

The research process of fuel cells in the automotive field

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Abstract:

Against the backdrop of global green development, fuel cells, as an efficient and pollution-free energy utilization device, are regarded as one of the crucial technologies to achieve Sustainable Development Goals (SDGs). Fuel cells can convert the chemical energy of fuels into electrical energy efficiently, and there are no greenhouse gas emissions during their operation process. They play an important role in energy utilization and environmental protection. This paper reviews the current development of fuel cells in the automotive field, focusing on the working principles, technical characteristics, and application scenarios of proton exchange membrane fuel cells and solid oxide fuel cells. Research shows that solid oxide fuel cells feature long service life and high fuel flexibility but have a long startup time, showing great potential for applications in long-haul transport vehicles. In contrast, proton exchange membrane fuel cells are widely used in the automotive field due to their advantages such as low operating temperature and simple structure. However, they still have some challenges, like the low tolerance to sulfur compounds, and potential safety hazards during the storage and transportation process of hydrogen. In addition, This paper discusses the improvement directions and development trends of fuel cell technology, such as the development orientation of materials and the application of artificial intelligence in fuel cell vehicles.

Keywords: Fuel cell vehicle; Proton exchange membrane fuel cell; Solid oxide fuel cell.

1. Introduction

Since the Industrial Revolution, energy consumption has worldwide risen quickly, and most of this energy consumption comes from nonrenewable fossil fuels. Moreover, fossil fuels are mostly utilized by

burning to generate chemical energy. During the combustion process, carbon oxides, sulfides, nitrogen oxides, as well as various harmful gases and dust are produced, causing environmental problems such as acid rain and photochemical smog. These issues seriously affect human health and normal life, and are

not conducive to sustainable development. For the ecological problems caused by such energy sources, humans are urgently seeking new energy sources that can replace fossil fuels. Currently, new energy sources such as solar energy, wind energy, and hydropower have achieved substantial development due to their advantages like strong sustainability and diverse energy channels. However, they still have drawbacks including significant vulnerability to weather, geographical factors and low energy density. Hydrogen is widely regarded as an efficient and clean energy source, attracting the attention of various high-tech enterprises. Compared with the traditional method of generating and utilizing internal energy through combustion, the method of directly converting the chemical energy contained in hydrogen and oxygen into electrical energy via electrochemical reactions is more efficient. Therefore, fuel cells which are based on this principle are regarded as the most promising energy utilization devices at present. Fuel cells, as a type of high-efficiency primary battery, have a plenty of advantages such as lower energy consumption, and abundant sources of raw materials and higher energy conversion efficiency compared to traditional internal combustion engines. The generated product of the reaction between hydrogen and oxygen inside a fuel cell is water, which holds great prospect in terms of environmental protection, achieving zero carbon emissions, and human sustainable development. Comparing different sectors such as commercial, residential, electric power, transportation, and industry, transportation produces the largest amount of greenhouse gases with about 29 % before 2021[1]. At the end of the 20th century, fuel cell vehicles (FCVs) using fuel cells as their power supply devices began to catch people's notice, and many automobile manufacturers started to carry out planned research and development of related products. The first real fuel cell vehicle is the Electron produced by General Motors in 1966, this provides an original sample for subsequent research on Fuel Cell Vehicles. In 2013, Hyundai ix35 FCV became the world's first mass-produced FCV model. The first model to achieve commercialization was the Mirai launched by Toyota in 2014, its actual range can up to 483 km and refueling time is only 3-5 minutes [2]. No major accidents caused by technical defects or malfunctions occurred during its sales period, which demonstrates Toyota's relatively mature FCV technology and marks a milestone in the history of FCV development. Currently, the FCV technologies of Toyota and Hyundai have developed rapidly and achieved commercialization. The application of fuel cell technology in vehicles is bound to be a major transformation in modern transportation. It will effectively alleviate energy pressure, address environmental issues, and provide a greener and cleaner energy solution for hu-

man survival and development.

2. Present development situation of fuel cell vehicles

Currently, fuel cell vehicles has become an importation part in Carbon neutrality process around the world, and it has been elevated to the status of a national strategy in many countries.

Fuel cell vehicles have advantages over both gasoline-powered vehicles and electric vehicles. In terms of range, the typical driving range is approximately 500-800 km. Some models can match that of typical electric vehicles (EVs), and the longest-range record for passenger vehicles even reaches 1,000 km. In terms of refueling, fuel cell vehicles take 3-5 minutes to refuel with hydrogen, whereas electric vehicles (EVs) take several hours. Finally, in terms of efficiency, fuel cell vehicles have an efficiency of 60%, which is much higher than that of gasoline-powered vehicles (16-30%). Currently, fuel cell vehicles have made significant progress, with different development processes in both passenger and commercial vehicle sectors.

In the passenger vehicle sector, FCVs represented by Toyota's Mirai and Hyundai's Nexo account for approximately 74% of the global market share. However, the widespread adoption of passenger FCVs remains limited due to factors such as high costs, an underdeveloped supply chain, and insufficient hydrogen refueling infrastructure. In 2023, the sales of the Nexo plummeted by 56% year-on-year to 5,012 units, with its Sport Utility Vehicle (SUV) variant experiencing a sharp decline from 11,179 units in 2022 to just 4,709 units [3]. Although governments in some countries made strong promotion and subsidies for passenger FCVs, their declining sales appear inevitable. In contrast, China has emerged as the largest market for commercial hydrogen fuel cell vehicles, with sales reaching 2,478 units in the first half of 2024, accounting for 44.1% of the global market share. From 2020 to 2023, China's commercial hydrogen FCEV sales have shown consistent growth, including models such as the Foton hydrogen fuel cell bus and the Yutong hydrogen energy heavy-duty truck. The U.S. and Japanese governments are also steadily advancing the commercialization of FCEVs, with commercial vehicle sales expected to maintain growth. All in all, while current adoption of passenger FCVs remains sluggish, the commercial sector has demonstrated stronger development momentum. Nevertheless, passenger FCVs still possess significant growth potential in the future.

3. Current Status of Vehicle-Mounted Fuel Cells

At present, fuel cell technology has garnered significant attention from global tech enterprises, research institutions, and even governments, with substantial efforts being made to advance its application and commercialization. For example, the Chinese government has increased subsidies for hydrogen fuel cell vehicles and hydrogen production plants in 2025. In fact, according to the selection of electrolyte and fuel used, fuel cells can be classified into six different types: Alkaline Fuel Cells (AFC), Phosphoric Acid Fuel Cells (PAFC), Molten Carbonate Fuel Cells (MCFC), Solid Oxide Fuel Cells (SOFC), Direct Methanol Fuel Cells (DMFC), Proton Exchange Membrane Fuel Cells (PEMFC). In the automotive fuel cell sector, PEMFCs currently dominate the market, SOFCs also hold promising development potential.

Although fuel cells are widely recognized for their zero-carbon emissions during operation, the current fuel cell industry cannot yet achieve zero-carbon emissions across the entire industrial chain. While nearly carbon-free hydrogen can be produced through methods like electrolysis

of deionized high-purity water, its industrial-scale production remains limited due to prohibitively high costs (the levelized cost of hydrogen production ranges from \$1.70-\$3.00/kg via natural gas reforming, compared to \$8.00-\$12.00/kg for renewable energy-based production [4]). Currently, hydrogen production still mainly depends on fossil fuels, it possesses the capability to be presented as a saleable sophisticated technology that can be implemented at a minimal expense, while simultaneously achieving remarkable efficiency [5]. Global policy frameworks adopt gray hydrogen as a transitional solution, and the fully green hydrogen production as the final goal.

3.1 Polymer electrolyte membrane fuel cell (PEMFC)

PEMFCs, or proton exchange membrane fuel cells, are a type of fuel cell using a proton-conducting membrane as the electrolyte. As show in Fig. 1, it usually uses perfluoro sulfonic acid resin as the electrolyte and hydrogen as fuel. Through electrochemical reactions, it generates pollution-free water while producing electrical energy.

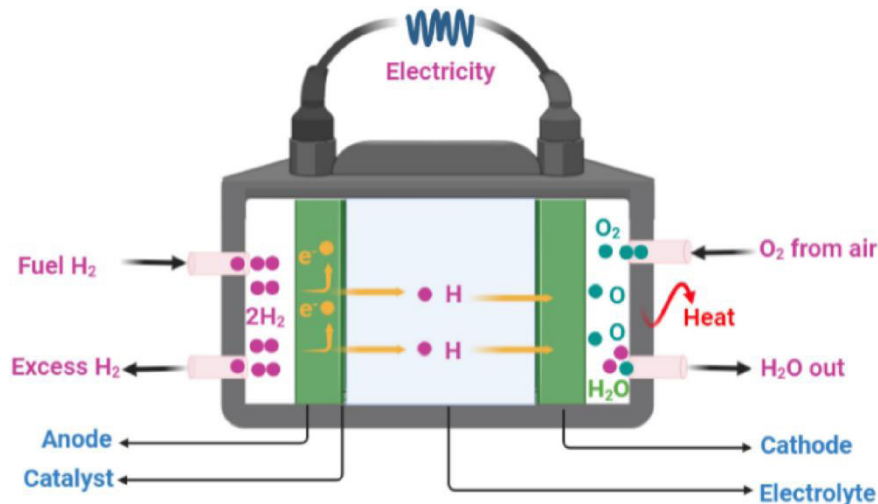


Fig. 1 The key components and working principle of proton exchange membrane fuel cell [6]

The reaction process can be summarized as follows: Hydrogen fuel enters the anode while oxygen enters the cathode as the oxidant. Under the action of catalysts (typically precious metals like platinum), hydrogen atoms dissociate into protons and electrons. The protons migrate through the proton exchange membrane to the cathode, while the electrons are forced to flow through an external circuit due to the membrane's blocking effect, thereby generating electric current. Simultaneously, at the cathode, the electrons, migrated protons, and oxygen combine to produce heat and water as byproducts. Operating typically at 60-80°C, PEMFCs exhibit exceptionally high-power density

[7]. As the most technologically mature fuel cell type, all current fuel cell vehicles use this kind of fuel cell exclusively.

Because of their relatively low operating temperatures, PEMFCs don't require lengthy startup periods like SOFCs. Under normal conditions, they typically start within one minute, with some systems achieving startup times measured in seconds even in subzero environments. A notable example is Toyota's third-generation Mirai PEMFC, which achieves cold starts at -40°C in just 30 seconds. This rapid-start capability enables their use both in passenger and commercial fuel cell vehicles.

PEMFCs use hydrogen as fuel, nearly achieving zero carbon emissions at the end-use product stage. Meanwhile, hydrogen as a fuel enables high energy efficiency (typically over 60%, much higher than the 30%-40% of gasoline-powered vehicles), improving energy utilization and extending range. However, challenges remain in hydrogen transportation and storage, such as the low energy density of gaseous hydrogen storage and the super high construction costs of pipeline transportation.

The structure of PEMFCs is simpler than other types of fuel cells. This is because they use a proton exchange membrane as the electrolyte, there is no need for an electrolyte management system like fuel cells with liquid electrolytes. Additionally, unlike high-temperature fuel cells (such as SOFCs), PEMFCs do not require heating or thermal insulation systems, reducing redundant components. This simplicity makes maintenance significantly easier compared to other fuel cell types, making PEMFCs the only fuel cell variety currently used in fuel cell vehicles.

Precisely due to these advantages of PEMFCs, all fuel cell vehicles worldwide currently adopt PEMFC technology. However, PEMFCs exhibit poor tolerance to sulfur compounds. The platinum-based catalysts used in PEMFCs have an extremely high affinity for sulfur, readily forming Pt-S bonds that are difficult to desorb at room temperature, leading to permanent catalyst deactivation. Moreover, unlike in high-temperature environments where sulfur compounds can desorb, they remain stably adsorbed on the catalyst in low-temperature conditions. Once sulfur contaminants enter the fuel cell, they persistently adhere to the catalyst, causing gradual degradation of catalytic activity and reducing the battery's lifespan.

Additionally, thermal management issues in PEMFCs can significantly impact the fuel cell's lifespan. During operation, PEMFCs generate substantial amounts of heat that must be efficiently dissipated. Otherwise, localized overheating may occur, which could degrade the proton exchange membrane's conductivity. In severe cases, this may lead to membrane dehydration, resulting in membrane perforation or thermal stress damage—both of which critically compromise the membrane's durability and operational safety [8].

Currently, although PEMFCs hold significant advantages over other fuel cell types in terms of startup time and energy efficiency, there are still several critical challenges needing to be solved like the reliance on precious metal catalysts that substantially increase system costs and the safety concerns in hydrogen fuel transportation and storage due to its highly flammable and explosive nature. These issues demand urgent solutions for broader commercialization.

3.2 Solid oxide fuel cell (SOFC)

SOFCs are fuel cells that operate at high temperatures (approximately 500-1000 degrees Celsius) using solid ceramic electrolytes like yttria-stabilized zirconia. Typically, nickel-based materials (such as nickel-yttria-stabilized zirconia) are used as anode material, and perovskite-based materials (such as strontium-doped lanthanum manganite) are used as cathode catalysts to assist in completing the redox reactions of fuels in the cell. Its principle is quite similar to PEMFCs.

Firstly, SOFCs have extremely high fuel flexibility and can be fed with various fuels such as hydrogen, natural gas, and methanol. However, due to difficulties in hydrogen production and storage, pure hydrogen is not commonly used as a fuel for SOFCs, despite its highest available electrical efficiency as a fuel and nearly zero carbon emissions [9]. Hydrocarbon substances represented by natural gas, due to their very stable molecular structure, are difficult to undergo electrochemical reactions at room temperature; when reacting at high temperatures, their products are complex and the efficiency is extremely low, making it impossible to stably generate electrical energy. Therefore, in SOFCs, reformers are usually used to reform hydrocarbons into hydrogen-rich gas before it enters the cells. Meanwhile, this property frees them from reliance on a single fuel, enhancing the convenience and reliability of SOFCs with compatible designs in the field of long-distance transportation.

Secondly, SOFCs have a relatively long service life, typically ranging from 40,000 to 80,000 hours. This is because their solid structure prevents corrosion issues caused by liquid electrolytes, and they can operate stably as long as the materials can withstand high-temperature environments. Meanwhile, their characteristic of high fuel flexibility enables SOFCs to have strong tolerance to fuel impurities, which can effectively reduce performance degradation caused by impurities (such as carbon deposition) and further extend the battery life.

Next, SOFCs perform better in sulfur tolerance than other low-temperature fuel cells (such as PEMFCs). As mentioned earlier, sulfides like hydrogen sulfide or sulfur dioxide are produced during the process of hydrogen production from fossil fuels. These substances may enter the fuel cell along with the fuel, poison the catalyst, and reduce its activity. However, the nickel-based materials used in the anode and perovskite-based materials used in the cathode of SOFCs have a lower affinity for sulfides than the platinum-based materials in PEMFCs. Additionally, the high-temperature conditions of SOFCs enhance the mobility of sulfide molecules, which in turn reduces their adsorption on the catalyst. Meanwhile, other substances

that are considered as impurities for SOFCs are: arsenic, As, phosphorus, P, antimony, Sb, and chlorine, Cl, which can cause a severe degradation in performance [10].

However, SOFCs are characterized by slow startup times due to their high-temperature operation mechanism. The electrolyte in SOFCs typically uses solid ceramic materials, at ambient temperatures, oxygen ions (the charge carriers) remain tightly bound to crystal lattices, rendering the material nearly non-conductive. However, at elevated temperatures, thermal excitation intensifies lattice vibrations, liberating oxygen ions from their equilibrium lattice sites and creating vacancies. These vacancies enable directional oxygen ion migration, thereby achieving high ionic conductivity. To prevent thermal stress-induced material damage, the heating rate must be strictly maintained at low levels. Notably, the system requires heating not only the fuel cell stack but also the reforming module, as the reforming catalysts only achieve efficient fuel conversion at high operating temperatures - a requirement that further prolongs the startup process. These inherent characteristics fundamentally determine SOFCs' suitability for long-distance transportation applications (where extended startup times are acceptable) rather than passenger vehicles requiring rapid start-stop operation.

Despite the numerous advantages and broad development prospects of SOFCs technology, its current commercial application is still restricted by multiple factors, with the problem of high raw material prices being particularly prominent. Since most catalysts used in SOFCs contain rare elements and their manufacturing processes are complex, it is difficult for SOFCs to replace mature fuel-powered vehicles and electric vehicles. Meanwhile, issues such as long startup time also limit the commercialization process of SOFCs. Currently, the scientific and industrial communities are committed to finding new and low-cost electrode and electrolyte materials. These materials need to maintain excellent electrical conductivity and catalytic performance even at reduced temperatures, so as to achieve efficiency equivalent to or higher than that of traditional high-temperature materials.

4. Future research perspectives

At present, fuel cells still face a considerable timeframe before achieving large-scale replacement of traditional internal combustion engines or electric motors, primarily due to their higher overall operating costs compared to both conventional fuel vehicles and electric vehicles, coupled with incomplete supporting infrastructure development.

PEMFCs are regarded as the most promising fuel cell technology for automotive applications, a status attrib-

utable to their versatile applicability and structural simplicity. However, they still face unresolved challenges in hydrogen storage/transportation, sulfur tolerance of materials, and cost competitiveness. Meanwhile, SOFCs require substantial improvements in cost reduction and startup time reduction to achieve practical viability.

In the future, automotive fuel cells could integrate AI technologies to achieve significantly higher energy efficiency. For instance, MAN EfficientCruise—developed by Germany's MAN Group—utilizes GPS-based predictive control to anticipate upcoming road gradients and proactively adjust vehicle speed, thereby reducing fuel consumption and improving energy utilization. Similarly, applying artificial intelligence to fuel cell management systems could enable dynamic optimization of hydrogen usage under varying road conditions. Such AI-driven systems would not only enhance fuel efficiency but also extend driving range, marking a critical advancement for fuel cell vehicle competitiveness.

5. Conclusion

The discussion in this paper on current fuel cell vehicles and vehicle-mounted fuel cells shows that the current situation of vehicle-mounted fuel cell technology is dominated by PEMFCs, while SOFCs are still under research. Currently, the adoption of passenger fuel cell vehicles remains low due to issues such as inadequate infrastructure and high operating costs. PEMFCs have become the mainstream automotive fuel cell due to its simplicity, but it faces challenges in hydrogen storage and transportation. However, methanol can be used as an alternative to hydrogen fuel. Meanwhile, SOFCs (Solid Oxide Fuel Cells) have advantages in terms of fuel flexibility and lifespan, but their commercialization is limited by high material costs and excessively long startup times.

Therefore, the fuel cell industry must strengthen the research and development of electrolyte or electrode materials to produce high-performance materials with market competitiveness in the future, accelerate the construction of industrial chains to further reduce vehicle operating costs and promote the adoption of fuel cell vehicles. At the same time, intensify research and development of related technologies, this will help enhance the safety and stability of fuel cells.

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