demonstrated ex-cellent results and may move toward extensive manufacturing and commercialization. Japan had the best hydrogen station infrastructure in the world by January 2021, with around one-third of the hydrogen refueling stations in the country and 4600 hydrogen FCVs already on the road, compared to the 9000 hydrogen FCVs in the USA. This fits Japan's goal of having a society free of carbon emissions by 2050 (Khan, Yamamoto& Sato 2021). According to Ajanovic, Glatt and Haas (2021), hydrogen and FCs can be used for various purposes. They will soon be a suitable alternative to fossil fuel- and battery-based electric heavy-duty vehicles, particularly for extended transporting ranges like buses. They stated that the refueling infrastructure's high cost, readiness, and attractiveness continue to be the key barriers to FCEV's quick penetration. According to Li et al. (2021), the authors think that the limited number of hydrogens refueling stations (HRSs) in China has hindered the selling of hydrogen FCEVs. According to their findings, selecting an appropriate and effective ap-proach for HRSs may raise market diffusion efficiency by 76.7% and increase EV sales by at least 40%. In comparison to BEVs, hydrogen FCEVs have a range of 500 km, comparable to that of ICE-based cars and over 200 km more than that of an EV (Wróblewski et al. 2021).

3.2. Basic Structure Type of PEM fuel cell in automobile applications

Fuel cells are frequently paired with additional auxiliary energy sources to power hybrid electric cars to create a hybrid system. Examples of these supplementary power sources are batteries, ultracapacitors, superconducting magnetic energy storage (SMES), solar photovoltaics (SPVs), and flywheels. Batteries and ultracapacitors are the two supplementary energy sources that are most frequently utilized (Iqbal et al. 2021). Batteries are inexpensive, low maintenance, and simple to install. As a result, the most prevalent architecture for electric cars is the fuel cell/battery hybrid, which is employed in many production settings. A storage device called an ultracapacitor is used to improve dynamic responsiveness. When the load swings quickly, it can immediately deliver the load or recover energy (Fu et al. 2020). Other supplementary energy storage devices are used less often than batteries and ultracapacitors (Luo et al. 2021). An energy storage system with a SMES has a high-power output and a low energy density. The conditions of work demanded by SMES are rather arduous. The application in fuel cell hybrid cars is also very uncommon because of the cost of the vehicle being considered. Although solar photovoltaics (SPV) are a sustainable, non-polluting form of energy production, their energy output is highly dependent on solar radiation. As a result, it is not the best supplemental energy for cars. The flywheel will store energy in the form of mechanical energy when torque is applied to it. The flywheel may release mechanical energy when the system needs more power and transform it into electrical energy to power the system. It has strong security requirements and is frequently utilized in power grid systems.

FCHEVs are often divided into five topological categories: Fully fuel cell, fuel cell and battery, fuel cell + ultracapacitors, fuel cell + battery + ultracapacitors, and fuel cell + other hybrids are all possible configurations.

Fuel cells and other supplementary energy sources are still used in a limited number of hybrid power systems in hybrid automobiles. Batteries can be replaced with flywheels as supplemental power sources. When the motor requires power, the flywheel's high-speed mechanical energy is transformed into electrical energy. However, flywheel operation is not frequently employed since it necessitates high security. Similar to SMES, which is not widely utilized because of its exorbitant cost. Due to its reliance on solar energy and the significant unpredictability of the energy supply, SPVs are also not commonly employed. This study doesn't go into detail on various auxiliary energy sources because it primarily focuses on hybrid power systems made up of fuel cells, batteries, and ultracapacitors.

4. CONCLUSION

In conclusion, developing fuel cell and electric automobile systems represents a transformative journey towards sustainable and environmentally responsible transportation. FCEVs and BEVs have emerged as promising alternatives to conventional internal combustion engines, offering unique benefits and addressing critical environmental challenges. Continued research, collaborative efforts, and supportive policies will be vital to overcoming technical barriers and accelerating the adoption of these technologies. As we look towards the future, fuel cell and electric systems are poised to play a central role in shaping a cleaner, greener, and more sustainable automotive landscape, driving us towards a better, more sustainable future.

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