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Current Status and Prospects of Direct Hydrogen Production from Seawater in China

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Abstract: This paper summarizes the current research status and future outlook of direct hydrogen production technology from seawater in China. With the growth of global energy demand and prominent environmental problems, hydrogen energy has been attracting attention as a kind of clean energy. The research on direct hydrogen production from seawater in China involves various fields such as electrolysis of water, photoelectrochemistry, electrocatalysis, membrane technology and polygeneration technology, and has made progress in demonstration projects, joint test bases, system integration and optimization, and industrial chain development. Technology application scenarios include offshore oil platforms, coastal islands, ocean development and protection, emergency energy supply and industrial parks. Looking ahead, China will focus on technology development priorities such as high-efficiency catalysts, advanced membrane technology, intelligent control systems, optimization of multi-generation technology, application of new energy integration technology, exploration of low-cost materials and improvement of seawater pretreatment technology. At the same time, it will promote the large-scale application and industrialization of seawater direct hydrogen production technology by constructing large-scale demonstration projects, perfecting industrial chain, expanding policy support and financing channels, strengthening international cooperation and technical exchanges, building human resources, as well as market promotion and application scenario expansion.

Keywords: China; Seawater Hydrogen Production; Status Quo; Outlook.

1. Introduction

As global energy demand continues to grow and environmental issues become more prominent, the search for clean and sustainable forms of energy becomes particularly important. Hydrogen energy, as an efficient and clean energy carrier, has been widely concerned. However, conventional hydrogen production mainly relies on fossil fuels, which not only leads to a large amount of carbon dioxide emissions, but also faces the problem of limited resources. As one of the most abundant natural resources on earth, the direct use of seawater for hydrogen production can not only solve the water and energy problems in hydrogen production, but also greatly reduce carbon emissions, which is of great significance for promoting the green energy revolution [1].

China's energy structure is dominated by coal, and energy transformation is facing great pressure and challenge. In recent years, the Chinese government has attached great importance to the development of new and clean energy, and proposed a "dual carbon" goal, that is, strive to achieve carbon peak by 2030 and carbon neutrality by 2060. In this context, seawater direct hydrogen production technology, as a cutting-edge clean energy technology, has been widely concerned. Chinese scientific research institutions and enterprises have carried out a lot of research and exploration in this field, and achieved certain results, but at the same time, they are also facing technical bottlenecks and challenges.

This paper systematically reviews the current research status of direct hydrogen production from seawater in China, analyzes the development of its technology research, technology application and application scenarios, and looks forward to the future focus of technology development and research and application, in order to provide references for research and application in related fields.

2. China's Direct Hydrogen Production from Seawater Research Status

2.1. Current Status of Technology Research

Direct hydrogen production from seawater is a complex multidisciplinary cross-research field, involving electrochemistry, materials science, chemical engineering and other disciplines. At present, China's direct hydrogen production from seawater technology research is mainly focused on the following aspects [2] [3].

2.1.1. Water Electrolysis Technology

Hydrogen production by electrolysis of water is one of the most direct and mature methods of hydrogen production, but its high demand for electrical energy limits its wide application. In recent years, Chinese research organizations have made significant progress in electrolysis water technology. For example, the proton exchange membrane (PEM) water electrolysis technology developed by the Dalian Institute of Chemical Physics of the Chinese Academy of Sciences (CAS) has made breakthroughs in the integration of seawater desalination and electrolysis, and improved the electrolysis efficiency and stability [4].

2.1.2. Photoelectrochemical Technology

Photoelectrochemical (PEC) technology utilizes solar energy to directly convert seawater into hydrogen, which is a highly promising green method for hydrogen production. Some universities and research institutes in China, such as

Tsinghua University and Peking University, have conducted in-depth research on photoelectrocatalytic materials and the design of photoelectrochemical reactors. For example, Tsinghua University has developed a new type of photoelectrocatalytic material based on cobalt-based oxides, which has reached the international advanced level in terms of sunlight-electricity-hydrogen conversion efficiency.

2.1.3. Electrocatalytic Technology

Electrocatalytic technology plays a key role in direct hydrogen production from seawater, especially in the selection and modification of electrode materials. Chinese research institutions have made important progress in the development of high-efficiency electrocatalysts. For example, the University of Science and Technology of China (USTC) has developed a nitrogen-doped graphene-based composite material that significantly improves the activity and stability of the electrocatalyst. In addition, the research team has explored the optimized design of a seawater direct electrolysis hydrogen production plant, and achieved good experimental results.

2.1.4. Membrane Technology

Ions and organic matter in seawater have a significant impact on the hydrogen production process, so membrane technology is of great significance in direct seawater hydrogen production. China has strong strength in the R&D and application of membrane materials. For example, palladium-based composite membranes developed by the Institute of Process Engineering of the Chinese Academy of Sciences (IPE, CAS), which are resistant to seawater corrosion, have demonstrated excellent performance in direct seawater electrolysis for hydrogen production. In addition, the team has conducted in-depth research on the integrated design and process optimization of membrane reactors, which has greatly improved the efficiency of hydrogen production.

2.1.5. Polygeneration Technology

Polygeneration technology combines seawater hydrogen production with other energy production and resource recovery, which can improve the overall energy utilization efficiency. Chinese research institutions have carried out preliminary exploration in direct hydrogen production from seawater and cogeneration technologies such as seawater desalination and cogeneration. For example, Ocean University of China has developed a polygeneration system based on the integration of membrane distillation and electrolysis of water, which achieves efficient synergy in seawater desalination and hydrogen production.

2.2. Current Status of Technology Application

In China, the applied research of seawater direct hydrogen production technology has gradually moved from the laboratory to the industrialization demonstration stage, and some representative application cases and demonstration projects have been initially formed [5].

2.2.1. Demonstration Projects

In recent years, China has established demonstration projects for direct hydrogen production from seawater in several coastal areas to verify the feasibility and stability of the technology through actual operation data. For example, the Chinese Academy of Sciences has built a megawatt-scale seawater electrolysis hydrogen production demonstration project in Hai nan, which integrates advanced electrolyzer, electrocatalyst and membrane technologies, and initially realizes the large-scale application of seawater direct hydrogen production. According to the project data, the hydrogen production efficiency and stability of the demonstration project reached the expected target, providing valuable experience for subsequent large-scale industrialization.

2.2.2. Joint Test Base

In order to accelerate the popularization of the technology application, Chinese research institutions and enterprises have cooperated to establish several joint test bases. For example, Tsinghua University and China National Offshore Oil Corporation (CNOOC) have established a joint test base for direct seawater hydrogen production in Fujian. This base integrates the technical R&D advantages of Tsinghua University and the production management experience of CNOOC, deeply explores the application of seawater direct hydrogen production technology on offshore oil platforms, and preliminarily verifies the feasibility and economy of this technology under actual working conditions.

2.2.3. System Integration and Optimization

With the continuous maturity of technology, the integration and optimization of seawater direct hydrogen production system has become the focus of research. Some research institutions and enterprises in China, such as the China Electric Power Research Institute and the China Three Gorges Corporation, are studying the integration of seawater direct hydrogen production systems with existing energy systems. For example, the comprehensive energy demonstration project built by China Three Gorges Corporation in Zhou shan, Zhe jiang Province, has successfully combined offshore wind power with a direct hydrogen production system from seawater, realizing the efficient use of green energy. The successful operation of the project shows that the technology of direct hydrogen production from seawater has great application potential in renewable energy systems.

2.2.4. Development of Industrial Chain China

has also made remarkable progress in all aspects of the seawater direct hydrogen production industry chain. From the upstream materials and equipment manufacturing, to the midstream hydrogen production system integration, and then to the downstream hydrogen utilization, has initially formed a relatively complete industrial chain. For example, the Institute of Process Engineering of the Chinese Academy of Sciences has conducted in-depth research on the manufacturing and application of electrolytic cells, and the advanced electrolytic cell equipment developed has been applied in a number of demonstration projects in China. In addition, some enterprises have also actively participated in the construction of the industrial chain, such as China Shipbuilding Industry Corporation in seawater hydrogen production equipment manufacturing and application has made a lot of investment, promoting the rapid development of the industrial chain.

2.2.5. Policy Support and Promotion

The Chinese government attaches great importance to the development of seawater direct hydrogen production technology and has introduced a series of policies and measures to support the research and application of this technology. For example, the "14th Five-Year Plan for Modern Energy System" issued by the National Development and Reform Commission clearly points out that it is necessary to actively promote the research and development and demonstration application of cutting-edge technologies such as direct hydrogen production from seawater. Local

governments also responded positively, such as Hai nan Province issued a special policy to support the development of seawater direct hydrogen production technology, providing a strong policy guarantee for the landing and implementation of the project.

2.3. Application Scenario Status China

has made positive progress in the exploration of application scenarios of seawater direct hydrogen production technology, and gradually applied it in many fields, showing broad application prospect and potential [6].

2.3.1. Offshore Oil Platform

As a typical scenario of high energy consumption and high emissions, offshore oil platforms are in urgent need of green energy solutions. By converting seawater directly into hydrogen, the technology not only provides clean energy for offshore platforms, but also reduces carbon dioxide emissions. China National Offshore Oil Corporation Limited has preliminarily verified the feasibility of the application of this technology in offshore platforms in the joint test base built in Fu jian. The test data show that the seawater direct hydrogen production system has high operational stability on the offshore platform, and the energy efficiency is significantly improved compared with the traditional energy system. The successful verification of this application scenario lays a foundation for large-scale promotion in the future.

2.3.2. Coastal Islands

China's coast is dotted with many islands, islands are mainly dependent on external delivery of energy supplies, there are problems of supply instability and high costs. Direct hydrogen production from seawater could provide a reliable source of clean energy for these islands. For example, the demonstration project of megawatt-level seawater electrolysis hydrogen production in Hai nan Province provides a new solution for the energy supply of the surrounding islands. The test data show that the technology has low power consumption and stable hydrogen production in island applications, which can meet the basic energy needs of the island. In addition, the seawater direct hydrogen production system can also be integrated with renewable energy systems such as solar and wind energy to further improve energy efficiency.

2.3.3. Marine Development and Protection

The development of Marine resources and the protection of Marine environment need a lot of clean energy support. Direct hydrogen production from seawater can provide clean energy solutions for Marine scientific investigation, Marine engineering construction and Marine ecological protection. For example, the demonstration project of direct hydrogen production from seawater built by the Chinese Academy of Sciences in Hai nan has been initially applied to the energy supply of Marine scientific research vessels. The experimental data show that the technology has good stability in the Marine environment and has no significant negative impact on the Marine ecology. In the future, the technology of direct hydrogen production from seawater is expected to be widely used in the field of Marine development and protection.

2.3.4. Emergency Energy Supply

In emergencies such as natural disasters, a fast and reliable energy supply is essential. As a green and efficient energy supply method, direct hydrogen production from seawater has high potential for emergency applications. For example, the China Electric Power Research Institute and the China Three Gorges Corporation cooperated to build a comprehensive energy demonstration project for direct hydrogen production from seawater in Zhoushan, Zhe jiang province, successfully verifying the feasibility of the technology in emergency energy supply. Test data show that the system can achieve efficient hydrogen production in a short time to meet emergency energy needs. In the future, the technology is expected to play an important role in emergency energy supplies.

2.3.5. Industrial Park

As a concentrated area with high energy consumption and high emissions, industrial parks are in urgent need of clean energy solutions. Direct hydrogen production from seawater can provide clean hydrogen for industrial parks and reduce carbon emissions in the production process by using local materials. For example, the demonstration project of direct hydrogen production from seawater built by the Dalian Institute of Chemical Physics of the Chinese Academy of Sciences in an industrial park in Shandong province has successfully verified the feasibility of the application of this technology in industrial parks. The experimental data show that the technology has high energy utilization efficiency in industrial parks, and the purity of hydrogen meets the needs of industrial production. In the future, with the further maturity of the technology and the reduction of the cost, the direct hydrogen production technology of seawater is expected to be widely used in industrial parks.

3. Research Prospect of Direct Hydrogen Production from Seawater in China

3.1. Future Technological Development Priorities

The future development of China's seawater direct hydrogen production technology requires breakthroughs in a number of key technology areas to improve hydrogen production efficiency, reduce costs, and enhance system stability, thus promoting the industrialization process of technology. The following are the key directions of future technological development [7].

3.1.1. Research and Development of Efficient Catalysts

Catalysts play an important role in the process of direct hydrogen production from seawater, and efficient and stable catalysts can significantly improve the efficiency of hydrogen production. In the future, China needs to strengthen the research on new metallic catalysts, non-metallic catalysts and bifunctional catalysts. For example, catalysts based on transition metals, precious metals and nanostructures are developed to optimize their electronic structure and surface activity to improve catalytic activity and stability. In addition, the design and preparation of multi-component catalysts are also the focus of future research to further improve catalytic performance through synergistic effects.

3.1.2. Innovation of Advanced Membrane Technology

Ions and organics in seawater have a significant impact on the hydrogen production process, so corrosion-resistant, high-performance membrane materials are essential. In the future, China needs to strengthen the research and development of high-performance membrane materials such as palladium-based composite membranes, polymer membranes and inorganic membranes. For example, doping modification and

nanostructure design can improve the oxidation resistance and ion selectivity of the membrane materials and reduce the mass transfer resistance of the membrane. In addition, the integrated design and process optimization of membrane reactors are also future research priorities to achieve higher hydrogen production efficiency and system stability.

3.1.3. Design of Intelligent Control System

The seawater direct hydrogen production system involves many complicated processes and requires advanced intelligent control system to achieve efficient and stable operation. In the future, China needs to make breakthroughs in intelligent control algorithms, sensor technology and automation equipment. For example, the artificial intelligence control system based on deep learning is developed to monitor and regulate the working state of electrolytic cells, catalysts and membrane materials in real time, optimize operating parameters, and improve the overall efficiency of the system. In addition, the innovation and application of sensor technology is also the focus of future research, through high-precision and high-sensitivity sensors to achieve real-time monitoring and feedback of key parameters.

3.1.4. Optimization of Polygeneration Technology

The organic combination of seawater direct hydrogen production with seawater desalination, cogeneration and other polygeneration technologies can improve the overall energy utilization efficiency. In the future, China needs to strengthen collaborative innovation in these areas. For example, the development of efficient multigeneration systems based on the integration of membrane distillation and electrolytic water, through the cascade utilization of energy and resource recycling, to achieve higher energy efficiency and economic benefits. In addition, the integrated design and operation optimization of polygeneration technology will also be the focus of future research, and the overall system performance will be improved through system engineering methods.

3.1.5. Application of New Energy Integration Technology

The integration of seawater direct hydrogen production technology with renewable energy systems such as solar energy and wind energy can realize the efficient utilization of green energy. In the future, China needs to strengthen technology research and development and application demonstration in these fields. For example, the development of a new energy integrated system based on the integration of solar photovoltaic and electrolytic water will directly convert solar energy into hydrogen and electricity through the photoelectric effect, improving energy conversion efficiency. In addition, the integration of wind power and seawater direct hydrogen production system is also a future research focus, through the seamless connection of wind power and seawater electrolysis, to achieve a continuous supply of green energy.

3.1.6. Exploration of Low-cost Materials

The cost of hydrogen production is a key factor in the industrialization process of seawater direct hydrogen production technology, and the development and application of low-cost materials can significantly reduce the cost of hydrogen production. In the future, China needs to strengthen research in low-cost electrode materials, membrane materials and catalyst materials. For example, developing catalyst and electrode materials based on low-cost metals such as iron, nickel, etc., optimizing their properties through material modification and surface engineering. In addition, the development and application of new carbon-based materials is also the focus of future research, through the innovative design of carbon nanotubes, graphene and other materials, to achieve efficient and low-cost hydrogen production materials.

3.1.7. Improvement of Seawater Pretreatment Technology

The impurities and salts in seawater have significant influence on the hydrogen production process. Efficient seawater pretreatment technology can improve the hydrogen production efficiency and system stability. In the future, China needs to strengthen research on pretreatment technologies such as seawater desalination, seawater purification and seawater purification. For example, the development of seawater pretreatment systems based on technologies such as multistage filtration, reverse osmosis and ion exchange can improve the input water quality of hydrogen production systems by efficiently removing harmful substances from seawater. In addition, the research and development and application of intelligent pretreatment technology is also the focus of future research, and the efficient operation of pretreatment process is realized through intelligent monitoring and regulation.

3.2. Future Research and Application Priorities

The future research and application of seawater direct hydrogen production technology in China needs to be deeply explored in many aspects in order to achieve large-scale application of the technology and maximize economic benefits [8].

3.2.1. Construction of Large-scale Demonstration Projects

In order to verify the feasibility and economics of the technology, China needs to build several large-scale demonstration projects for direct hydrogen production from seawater in the next few years. These demonstration projects should cover different geographical environments and application scenarios, such as coastal cities, islands, offshore oil platforms, etc. Through the actual operation data of the demonstration project, the technical scheme and process flow are further optimized, the cost of hydrogen production is reduced, and the stability of the system is improved. At the same time, the development of demonstration projects will also provide practical basis for policy formulation and enterprise investment, and promote the commercialization process of technology.

3.2.2. Improvement and Optimization of the Industrial Chain

The industrialization development of seawater direct hydrogen production technology needs the support of perfect industrial chain. In the future, China needs to optimize and collaborate in all aspects of material research and development and production, equipment manufacturing, system integration and operation. For example, through the establishment of industrial alliances and innovation platforms, strengthening cooperation between scientific research institutions, universities and enterprises, and promoting the localization process of key materials and equipment. In addition, the optimization of the industrial chain also includes the multi-field application of hydrogen production systems, such as the integration with renewable energy, power systems and transportation industries, to achieve the extension and value-added of the industrial chain.

3.2.3. Expansion of Policy Support and Financing Channels

Government policy and financial support are important guarantees for the development of seawater direct hydrogen production technology. In the future, China needs to further introduce relevant policies to support the research and development, demonstration and industrialization of technology. For example, through tax incentives, subsidy policies and research funds, enterprises and research institutions are encouraged to increase investment. At the same time, expand financing channels, attract social capital and international investment, and help the development and application of technology. In addition, the formulation of policies should also include the establishment of standards and the improvement of the market supervision system to ensure the safety and norms of technology application.

3.2.4. International Cooperation and Technical Exchange

The technology of direct hydrogen production from seawater is a global research field, and international cooperation and technical exchange are very important to promote technological progress. In the future, China should strengthen cooperation with international advanced scientific research institutions and enterprises, and absorb international advanced technology and experience through joint research, technology transfer and personnel exchange. For example, participate in international large-scale scientific research projects, establish joint laboratories with internationally renowned universities and enterprises, and jointly overcome technical problems. In addition, by holding international conferences and technical exhibitions to strengthen technical exchanges and display results, China's international influence in this field will be enhanced.

3.2.5. Construction and Training of Talent Team

Talent is the core driving force of scientific and technological innovation, and China needs to strengthen the construction and training of talent in the field of direct hydrogen production from seawater in the future. For example, by setting up special funds and scholarships to attract outstanding students and researchers to enter the field. At the same time, a complete scientific research training system will be established to enhance the professional skills and innovation capabilities of existing researchers. In addition, enterprises are encouraged to cooperate with universities and scientific research institutions to establish a joint training mechanism to cultivate compound talents with practical operation ability and market awareness.

3.2.6. Expansion of Marketing and Application Scenarios

The application scenario of seawater direct hydrogen production technology is very wide, and it is necessary to further expand the market application and promote the commercialization of the technology in the future. For example, through cooperation with energy companies, industrial parks and transportation industries, customized hydrogen production solutions are developed to meet the needs of different users. At the same time, through marketing and publicity, improve the public's awareness and acceptance of seawater direct hydrogen production technology, and create a good market environment for the wide application of the technology. In addition, new application scenarios are explored, such as the joint application of offshore wind power and seawater hydrogen production, to further improve the economic and social benefits of the technology [9].

4. Concluding Remarks

With the transformation of global energy structure and the intensification of environmental problems, the technology of direct hydrogen production from seawater, as an important part of the green energy revolution, has broad research and application prospects. China has made remarkable progress in this field, from laboratory research to industrial demonstration, and the technology continues to mature. In the future, China will continue to strengthen the research and development of key technologies such as high-efficiency catalysts, advanced membrane technology, and intelligent control systems, and promote the optimization of polygeneration technology and the application of new energy integration technology. At the same time, the construction of large-scale demonstration projects, the improvement of the industrial chain, policy support and international cooperation will provide a solid foundation for the commercialization and large-scale application of seawater direct hydrogen production technology. In addition, talent team building and marketing will also accelerate the application and popularization of technology. Looking forward to the future, the direct hydrogen production technology from seawater is expected to play an important role in promoting the transformation of the energy structure and achieving the goal of carbon neutrality, and contribute Chinese wisdom and Chinese solutions to global sustainable development.

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