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A Recent Comprehensive Review of Fuel Cells: Development History, Types, and Applications

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Abstract. As global energy demand rises, fossil fuel combustion has caused severe CO_2 emissions and environmental pollution. Hydrogen energy has gained growing attention. Fuel cell as a new technology, has developed fast recently. The paper mainly introduces two types of fuel cell. Direct methanol fuel cell and proton membrane fuel cell. The proton exchange membrane fuel cell (PEMFC), which converts hydrogen into electricity and produces only water and heat as by-products, offers high efficiency and zero emissions, making it a key technology for energy transformation. However, PEMFC's commercialization faces three major barriers: high platinum catalyst costs, loss of membrane conductivity above 80 °C, and limited durability. This paper reviews recent progress over the past five years, it also briefly discusses global fuel cell developments in Japan, the United States, Europe, and South Korea, as well as direct methanol fuel cells (DMFCs) as a related technology. Future challenges include cost reduction, limited durability and material recycling. These advances have laid a solid foundation for PEMFCs to play a significant role in the clean energy transition.

Keywords: fuel cell, global economy, high efficiency, development history

1. Introduction

As the increasing demand for energy sources, the consumption of chemical fuels and the fossil fuel combustion bring massive carbon dioxide emissions, all of them have increased the global warming level and caused the environmental pollution. The development and utilization of hydrogen energy is extremely urgent, in order to realize the sustainable development and achieve carbon naturally. As an perfect secondary energy carrier, hydrogen only produce water after the electrochemical reaction. The advantages of hydrogen fuel cell are very clear: high energy conservation efficiency, low noise and zero carbon emissions. Furthermore, hydrogen fuel cell has already become one of the principal technologies to promote the energy transformation and being used in the development of new energy vehicles. The development of fuel cell is a great way to reshaping the environmental structure and reducing greenhouse gas emissions.

At present, hydrogen energy and fuel cells have been commercialized in some fields. The research and commercialization of hydrogen fuel cell and fuel cells vehicles are relatively fast developed in Japan, the United States and Europe. They are constantly innovating in hydrogen production, hydrogen storage and hydrogen utilization [1].

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Until nowadays, the main types of fuel cell are proton exchange membrane fuel cells (PEMFCs) and direct methanol fuel cells (DMFC). The proton exchange membrane fuel cell generates electricity through electrochemical reactions. Chemical energy is directly converts into electric energy without combustion. The direct methanol fuel cell is another typical proton-exchange membrane fuel cell. It uses liquid methanol as fuel directly without hydrogen production in advance. The hydrogen proton passes through the proton exchange membrane to the cathode, while electrons pass through external circuits to generate electric energy. Oxygen reacts with protons to produce water at the cathode.

This paper will divide into four parts: the research progress of fuel cells in different countries; mainly talk about the proton membrane fuel cell; the introduction of direct methanol fuel cell; the future prospects of fuel cell. Based on the above research background, this paper will mainly summarize the latest research progress of materials proton exchange membrane fuel cells. The existing technical and industrial problems are analyzed systematically, and the domestic actual conditions, the future development direction of hydrogen fuel cells is prospected.

2. The research progress of fuel cell around

The global fuel cell market is expanding, with its size reaching about $13.7 billion in 2024 and is predicted to reach $40.7 billion by 2030. The Asia-Pacific region dominates, led by China in installed capacity, Japan in residential cogeneration systems, and South Korea in power generation. Europe focuses on heavy-duty trucks, while North America emphasizes data center backup power. System costs have fallen sharply, but passenger FCEV sales have declined for several years. Insufficient refueling infrastructure and high hydrogen costs are the key barriers [2].

Japan has been a global pioneer in fuel cell electric vehicles (FCEVs) since the 1990s, when it began exploring hydrogen as a power source for vehicles. Toyota, as an example, set a dedicated research team that later evolved into its new energy division, and in 2014 it launched the world's first mass-produced hydrogen fuel cell sedan, the "MIRAI," which achieved significantly sales. In terms of technology and intellectual property, Japan holds a Dramatic advantage: it stands for more than 50% of global FCEV patent filings, with Toyota ranking first worldwide in fuel cell vehicle patents—more than double that of its closest competitor. The Japanese government has long promoted a "hydrogen society," investing heavily in hydrogen infrastructure since the 1980s. However, due to unresolved technical problems in hydrogen storage, transport, and cost, FCEVs hadn't reached large-scale commercialization. Despite this, Japanese vehicle producers continue to promote research, development and innovation, laying a solid foundation for future widespread utilization.

The United States holds a strong position in hydrogen production and storage, with world-leading companies such as Air Products and Praxair, and advanced proton-exchange membrane water electrolysis technologies. It also dominates liquid hydrogen production, scale, and pricing. The U.S. has the largest fleet of fuel cell passenger cars and forklifts globally: over 2,900 Toyota Mirai units have been sold in the U.S., and Plug Power operates more than 20,000 fuel cell forklifts with over 6 million hydrogen refueling operations. With the 68 hydrogen stations in North America, 67 are located in the U.S., mostly concentrated in California. Notably, 14% of the nation's annual liquid hydrogen demand is used for fuel cell vehicles [3].

Europe has taken a strategic, long-term approach. The Fuel Cells and Hydrogen Joint Undertaking published the "Hydrogen Roadmap Europe," which predicted that hydrogen would meet 24% of final energy demand and create 5.4 million jobs by 2050. The roadmap identifies hydrogen as an essential for decarbonizing gas networks, heavy transport, and industrial feedstocks,

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while it also enabling large-scale renewable integration and seasonal energy storage. It projects that by 2050; hydrogen could supply 10–18% of building heating and power and 23% of industrial high-grade heat. Economically, the hydrogen sector is expected to generate €130 billion in revenue for EU companies by 2030 and €820 billion by 2050, with net exports reaching €50 billion in 2030 [4].

South Korea, though slightly behind in core technologies, has aggressive government plans. Backed by Hyundai, the government would allocate €2 billion over five years for fuel cell vehicles and refueling stations, targeting 15,000 FCEVs and 1,000 hydrogen buses by 2022, along with 310 new stations. In January 2019, Korea released its "Hydrogen Economy Roadmap," aiming for 6.2 million FCEVs and 1,200 stations by 2040. The plan also includes subsidies for fuel cell taxis and trucks, replacing police cars with fuel cell vehicles from 2021, and expanding fuel cell buses to 2,000 by 2022. In stationary applications, Doosan Group completed Korea's largest hydrogen fuel cell power plant in 2017, with an annual production capacity of 144 units of 440-kW systems [5].

3. Different types of fuel cells

3.1. Proton membrane fuel cell

To begin with, it is essential to understand how proton exchange membrane fuel cells work and where they can be applied. The PEMFC is an electrochemical device that changes the chemical energy of hydrogen into electrical energy, and the only by-products are water and heat. The key part of the cell is the membrane electrode assembly, which contains a polymer membrane that conducts protons, with catalyst layers and gas diffusion layers on both sides. At the anode, the platinum catalyst helps split hydrogen molecules into protons and electrons: $H_2 \rightarrow 2H^+ + 2e^-$. The protons go through the wet membrane to the cathode, while the electrons are forced to move through an external circuit, producing a direct current that can drive external devices. At the cathode, oxygen from the air reacts with the protons and electrons to form water: $O_2 + 4H^+ + 4e^- \rightarrow 2H_2O$. The overall reaction is $2H_2 + O_2 \rightarrow 2H_2O$. PEMFCs normally operate at 60–80 °C, which allows quick start-up, but they need high-purity hydrogen because impurities like carbon monoxide can damage the catalyst. Two major difficulties still hold back the wider use of PEMFCs: keeping the membrane at the right level of wetness, and the other is the high price of platinum catalysts. The figure 1 has shown the whole process of PMFCs.

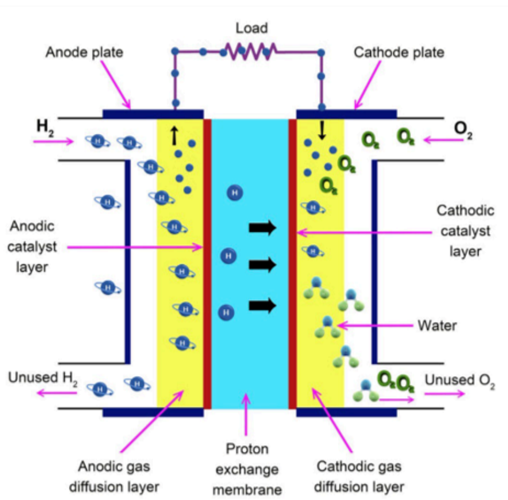

Figure 1. Schematic illustration of PEMFC reaction process [4]

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After understanding the basic mechanism, there are some recent research progresses of PMFCs. The commercialization of this technology has been held back by three main problems. Firstly, the catalyst needed for the oxygen reaction is platinum, which is very expensive. Secondly, the common membrane (Nafion) loses its ability to conduct protons when the temperature is higher than 80 °C, because the water inside evaporates. Thirdly, the membrane and catalyst layers can break down over time during long use. Over the past five years, the international research community has conducted extensive and productive investigations around these challenges, yielding multiple breakthroughs that offer new technological pathways for enhancing PEMFCs performance and reducing costs.

One major breakthrough came in 2025, which is published by Professor Wang Dan and Academician Zhang Suojiang from the Chinese Academy of Sciences in Nature. They created a new catalyst made of single iron atoms arranged on a curved hollow carbon shell. The clever design puts the iron atoms on the inside, while the outside carbon layer protects them and also helps the reaction go faster. In tests, this catalyst reached a power density of 0.75 W cm^{-2} under normal air conditions, and it kept 86% of its activity after running for 303 hours. This is the first time that a non-platinum catalyst has performed almost as well as platinum ones, which could greatly reduce the cost of fuel cells [6].

There has also been good progress in membrane materials. In 2024, Professor Wang Bo and Professor Feng Xiao from Beijing Institute of Technology reported in science a new type of proton conductor. They added a material called COF (a porous framework) into the Nation membrane. The COF has many carbonyl groups that can form hydrogen bonds with water molecules. This helps to hold water inside the membrane even at high temperatures, while still letting gases pass through. At 105 °C, the fuel cell with this new membrane produced 1.9 times power which is more than the traditional one. This result allows PEMFCs to work at higher temperatures, making the cooling system simpler [7].

Perhaps the most exciting advance came in 2026, when Professor Lu Shanfu's team at Beihang University published in Nature Energy. They made a membrane with only 20 μm thick, using copper ions to crosslink the polymer chains. Previously, high-temperature membranes (doped with phosphoric acid) had to be thicker than 50 μm because the acid made them too soft. The new connected membrane is not only thin but also strong and self-healing. The fuel cell reached a peak power density of 3.08 W cm^{-2} at 200 °C, and after running for 503 hours at 160 °C, its performance has hardly dropped. This is the first time that a high-temperature PEMFC can compete with low-temperature ones in both power and durability [8].

In summary, the past five years have seen many new ideas, from better catalysts to thinner membranes. That have made PEMFCs more efficient and cost-effective. There are still some engineering problems to solve before they can be mass-produced, but these breakthroughs have built a strong foundation for the future use of fuel cells.

3.2. Direct methanol fuel cell

Direct Methanol Fuel Cells (DMFCs) represent an energy conversion technology that directly transforms the chemical energy of methanol into electricity through electrochemical reaction. Compared to hydrogen-oxygen fuel cells, DMFCs exhibit superior advantages including higher energy density, environmental benignity, as well as enhanced safety in fuel storage and the system operation. The figure 2 below has shown the whole process of the reaction in DMFCs [9].

Current market valuation is ranging from $128 million to $282.5 million due to different statistical methods. The industry is generally optimistic, with projected compound annual growth

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rates between 8% and 19%. The global market is expected to reach from \$685 million to \$9.92 billion by 2032–2034 [10].

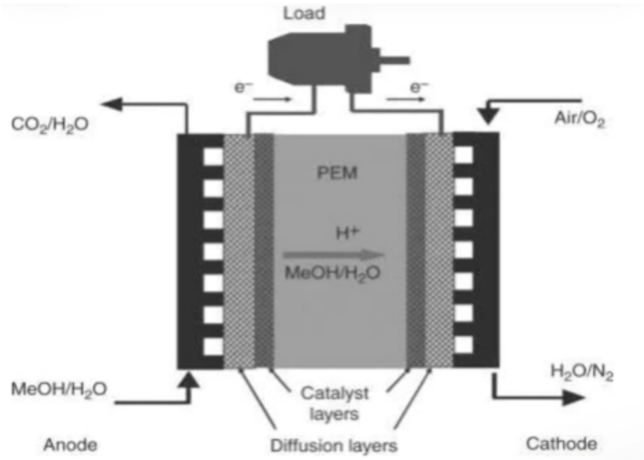

Figure 2. Schematic illustration of process of the reaction in DMFCs [9]

4. Future outlook

The breakthroughs described above: from curved single-atom iron catalysts to breathing ion conductors and ultra-thin connected membranes – have brought PEMFCs significantly closer to commercial reality. However, several challenges remain before this technology can be widely adopted.

First, non-platinum catalysts still need further improvement. Although the curved single-atom iron catalyst has achieved excellent performance, its long-term stability under real operating conditions still needs more testing. Future research will focus on making these catalysts last longer and work even better, so they can completely replace platinum in commercial fuel cells. Second, the durability of PEMFCs must be extended. Current fuel cells degrade over time due to catalyst corrosion and membrane damage. These goals will require continued work on more stable materials and better system designs. Third, costs must be reduced further. The high price of platinum catalysts and expensive membrane materials remain major barriers. Recycling and sustainability are becoming important topics. As more fuel cells are produced, finding ways to recover valuable materials like platinum from used cells will be essential. Future research will need to design fuel cells that are easier to recycle and develop more efficient recovery methods.

In conclusion, the past five years have seen remarkable progress in PEMFC technology. With continued research on catalysts, membranes, durability, cost reduction, and recycling – supported by emerging tools like AI – PEMFCs are likely to play an increasingly important role in the world's transition to clean energy. While challenges remain, the foundation laid by recent breakthroughs makes the future of this technology look promising.

5. Conclusion

This paper introduces the recent progress in proton exchange membrane fuel cell (PEMFC) and direct methanol fuel cells （DMFCs） research, focusing on the three major barriers to commercialization: high cost, loss of membrane conductivity at specific temperatures, and limited durability. By improving the key material over the past few years—including non-platinum catalysts, high-temperature proton conductors, and ultra-thin reinforced membranes, the review

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shows improvements in both performance and cost. It has shown that the material innovation is the most important factor to overcome the commercialization bottleneck, a large number of technologies also show a significant potential. The findings showed in this paper carry important implications for both research and practice. Talk to the research, the summarized strategies for catalyst design, membrane modification, and durability enhancement offer a reference for future studies, helping to clarify priority research directions and avoid redundant efforts. After this, these advances are expected to reduce manufacturing costs, expand operating temperature ranges, and extend service life, thereby accelerating the adoption of PEMFCs in new energy vehicles, heavy-duty transport, and distributed power generation. Furthermore, the paper described the industrial landscape across major countries, and points out remaining challenges such as long-term stability, system integration, and material recycling. Overall, this review provides a solid foundation for researchers, policymakers, and industry holders to further advance PEMFC technology toward a clean energy future.

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