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Research Progress on Different Types of Hydrogen Fuel Cells

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Abstract:
As a clean and sustainable form of energy, Hydrogen Fuel Cells are regarded as a part of the key technologies of renewable energy. Hydrogen fuel cells, as the core of a new type of energy, can generate electricity solely by consuming the raw material water. During the process of energy generation, no chemical pollution is produced, which plays a key role in energy security and environmental protection. This paper systematically reviews the research progress of hydrogen fuel cell technology through literature study, focusing on the working principles, technical characteristics and application status of proton exchange membrane fuel cells, alkaline fuel cells and anion exchange membrane fuel cells. It is found that hydrogen fuel cells dominate the market due to their high energy density and zero end-point emissions. However, their production process consumes high energy, and their instability imposes extremely high requirements on transportation and storage. Hydrogen fuel cells have indeed shown great potential in the field of environmental protection, but their commercialization process still faces some challenges. Fuel cell technology faces issues such as material stability and hydrogen leakage in practical applications. To promote the development of this technology, this article will start from analyzing the working mechanisms of different types of fuel cells and explore the future development prospects of materials.

Keywords: Green energy; fuel cells; development prospects.

1. Introduction

Global climate change and energy security issues are becoming increasingly serious, and the large-scale use of fossil fuels such as coal and oil has led to sustained greenhouse gas emissions, exacerbating climate change and posing long-term risks of resource depletion to humanity. In this context, developing clean, efficient, and sustainable alternative energy has become a global strategic consensus. Hydrogen energy, as an energy carrier with high energy density and zero carbon emissions at the end of use, is regarded as an important way to promote the transformation of energy structure. Among them, hydrogen fuel cells

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play an irreplaceable key role as the core device that directly converts hydrogen energy into electrical energy [1].

The transportation industry is one of the main sectors responsible for fossil energy consumption and carbon emissions. Especially for heavy mobile equipment such as commercial vehicles and ships, due to their high durability and heavy load requirements, it is difficult to achieve deep decarbonization solely relying on power batteries. The energy conversion efficiency of traditional internal combustion engine vehicles is only 25% -40%, while emitting a large amount of pollutants such as nitrogen oxides and particulate matter. Hydrogen fuel cell vehicles combine the advantages of zero emissions, fast energy replenishment, and long range, making them an ideal solution to address decarbonization challenges in the transportation sector.

Hydrogen, as a clean and low-carbon energy carrier, can be converted into usable energy through methods such as fuel cell power generation, driving turbines, or direct combustion of internal combustion engines. Due to its zero carbon emission form during use, hydrogen is considered an important choice for promoting deep decarbonization in the automotive industry. Among its multiple utilization methods, compared with traditional energy conversion modes (such as internal combustion engine combustion), fuel cell technology not only breaks the single dependence on fossil fuels but also significantly improves energy conversion efficiency—for example, the theoretical efficiency of hydrogen fuel cells can reach more than 60%, far exceeding the average efficiency of 25%-40% of traditional internal combustion engines, fundamentally reducing energy loss.

Of particular importance is the production and application of "green hydrogen" (hydrogen produced by electrolyzing water using reproducible energy): although the current cost of green hydrogen is still affected by factors such as geopolitics (e.g., the stability of renewable energy equipment supply chains) and price fluctuations of traditional fossil fuels (e.g., cost competition from gray hydrogen/ blue hydrogen), its near-zero carbon emission characteristic throughout the entire life cycle has enabled it to continuously receive high attention from both policy and industrial levels under the global "dual carbon" goals. In China, the strategic position of hydrogen energy is becoming increasingly clear. In 2019, hydrogen energy, which can be regarded as a key node in China's hydrogen energy development, was included in the government work report for the first time [2]. This not only means that it has been officially included in the strategic layout of national energy transformation, but also marks the confirmation of its identity as a key development direction.

This article focuses on the working principles of various hydrogen fuel cells, and systematically explores the influence of material selection on energy storage performance by comparing and analyzing the characteristics and performance differences of materials used in different types of batteries. The article will review typical technical routes of proton exchange membrane fuel cells (PEMFC), alkaline fuel cells (AFC), and anion exchange membrane fuel cells (AEMFC), summarize their material system status, and based on this, look forward to the future development trend of fuel cell materials, in order to provide reference for the development of hydrogen fuel cells that combine high energy density and long service life.

2. Working Principle, Structure and Characteristics of Hydrogen Fuel Cells

The working principle of a hydrogen fuel cell is actually very simple: it uses the electrochemical reaction between hydrogen and oxygen to directly convert hydrogen energy into electrical and thermal energy, without the need for other complex steps. The entire process does not involve combustion and will not cause environmental pollution. Compared with lithium-ion batteries, the structure of hydrogen fuel cells is slightly more complex, mainly including fuel cell stacks and corresponding system components. For a fuel cell system, the core component is the fuel cell stack, which consists of battery cells, current collectors, end plates, sealing rings, and other parts. Among these components, the battery cell is the primary one, and it is composed of a membrane electrode assembly (MEA) and bipolar plates [3]. The membrane electrode assembly (MEA) is the core component of a hydrogen fuel cell. Structurally speaking, it's made up of several key parts—you'll typically find an anode gas diffusion layer, an anode catalyst layer, a proton exchange membrane, along with a cathode catalyst layer and a cathode gas diffusion layer. As the critical determinant, the MEA governs the fuel cell's power density, durability, and service life [4].

3. The Hydrogen Fuel Cells

3.1 The Current Development Status of Hydrogen Cells Abroad

In the 1970s, Americans started to research the fuel cells. Owing to its long-standing investment in research, it currently holds a wealth of cutting-edge technologies in the field of fuel cells. Currently, a number of fuel cell-based products in the United States have entered commercial promotion, such as fuel cell-powered forklifts and fuel cell-based backup power supplies. Currently, several other fuel cell-related products—including passenger vehicles equipped with fuel cell technology—are getting promotion support through government subsidies. Besides that, certain types of fuel cell vehicles, such as buses, trucks, and commercial models, are still in the experimental stage. In 2018, the United States took on the role of Chair for the International Partnership for Hydrogen and Fuel Cells in the Economy (IPHE) [5].

Japan and South Korea are global leaders in the field of fuel cell research, and companies such as Nissan, Toyota, and Hyundai have mastered cutting-edge technologies in the industry. However, the two countries also face different challenges in the process of industrialization. Japan has achieved large-scale production of hydrogen fuel cell vehicles, but has not yet established a complete hydrogen energy industry chain, which hinders its sustainable development in the future. South Korea is mainly limited by insufficient hydrogen refueling infrastructure - the number of hydrogen refueling stations is severely lacking, making it difficult to meet actual demand; In addition, compared to traditional fuel vehicles, the longer waiting time for refueling further hinders the widespread acceptance and technology promotion process among users.

3.2 The Domestic Development Status of Hydrogen Cells

These days, China stands second in the world when it comes to the number of patent applications for hydrogen fuel cells and related areas. But when it comes to core technologies and overall technical strength, it still falls behind the top countries. A case in point: China didn't file its first invention patent related to hydrogen fuel cells until 1998. Even now, though China has applied for a huge number of fuel cell-related patents, core ones only make up around 1% of the global total—and that definitely brings some challenges to the development of China's hydrogen energy industry [6].

3.3 The Types of Hydrogen Cell

3.3.1 PEM-based fuel cell

Known as PEMFC, the Proton Exchange Membrane Fuel Cell works as a device: it uses an electrochemical reaction to convert the chemical energy of hydrogen straight into electrical energy. Its core relies on the proton exchange membrane's ability to „conduct protons while blocking electrons" A Proton Exchange Exchange Membrane Fuel Cell (PEMFC) working unit typically consists of a Membrane Electrode Assembly (MEA) and a Bi Polar Plate (BPP). The MEA is composed of a Gas Diffusion Layer (GDL), a Micro Porous Layer (MPL), a Catalyst Layer (CL), and a Proton Exchange Membrane (PEM). The membrane electrode assembly exhibits a symmetric structure with the proton exchange membrane as the central plane [7]. The catalyst layer (CL) is the core area for reactions, with Pt and Pt-based catalysts commonly used. The proton exchange membrane is responsible for proton conduction, electron blocking, and isolation of the anode and cathode. The energy conversion of fuel cells requires precise collaboration among all these components.

Proton Exchange Membrane Fuel Cells (PEMFCs) are a leading fuel cell technology, widely applied in transportation (e.g., fuel cell vehicles) and distributed power. Their advantages stem from low operating temperatures and high efficiency, while limitations mainly lie in cost and fuel-related challenges.

3.3.2 Alkaline fuel cells

A typical AFC consists of five key component : Anode, Cathode, Alkaline Electrolyte, Separator and Bipolar Plates. AFCs rely on electrochemical reactions in an alkaline environment to convert chemical energy into electricity, with hydrogen (H_2) as the typical fuel and oxygen (O_2) as the oxidant.

Alkaline Fuel Cells (AFCs) count among the earliest fuel cell technologies that have been commercialized, and their operation relies on an alkaline electrolyte environment. Their core strengths are tied to low catalyst costs, while their main drawbacks have to do with electrolyte sensitivity and limits on where they can be applied.

Unlike PEMFCs that use expensive platinum catalysts, AFC can use non precious metals such as nickel, silver, and manganese dioxide as catalysts in both the anode and cathode, significantly reducing material costs. In addition, the alkaline environment promotes the kinetic process of cathodic oxygen reduction reaction (ORR), which not only reduces the dependence on highly active precious metal catalysts, but also improves the reaction efficiency.

These precipitates block electrode pores and degrade electrolyte conductivity, requiring CO_2-free oxidants or costly CO_2 removal systems. Traditional liquid-electrolyte AFCs face electrolyte leakage, which corrodes components and shortens service life [8]. While solid alkaline membranes (for AMFCs, a subset of AFCs) solve this, their conductivity and stability still lag behind PEMFC membranes.

Besides, AFCs typically have a power density of 50–150 mW/cm², far lower than PEMFCs (300–500 mW/cm²), limiting their use in high-power scenarios (e.g., passenger vehicles) [9].

3.3.2 Anion exchange membrane fuel cells

Compared to proton exchange membrane fuel cells (PEMFCs), anion exchange membrane fuel cells (AEMFCs) are seen as a more cost-effective technology. But AEMFCs

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still can't match PEMFCs in terms of performance and durability—and the main reason is trickier water management.

H_2 reacts with OH^- to produce H_2O and release electrons: $H_2 + 2OH^- \rightarrow 2H_2O + 2e^-$ (electrons flow through external circuit to generate current). OH^- migrates from cathode to anode through AEM, maintaining charge balance. O_2 combines with electrons (from external circuit) and H_2O to generate OH^-: $O_2 + 2H_2O + 4e^- \rightarrow 4OH^-$. $2H_2 + O_2 \rightarrow 2H_2O$ (zero pollutant emissions) [10].

Anion exchange membrane fuel cell (AEMFC), as a promising fuel cell technology, has many advantages. In terms of catalysts, AEMFC can use non precious metals such as nickel based materials as anode catalysts, while cobalt nitride, carbon materials, or manganese dioxide can be used as cathodes, thereby eliminating dependence on expensive platinum catalysts and significantly reducing material costs. The core component of the anion exchange membrane serves as a solid ion conductor, effectively avoiding potential leakage problems of liquid electrolytes and improving the stability and reliability of the system.

In addition, compared to traditional alkaline fuel cells, AEMFC exhibits better carbon dioxide tolerance by directly using air as the oxidant. In addition, the battery is compatible with liquid fuels such as low purity hydrogen and even methanol, reducing reliance on high-purity fuels and expanding its practical application range.

Despite its significant advantages, AEMFC still faces several technical bottlenecks in the large-scale commercialization process. The widely used anion exchange membranes still have shortcomings in comprehensive performance: their key functional groups (such as quaternary ammonium groups) are prone to degradation in alkaline working environments, resulting in poor chemical stability; Meanwhile, the conductivity efficiency of hydroxide ions (OH^-) in the membrane is generally lower than the proton conductivity in the proton exchange membrane [11]. Water management is another key challenge: insufficient moisture can affect the ion transport process, while excessive moisture can easily cause electrode „flooding", hindering the reaction gases from reaching the active sites of the catalyst, thereby affecting the overall performance of the battery.

4. The Development and Prospects of Fuel Cells

Due to its advantages of zero emissions, clean and renewable, and high energy density, fuel cells have shown broad development prospects. The current research focus is gradually shifting towards low platinum or even platinum free catalyst systems. In addition, the performance of membrane electrode components directly determines the efficiency of the entire system. With the continuous development of new proton exchange materials and the optimization of hydrothermal management design, the service life of these core components has greatly increased. It is worth noting that modern fuel cell systems are rapidly developing towards intelligence - by introducing advanced control algorithms, the system can accurately adjust intake and cooling parameters in real time, thereby significantly improving output power levels and dynamic response performance.

In terms of cost, the fuel cell industry is shifting from "technology cost reduction" to "scale cost reduction". The application of hydrogen fuel cells in commercial fields such as trucks and buses is gradually becoming popular. Once mass production is achieved, the unit cost of core components such as stacks and air compressors will significantly decrease. At the same time, with the reduction of wind and photovoltaic costs, the price of "green hydrogen" produced from renewable energy is becoming increasingly competitive, which further promotes the commercialization process of the entire hydrogen fuel cell industry chain.

5. Conclusion

Through literature research and systematic analysis, under the promotion of energy transformation and the „dual carbon" goal, hydrogen fuel cells, as the core device for efficient conversion of hydrogen energy, have become a key path for achieving deep decarbonization in the transportation sector due to their zero terminal emissions, high energy density, and long range adaptability. From a technical perspective, proton exchange membrane fuel cells are most widely used in vehicle scenarios due to their low operating temperature and high power density. However, their development is constrained by the cost of platinum catalysts and hydrogen purity requirements; Alkaline fuel cells can use non precious metal catalysts to effectively reduce costs and have excellent reaction kinetics, but problems such as sensitivity to CO_2, easy leakage of liquid electrolytes, and low power density are still prominent; As an emerging route, anion exchange membrane fuel cells have the advantages of solid-state structure and low-cost catalysts. By regulating the hydrophilicity of polymers, their performance and durability can be further improved. However, current water management challenges and membrane stability still hinder their commercialization process.

From the perspective of industrial development, internationally, the United States, Japan, and Korea lead in hydrogen fuel cell technology research and product implementation (such as Toyota fuel cell vehicles, American fuel cell forklifts), but they respectively face issues such as reliance on subsidies, incomplete hydrogen industry chain, and insufficient hydrogen refueling stations; although China ranks second in the global number of related patents, the proportion of core patents is only about 1%, and its core technology and comprehensive strength still lag behind the international leading level. In summary, hydrogen fuel cell technology has formed a „parallel development of multiple types, with vehicle scenarios as the core breakthrough point" pattern, but material performance, cost control, and industrial chain support are still key bottlenecks restricting its large-scale application.

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