Hydrogen energy vehicle progress and prospect

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Abstract. Hydrogen energy vehicles, as one of the key technologies to address climate change and energy crises, have attracted widespread attention regarding their current development status and future prospects. This article reviews the progress in key technologies for hydrogen energy vehicles, including catalysts, proton exchange membranes, and bipolar plate materials, which are crucial for enhancing the performance and reducing the costs of hydrogen energy vehicles. Despite the significant potential of hydrogen energy vehicles in terms of efficiency and environmental protection, their commercialization process still faces numerous technical challenges and cost barriers, such as the current issues with hydrogen storage and transportation. The article analyzes the existing technological bottlenecks and discusses potential future technological breakthroughs that could help hydrogen energy vehicles play a more important role in the field of sustainable transportation. With technological advancements and cost reductions related to hydrogen energy vehicles, it is expected that in the near future, hydrogen energy vehicles will become a significant force in promoting environmental protection and energy transition.

Keywords: Hydrogen energy vehicles, catalysts, proton exchange membranes, bipolar plate materials.

1. Introduction

With the intensification of the global energy crisis and the increasingly severe environmental pollution issues, the search for clean, sustainable energy has become an urgent need for the global energy transition. Against this backdrop, hydrogen energy vehicles, as a new type of clean energy transportation tool, have attracted widespread attention due to their unique environmental protection characteristics and energy efficiency. Particularly, hydrogen fuel cell technology stands out as it converts chemical energy directly into electrical energy through electrocatalysts that facilitate the oxidation of hydrogen and the reduction of oxygen, demonstrating high efficiency and environmental friendliness. In this system, hydrogen gas under high pressure is decomposed into two hydrogen ions and two electrons by platinum catalysts. These electrons form a powerful electric current that drives the vehicle's electric motor, while hydrogen ions combine with oxygen to form water, which is expelled as a liquid [1].

Electrocatalysts, as one of the core materials in hydrogen fuel cells, directly affect the cell's discharge performance and lifespan, and are key to improving battery efficiency and reducing costs. Currently, precious metals like Pt and its alloys remain the best catalysts for catalyzing these reactions [2]. With the development of new technologies, platinum-free catalysts and other technological advancements have also emerged. Proton Exchange Membrane Fuel Cells (PEMFCs)utilize proton-conducting materials as electrolytes. Compared to conventional fuel cells, they have the advantages of fast start-up at room temperature, no electrolyte loss, and high specific power and energy density. The proton exchange membrane, as a core material of the fuel cell, significantly impacts the stability and durability of the fuel cell [3]. Despite the significant environmental and efficiency advantages of hydrogen energy vehicles, their technological development still faces many challenges, including the cost of hydrogen itself and the safety issues related to storage and transportation.

In summary, the technological development of hydrogen energy vehicles is an important way to achieve the goals of energy transition and environmental protection. With continuous technological progress, the future prospects of hydrogen energy vehicles are promising. Based on the research background, this article will analyze the technical details of hydrogen energy vehicles in detail, discuss the challenges and opportunities they may face in the future, as well as the development and breakthroughs of related technologies in the future.

2. Introduction to Hydrogen Energy Vehicle Technology

2.1. The Working Principle of Hydrogen Energy Vehicles

The working principle of hydrogen energy vehicles mainly relies on hydrogen fuel cell technology. Hydrogen fuel cells enable hydrogen and oxygen to react without combustion, converting hydrogen energy into electrical energy. The chemical reactions in hydrogen fuel cells primarily include an oxidation reaction at the anode (hydrogen electrode) and a reduction reaction at the cathode (oxygen electrode). The electrochemical process of hydrogen fuel cells involves three key components: catalysts, proton exchange membranes, and bipolar plates.

Catalysts, typically made of platinum (Pt) or other precious metal materials, are used to accelerate the chemical reactions at both the anode and cathode. At the anode, the catalyst prompts hydrogen molecules to decompose into protons and electrons; at the cathode, the catalyst facilitates the combination of oxygen, protons, and electrons to produce water.

A proton exchange membrane is a special polymer membrane that allows protons to pass through but blocks electrons. In this way, protons move from the anode to the cathode, while electrons are forced to flow through an external circuit, generating a current. The proton exchange membrane also serves to isolate hydrogen and oxygen, preventing them from directly contacting and exploding.

Bipolar plates are structural components in fuel cell stacks that separate individual fuel cell units and provide channels for gas flow. Bipolar plates are usually made of graphite composites or metals, possessing good electrical conductivity and corrosion resistance. These plates account for more than 70% of the total mass and approximately 50% of the total volume of the fuel cell stack, and their cost constitutes 30% to 50% of the total cost of the battery. Therefore, bipolar plates are an indispensable component of the battery [4].

2.2. Advantages and Characteristics of Hydrogen Energy Vehicles

Firstly, hydrogen energy vehicles have the advantage of zero emissions. They only emit water vapor during operation, resulting in no tailpipe emissions and thus causing no environmental pollution. Compared to traditional engines, hydrogen energy vehicles can effectively reduce the greenhouse effect and environmental pollution, making them a clean energy solution. Since hydrogen energy vehicles produce only water after the reaction, they achieve true zero emissions, playing a vital role in addressing environmental challenges and ensuring national energy security [5].

Secondly, hydrogen energy vehicles have the advantage of high-energy conversion efficiency. Hydrogen, as an energy source, has an excellent energy content, with its energy release per unit mass being three times that of traditional gasoline, and more than 30 times that of the batteries used in electric vehicles. This high energy content allows vehicles to travel long distances with only a small amount of hydrogen fuel. In terms of energy conversion efficiency, hydrogen fuel cells also perform exceptionally well, with an efficiency that can exceed 50%, which is significantly higher than the energy utilization rate of gasoline engines, thereby greatly enhancing overall energy efficiency [5].

Lastly, hydrogen energy vehicles have better low-temperature adaptability compared to electric vehicles. Hydrogen energy vehicles can operate normally at very low temperatures, whereas the performance of electric vehicles declines in such conditions. Low temperatures increase the viscosity of the electrolyte in electric vehicle batteries, slow the migration speed of lithium ions, reduce battery capacity, increase internal resistance, and lower discharge efficiency. Below -10°C, electric vehicles experience performance degradation, including longer charging times, reduced charge and discharge capacity, diminished battery capacity, and faster battery discharge rates, which affect the driving range of electric vehicles.

2.3. Key Technologies for Hydrogen Energy Vehicles

2.3.1. Hydrogen Fuel Cell Catalyst Technology

In hydrogen fuel cells, the hydrogen oxidation reaction (HOR)primarily occurs at the anode, while the oxygen reduction reaction (ORR) takes place at the cathode. The HOR at the anode is a fast kinetic process, whereas the ORR at the cathode involves multiple electron transfer and proton transfer steps, making its kinetic process relatively slow, with a reaction rate about five orders of magnitude slower than HOR. Therefore, the rate of the ORR has become the main factor limiting the power output of hydrogen fuel cells [6]. Platinum (Pt)and its alloys are widely considered the most effective catalysts for both HOR and ORR due to their excellent catalytic performance. However, the high cost, limited resource reserves, and susceptibility to poisoning during use limit the feasibility of their large-scale commercial application in hydrogen fuel cells. These challenges have prompted researchers to seek solutions to reduce catalyst costs, improve the kinetic performance of the ORR, and enhance catalyst durability. Against this backdrop, catalyst preparation technology has been advancing, and the development of ORR catalysts has shown a trend of diversification based on factors such as catalyst structure, morphology, and elemental composition. ORR catalysts are roughly divided into six major categories [7], namely Pt/C catalysts, platinum-based alloy catalysts, core-shell structured catalysts, non-precious metal catalysts, morphology-controlled catalysts, and nano-framework structured catalysts [8].

Despite the many advantages of fuel cells, their large-scale commercialization process has always been constrained by technical and economic barriers. One of the main obstacles is the substantial demand for the rare and expensive platinum (Pt)in catalysts, which limits the widespread application of fuel cells. Therefore, the development of efficient and stable non-platinum catalysts has become particularly critical.

The development of platinum-free catalysts is currently focused on palladium-based catalysts, transition metal nitrogen-doped carbon material catalysts, metal oxide catalysts, and non-metal carbon-based material catalysts. The key to platinum-free catalysts is to approach the overpotential of platinum-based ORR or enhance the catalyst's own adsorption of oxygen. The performance of known platinum-free catalysts still has a gap compared to platinum-based fuel cells, but their development is rapid, and performance is improving year by year, showing a promising prospect [9].

2.3.2. Proton Exchange Membrane Fuel Cell technology

Proton Exchange Membrane Fuel Cells are favored for their high energy conversion efficiency, rapid start-up capability, and longer service life. These batteries maintain good working performance at lower temperatures. Currently, the research and development of hydrogen fuel cells are mainly focused on Proton Exchange Membrane Fuel Cells. According to the different polymer matrix, proton exchange membranes are mainly divided into three categories: perfluoro sulfonic acid proton membranes, partially fluorinated polymer proton membranes, and non-fluorinated polymer proton membranes [10].

Perfluoro sulfonic Acid (PFSA)proton exchange membranes are the most widely used proton exchange membrane system at present, with excellent chemical and physical stability, and high proton conductivity. Although the industrialization process is in an absolute leading position, PFSA proton membranes also have issues such as easy degradation under high-temperature conditions, low proton conductivity under low-humidity conditions, and high costs. Therefore, researchers have begun to shift the focus of development to the preparation of partially fluorinated polymer proton exchange membranes [10].

Partially fluorinated polymer proton exchange membranes use non-perfluoro polymers as the base material, such as polytrifluorostyrene, polyvinylidene fluoride (PVDF), etc., which are made into membrane materials through specific modification processes. Polytrifluorostyrene sulfonic acid membranes are the pioneering products of partially fluorinated polymer proton exchange membranes. These membranes are prepared by introducing non-fluorinated functional groups into the molecular chains of polytrifluorostyrene and through sulfonation reactions. The BAM3G series developed by

Ballard Power Systems in Canada is a typical representative of such products. They significantly improve the stability of the membrane, with a service life exceeding 1000 hours, while reducing the overall fluorine content of the polymer [11]. Compared to perfluoro sulfonic acid membranes (PFSA), the BAM3G series is lower in cost. Although there is still room for performance improvement, it has shown certain commercial potential [10].

Due to the cost, performance limitations in high-temperature, low-humidity environments, and inevitable environmental issues in the production and processing of perfluoro polymer and partially fluorinated polymer proton exchange membranes, researchers have begun to turn their attention to non-fluorinated polymers for the preparation of proton exchange membranes. Research in this field has become a hot topic because non-fluorinated polymer proton exchange membranes show potential advantages in cost-effectiveness, environmental impact, and performance. Non-fluorinated polymer proton exchange membranes are usually prepared using aromatic polymers with benzene ring structures as the main chain, and their proton conductivity is improved by sulfonation modification, such as sulfonated poly (arylene ether sulfone), sulfonated poly ether ketone, sulfonated polyimide, polybenzimidazole, etc. Although fluorine-free proton exchange membranes are relatively inexpensive and easy to prepare, they lack the strong carbon-fluorine bonds, leading to a short service life. The comprehensive performance of newly developed materials is still difficult to surpass the commercially available perfluoro sulfonic acid proton exchange membranes [10].

2.3.3. Bipolar Plate Technology

The bipolar plates (BPs) in hydrogen fuel cells, also known as flow field plates, serve to separate reactant gases, remove heat, and discharge chemical reaction products (water). Based on the type of substrate material, they can be classified as graphite BPs, metal BPs, and composite material BPs. Graphite-based bipolar plates (BPs) occupy a dominant position in commercial applications due to their excellent electrical conductivity and corrosion resistance, with a relatively high level of technological maturity [10]. However, they suffer from inadequate mechanical strength and difficulties in achieving significant thickness reduction, which limits their use in applications requiring compact design and impact resistance.

Given these limitations, metal bipolar plates have emerged as a research focus due to their performance and cost-effectiveness. These metal BPs typically have a thickness not exceeding 0.2 millimeters, which not only significantly reduces volume and mass but also greatly enhances the power density of the fuel cell stack [12]. Metal BPs also exhibit good ductility, enabling them to adapt to different shapes and size requirements. Furthermore, they perform well in terms of electrical and thermal conductivity and have high fracture toughness. However, the corrosion resistance of metal bipolar plates (BPs) is relatively weak, particularly in acidic environments, where metals can easily dissolve, and the released ions may cause poisoning effects on the membrane electrode assembly. As the solubility of metal ions increases, the ohmic resistance also increases, leading to a decrease in the output power of the hydrogen fuel cell.

To improve the corrosion resistance of metal BPs, two approaches can be taken: firstly, applying a corrosion-resistant protective layer on the surface of the metal BPs, such as precious metals, metal compounds, or carbon-based films (e.g., diamond-like carbon films, graphite films, polyaniline films, etc.); secondly, developing composite material BPs. These composite material BPs consist of corrosion-resistant thermoset or thermoplastic resins, polymer materials, and conductive fillers, which can be metal-based or carbon-based composites (such as graphite, carbon fibers, carbon black, carbon nanotubes, etc.). Novel polymer/carbon composite material BPs offer advantages such as low cost, strong corrosion resistance, and light weight, making them ideal substitutes for metal BPs and pure graphite bipolar plates (PBs).

3. The technological challenges and future development trends of hydrogen energy vehicles

3.1. Technical challenge

Firstly, the high price of hydrogen remains a significant issue. This is not only related to the current lack of widespread adoption of hydrogen fuel cell vehicles but also to several other factors. These include high manufacturing costs, difficulties in purification, and unresolved challenges in hydrogen storage technology. Hydrogen used in fuel cell vehicles requires a purity level of over 99%, and purification technologies need further advancement to meet these high-purity demands. Technologies such as pressure swing adsorption, metal hydride methods, catalytic oxygen removal, and molecular sieves are employed for hydrogen purification. However, these technologies still face challenges in controlling hydrogen purity and maintaining stability. Storage technologies, such as high-pressure gaseous storage, cryogenic liquid storage, and solid-state storage, all have bottlenecks. The development of these technologies is crucial for the future of hydrogen energy vehicles.

Secondly, hydrogen, as a highly reactive gas, indeed poses certain safety challenges. In open spaces, hydrogen diffuses very quickly, at a rate 12 times faster than gasoline. This means that once hydrogen leaks into the air, even a small spark can cause an explosion if it reaches a certain concentration, leading to severe safety risks. Therefore, the consequences of hydrogen leakage could be catastrophic, imposing extremely high safety requirements for the storage and transportation of hydrogen [13].

Thirdly, hydrogen transportation technology also faces significant challenges. When metal materials are in long-term contact with hydrogen, hydrogen may infiltrate the material, causing a reduction in material strength, an acceleration in crack propagation, and a decrease in fracture toughness. This leads to risks such as hydrogen embrittlement, permeation, and leakage.

3.2. Future Technology Development Trend

Exploring and developing low-cost yet efficient catalysts is crucial for the development of hydrogen energy vehicles. To promote the widespread application of hydrogen energy vehicles, accelerating research on such catalysts is key. Future research will focus on metal surface treatment, development of alloy materials, improvement of non-metal composite materials, and the application of graphene technology. These research directions will help develop catalysts for hydrogen fuel vehicles that are highly active, stable, and resistant to decay.

Proton exchange membranes are key components in hydrogen fuel cell vehicles, responsible for facilitating the chemical reactions within. Although there are some exchange membrane products on the market, their efficiency is not high and the cost is expensive in practical applications, which limits the further development of hydrogen fuel cell vehicles. Therefore, future research trends will focus on developing new materials and improving the molecular structure and functional groups of materials to enhance the stability and proton conductivity of the membrane, and reduce costs. These efforts aim to improve the durability of fuel cells to meet the needs of long-term operation, which is of great significance to the industrial development of hydrogen fuel cell vehicles.

The quality and cost of bipolar plate materials directly relate to the service life, performance, and manufacturing cost of hydrogen fuel cells. Therefore, finding suitable bipolar plate materials and optimizing their structural design is crucial. Enhancing the corrosion resistance and stability of low-cost, high-conductivity metal bipolar plates through surface modification technology, and innovating the flow field design on the plate surface using bionics and natural laws, will be key research directions for improving the performance of bipolar plates and extending the life of hydrogen fuel cells in the future [4].

4. Conclusion

This article provides a comprehensive analysis of the current status and prospects of hydrogen energy vehicles, from which we conclude that hydrogen energy vehicle technology is gradually maturing, but breakthroughs are still needed in key materials and technologies to achieve broader market application. The article organizes the research progress on key technologies such as catalysts, proton exchange membranes, and bipolar plate materials, from the working principle, key technologies, technical challenges to future development trends of hydrogen energy vehicles. Research on catalysts has promoted metal surface modification, alloy development, and the transformation of non-metal composite materials to improve performance and reduce costs. The technological development of proton exchange membranes has increased conductivity and stability through the application of new materials and molecular structure modification, while also reducing costs. Research on bipolar plate materials focuses on enhancing corrosion resistance and mechanical strength to improve the durability and reliability of the battery. Continuing to optimize catalyst performance, improve the conductivity and stability of proton exchange membranes, and develop more durable bipolar plate materials will be the main directions for the future development of hydrogen energy vehicles. Overall, the prospects for hydrogen energy vehicles are promising, and they are expected to play an important role in the future transportation sector.

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