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Application of Hydrogen Fuel Cell in Marine Power

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Abstract

The current development of hydrogen fuel cells as a ship power source is reviewed, and the characteristics of hydrogen fuel cell-powered ships are summarized, along with the development and research status of relevant technologies. These include the standardized specification of hydrogen fuel cell power, the hydrogen system's safety, and hydrogen production and storage. Based on current research from various countries, the challenges faced by the development of hydrogen fuel cell-powered ships are presented. According to the research survey, hydrogen fuel cells are the safest and most environmentally friendly method to apply hydrogen fuel to ship power.

Keywords: Hydrogen fuel cell powered vessels, Hydrogen production, Hydrogen storage, Hydrogen safety

Introduction

In my opinion, hydrogen fuel cells are among the most promising development prospects in the 21st century and one of the most promising power sources to replace traditional fossil fuels due to their low cost, diverse access methods, high safety, and zero pollution to the environment.

As an important means of transport in the world, ships have significant impacts on the economic development of almost all countries. Nowadays, many countries are becoming increasingly environmentally friendly. Traditional ships, however, produce large amounts of greenhouse gases and atmospheric contaminants such as CO2, NOx, SOx, CO, and particulate matter when they operate.

The hydrogen fuel cell system is one of the ideal applications of hydrogen energy in marine power systems, which has the advantages of a simple structure, low vibration noise, and easy maintenance. Several companies and countries are studying the application of the hydrogen fuel cell system, such as Siemens AG, Honeywell, Plug Power, and others. Moreover, countries and regions have formulated diverse hydrogen energy development policies. For example, in the "13th Five-Year Plan" National Strategic Emerging Industry Development Plan, "Energy Production and Consumption Revolution Strategy (2016-2030)", and other government-released publications, China has pointed out the importance of developing the hydrogen energy industry and realizing the promotion and application of several technologies in the use of hydrogen fuel.

Hydrogen fuel power was first used in the military field. In the 1980s, the German Navy's submarines began to be equipped with Proton Exchange Membrane Fuel Cells (PEMFC) provided by Siemens, and in 1990, Howaldtswerke-Deutsche Werft (HDW) transformed the Class 209 type 1200 submarine and developed the world's first type 212A Air Independent Propulsion (AIP) submarine equipped with hydrogen and oxygen fuel cells. There are also many other examples, such as DNV's Thames Hydrogen Eco-project, Samsung Heavy Industries' collaboration with Bloom Energy's hydrogen fuel-powered vessel, Norled AS's hydrogen ferry, the Water-Go-Round hydrogen-powered vessel built by Hydrogenic and Golden Gate Zero Emission Marine (GGZEM), the Viking Sun liquid hydrogen-powered tanker built by Viking Cruises, The SF-BREEZE high-speed passenger ferry built by Sandia National Laboratories in collaboration with Red and White Fleet, the River Cell-Elektra hydrogen-fueled hybrid tugboat carried out by TUBerlin, BEHALA and DNV, as well as the SX190 DP2 hydrogen-powered Marine vessel jointly built by the Ustan Group and Nedstack Fuel Cell Technology company.

Literature Review

The comprehensive guidelines provided by DNV (2021) in the Handbook for Hydrogen-fuelled Vessels offer a foundational roadmap towards navigating the complex regulatory landscape for safe hydrogen operations. This is complemented by the critical examination in the Global Standards and Regulatory Frameworks for Hydrogen Fuel Cell Ships, which underscores the need for international harmonization of safety practices. This study reveals the disparity in safety regulations across different jurisdictions and advocates for unified standards to facilitate the global adoption of hydrogen fuel cell technology, ensuring safe and efficient maritime operations.

Based on the technical route and industrial chain development of hydrogen fuel cell powered ships, the technical structure of hydrogen fuel cell powered ships and the development status of domestic and foreign projects were systematically reviewed. By analyzing the status quo of hydrogen fuel and hydrogen fuel cell technical regulations of classification societies, the current hydrogen energy standards at home and abroad were investigated, classified and summarized. In the framework of green shipping system, by comparing the industrial technology of hydrogen fuel cell powered vehicles and vessels, the results show that there are differences in application scenarios, power, hydrogen storage, filling facilities, etc., and there are also obvious similarities and differences in service life, starting conditions, space requirements, installation methods, ventilation and airtight requirements. On this basis, the construction of a standard system for hydrogen fuel cell powered ships, the applicability of reference to automotive hydrogen energy standards, the special formulation of core standards for hydrogen fuel cell powered ships industry chain, and the formulation of safety regulations and standards for hydrogen fuel cell powered ships technology are the main lines. To form a framework and direction for the development of technical specifications, certifications and product standards for hydrogen fuel cell powered ships under the green shipping system. (Wang Dongxing, et al. ,2023) The lack of standardized specifications for hydrogen fuel cell-powered vessels, as noted by Wang Dongxing et al. (2023), poses a significant challenge to the industry's growth, which argues for the development of comprehensive, internationally recognized standards. By highlighting the critical need for a unified regulatory framework that encompasses fuel storage, ship operation safety, and fuel cell technology, this reference provides a roadmap for future standardization efforts, ensuring that hydrogen fuel cell ships can operate safely and efficiently on a global scale.

With the implementation of hydrogen fuel cell vehicle demonstration projects worldwide, the supporting hydrogen energy infrastructure—hydrogen refueling stations—is also developing rapidly. As an emerging energy infrastructure, whether it can provide enough security for the public has always been a matter of great concern to the government and the public. Currently, the main controversy in the world's risk assessment of hydrogen refueling stations is the determination of damage limits and risk acceptance criteria. The methodologies for hydrogen safety risk assessment outlined by Li Zhi-yong et al. (2009) set a precedent for addressing safety concerns in hydrogen fueling stations, providing a crucial basis for risk analysis. Building on this, the insights from the Global Standards and Regulatory Frameworks for Hydrogen Fuel Cell Ships underscore the paramount importance of standardized safety protocols. This comprehensive review not only highlights the gaps in current safety standards but also proposes a structured approach towards achieving international regulatory alignment, illustrating the critical need for standardized safety measures to promote the safe and effective integration of hydrogen fuel cell technology in maritime applications.

In this essay, the main storage technologies and development of hydrogen are summarized from four aspects: liquefied hydrogen storage, high-pressure gas hydrogen storage, metal hydride hydrogen storage, and composite hydrogen storage. The research progress and application of metal hydride hydrogen storage materials are introduced. The work of Gao Jin-liang et al. (2016) on hydrogen storage technology provides a critical foundation for understanding the current state of hydrogen storage methods and their implications for maritime use. Gao further advances this discourse by introducing cutting-edge storage solutions that offer enhanced safety and efficiency. Highlighting the latest technological breakthroughs, this reference emphasizes the importance of continuous innovation in storage technology to improve the operational efficacy and safety of hydrogen fuel cell-powered ships, thereby addressing one of the key challenges in the widespread adoption of this sustainable energy source.

The focus of this review is on different storage methods, and we discuss the storage of hydrogen at high pressure, in liquefied form at cryogenic temperatures, and bound to liquid or solid-state carriers. This work provides a theoretical introduction to different hydrogen storage methods and analyzes the energy efficiency and practical storage density of the carriers. In the final section, the major challenges and hurdles for the development of hydrogen storage for the maritime industry are discussed. Van Hoecke et al. (2021) delve into various hydrogen storage methods, their efficiency, and their application within the maritime industry, presenting a nuanced discussion on the challenges and opportunities these storage technologies entail. The Economic Viability and Environmental Impact Assessment of Hydrogen Fuel Cell Maritime Transportation, further enriches this discussion by assessing the economic and environmental ramifications of adopting hydrogen fuel cells in ships. This pivotal reference highlights the necessity of developing cost-effective, sustainable storage and bunkering solutions that can support the widespread use of hydrogen fuel cells, emphasizing the balance between technological innovation and environmental stewardship.

Eventually, in my opinion, there are still many challenges and difficulties for different stages of hydrogen system development in the future. These challenges are all quite important and need to be addressed urgently, however, the difficulties are not readily to be solved and need the powerful nations of hydrogen industry around the world to corporate.

Chapter 1: Standards for Hydrogen Fuel Cell Power

Standardized specifications for hydrogen fuel cell power form the foundation for promoting and applying hydrogen fuel cell-powered ships. The following are regulations related to hydrogen fuel cell power in China and other countries, mainly concerning fuel cells, hydrogen storage, supply systems, and hydrogen safety:

1. American Bureau of Shipping (ABS): Guide for Fuel Cell Power Systems for Marine and Offshore Applications.

It provides guidance and a reference for the design, evaluation, and establishment of an auxiliary support system for marine fuel cells and defines the types of ships that can use fuel cells.

2. Det Norske Veritas (DNV): Handbook for Hydrogen-Fueled Vessels. ALVESTAD L, BERGE K. Handbook for hydrogen-fueled vessels[R]. Oslo: DNV, 2021.

A hydrogen safety roadmap for the shipping industry has been identified, offering guidance on how to conduct the safety and regulation of fuel cell power vessels.

3. Chinese National Hydrogen Energy Standardization Technical Committee: Basic Requirements for Hydrogen System Safety. (GB/T 29729—2013)

The risk factors of the hydrogen system and the basic requirements of risk control, which are suitable for the design and use of hydrogen production, storage, and transportation systems, are specified.

4. Chinese National Safety Production Standardization Technical Committee and Chemical Safety Standardization Sub-technical Committee: Safety Technical Regulations for the Use of Hydrogen (GB 4962—2008).

It specifies the technical requirements for gaseous hydrogen in its use, replacement, storage, compression, and filling, the discharge process, fire and emergency treatment, and safety protection.

As can be seen from the above, the development of hydrogen fuel cell-powered ships is still in its initial stage, and the relevant specifications are relatively scarce, with most being general standards. The only example of hydrogen fuel cell-powered vessels is the Handbook for Hydrogen-Fueled Vessels, published by DNV.

DNV primarily focuses on the safety of hydrogen fuel cell-powered vessels in the Handbook for Hydrogen-Fueled Vessels. It clarifies the relevant safety regulations and standards for hydrogen as a ship fuel, as well as the required risk assessment methods and disposal measures for safety issues. In this handbook, the requirements for constructing hydrogen fuel cell-powered ships are explained from four different aspects: design, manufacturing, commissioning, and operation and maintenance. Then, in conjunction with the International Code for the Construction and Equipment of Ships Carrying Liquefied Gases in Bulk (IGF rule) and the Convention on the Safety Of Life At Sea (SOLAS convention), it restricts the energy conversion of fuel cells and hydrogen storage on board. Finally, it outlines the risk judgment analysis method and the corresponding risk control measures for hydrogen fuel cell-powered ships. However, the manual currently only considers high-pressure gaseous and liquid hydrogen storage and mainly uses PEMFC as a power source; it does not consider other cases, such as Liquid Organic Hydrogen Carrier (LOHC) hydrogen storage or hydrogen fuel engines as power sources.

Compared with ships, the development of relevant regulations for hydrogen fuel cell vehicles is more comprehensive, such as the “Fuel cell electric vehicle fuel cell stack safety requirements” (GB/T 36288—2018), “Fuel cell electric vehicle safety requirements” (GB/T 24549—2009), etc. In the absence of relevant standards for hydrogen fuel cell-powered ships, these regulations on fuel cell vehicles can provide a reference for the construction, testing, and use of hydrogen fuel cell-powered ships.

Chapter 2: Safety of Hydrogen Systems

1. Physical and Chemical Characteristics of Hydrogen

The physical and chemical characteristics of hydrogen make it one of the important factors affecting the safety, application, and commercialization of hydrogen fuel cell-powered vessels.

According to “Review of hydrogen safety control for automotive fuel cell systems” (Huang Xing et al. , 2019), five physical and chemical properties of hydrogen can be summarized as leakage, diffusivity, flammability, explosiveness, and compatibility with metal materials.

1.1 Leakage and Diffusivity of Hydrogen

The density of hydrogen is low (about 1/14 the density of air), the molecule is small, and the viscosity is low, making it easy to leak from holes or gaps. The diffusion rate of hydrogen is extremely high; its speed through the same hole or gap is 1.2-2.8 times that of natural gas. However, when hydrogen leaks, it can also spread rapidly in more directions than natural gas, so the concentration can be reduced, which can decrease the possibility of a hydrogen explosion to a certain extent.

1.2 Flammability and Explosiveness of Hydrogen

The ignition energy of hydrogen is low, and the combustion range is wide (4%-75%). The flame propagation speed is fast, and the low density of hydrogen causes the flame to rise quickly after combustion. At the same time, the volume fraction of the explosion limit of hydrogen is also very wide (4%-75%), which is much larger than that of natural gas. Therefore, hydrogen is actually a relatively dangerous gas, and extra attention must be paid to safety issues when dealing with hydrogen.

1.3 Compatibility of Hydrogen with Metal Materials

When metal materials are in contact with hydrogen for a long time, hydrogen penetration or hydrogen absorption can occur, which will degrade the mechanical properties of metal materials and lead to hydrogen embrittlement. Once hydrogen embrittlement occurs, it is not reversible, so it needs to be prevented. Currently, hydrogen embrittlement on the surface of metal materials can be prevented by surface treatment technologies, such as surface coating and surface modification technology. Material micro-structure modification techniques can also be used to add, subtract, or remove an alloying element inside a metal to optimize the microstructure of the metal. However, today's hydrogen storage materials have gradually developed from metal materials to a system dominated by lightweight elemental hydrides (such as borohydrides, amino compounds, etc.) and porous adsorption materials, which can effectively avoid the occurrence of hydrogen embrittlement.

2. Risk Analysis of Hydrogen Safety

To effectively control and prevent hydrogen safety accidents, alleviate concerns about using hydrogen as a fuel, and promote the application of hydrogen fuel cell power in ships, hydrogen safety risks should be analyzed from the beginning of ship design. Currently, hydrogen safety risk analysis is mainly divided into Rapid Risk Ranking (RRR) and Quantitative Risk Assessment (QRA)(LI Zhiyong, et al. , 2009 (In Chinese)).

RRR is a qualitative risk assessment method commonly used for the equipment and facilities required in the utilization of hydrogen energy. It is based on the analysis of the situation by several experts in related fields. The analysis is quick, but the subjectivity is significant, limited by the knowledge level and experience of the experts; only rough judgments can be made. If a more in-depth assessment of risk is required, the QRA approach is necessary.

Chapter 3: Preparation and Storage of Hydrogen

Hydrogen rarely occurs in nature as an elementary substance, so it needs to be extracted from hydrogen-containing substances. The production of hydrogen from renewable sources is a minority. At present, the majority of hydrogen produced is Gray/Blue Hydrogen (extracted from coal and natural gas, respectively), while Green Hydrogen is produced by the electrolysis of water. Therefore, we should vigorously develop electrolytic water hydrogen production so that Green Hydrogen gradually replaces Gray Hydrogen and Blue Hydrogen, which produce a lot of greenhouse gases harmful to the environment. It plays an important role in promoting the development of hydrogen fuel cell-powered ships.

Hydrogen production by electrolytic water refers to the dissociation of water molecules under the action of direct current to form oxygen and hydrogen, respectively, at the anode and cathode of the electrolytic cell. According to the different electrolytes, it is mainly divided into Alkaline Water Electrolysis (AWE), Proton Exchange Membrane (PEM) electrolysis, Solid Oxide Electrolysis (SOE), and Solid Polymer Anion-Exchange Membrane (AEM) electrolysis. AWE electrolysis technology is the most mature, but the highly corrosive liquid leads to complex system operation and maintenance and high cost. PEM water electrolysis technology has developed rapidly in recent years, mainly offering the advantages of flexible operation, stability, and low operation and maintenance costs. The technologies of SOE and AEM electrolysis are in the initial stages.

Because PEMFC must use high-purity hydrogen, the endurance of hydrogen fuel cell-powered ships is closely related to the amount of hydrogen fuel it carries. The most widely used hydrogen storage technology is high-pressure gaseous hydrogen storage, using high-pressure-resistant vessels. At the same time, metal alloy hydrogen storage technology is also being studied. However, this technology is still in the stage of technical research, and it needs to be developed more before it can be gradually promoted (Gao Jin-liang, et al. , 2016).

High-pressure gas hydrogen storage technology is mature and a good choice to achieve large-scale commercialization of hydrogen fuel cell-powered ships in the short term. However, high-pressure gaseous hydrogen storage has a low volume-density ratio and small capacity, requiring a large amount of space on a ship or even several times the volume of diesel to store the same amount of energy is unable to meet the requirement of future ship endurance, ship hydrogen storage will develop in the direction of higher hydrogen energy density. Because this storage method is prone to leakage, to ensure the safety of the ship, high-pressure hydrogen storage tanks should not be placed in the ship's cabin but should be fixed on the deck. Metal Hydride(Tong Liang, et al. , 2021) , namely adsorption hydrogen storage technology, in which the hydrogen storage carrier cannot be used directly as fuel for hydrogen fuel cells, and the hydrogenated storage carrier cannot be mixed with the carrier of dehydrogenation after use. However, adsorption hydrogen storage technology is the most suitable for commercial hydrogen storage in the long run. (Tong Liang, et al. ,2022) (Cavo M, et al. ,2021)

In summary, each hydrogen storage method has its own advantages and disadvantages, and no method is without drawbacks. According to VAN HOECKE L, LAFFINEUR L, CAMPE R, et al. , 2021, high-pressure gaseous hydrogen storage requires the least amount of energy. Although adsorption hydrogen storage has many advantages, it necessitates extra space on the ship to store the hydrogen storage carrier after dehydrogenation.

Chapter 4: Challenges and Development Proposals

In recent years, various industries related to hydrogen energy have been vigorously promoted by countries worldwide, and technologies related to it have also made significant progress. However, there is still much room for improvement in the application and standardization of some technologies for hydrogen fuel cell-powered ships, presenting several challenges with development proposals.

First and foremost, there is a lack of standardized specifications for hydrogen fuel cell-powered vessels. In the cases mentioned above, only DNV's Handbook for Hydrogen-Fueled Vessels (HHFV) is a targeted standardized specification. Moreover, most of the existing standards for hydrogen fuel cell-powered ships mainly provide technical requirements for marine hydrogen fuel cells and do not include specific standards for fuel storage and ship operation safety. For the development proposals of the standardization of hydrogen fuel cell powered ships in the future mainly start from the following directions: the construction of the standard system of hydrogen fuel cell powered ships; The automobile hydrogen energy standard is used for appropriate reference and tailored according to the characteristics of Marine hydrogen energy industry. Special verification of core technical standards for Marine hydrogen energy storage, supply, refueling and fuel cell systems; Specific normative methods of safety supervision. (Wang Dongxing, et al. ,2023)

Furthermore, the experiments and simulations on hydrogen safety are mainly about hydrogen fuel cell vehicles, while the risk analysis of hydrogen fuel cell powered ships considers the cabin layout, ventilation, fire protection, and other conditions, which are still blank spaces. It is still difficult to verify the accuracy of various safety analyses of some existing data simulation models for hydrogen fuel cell-powered ships. In addition to the ship itself, the surrounding environment of the ship and other ships also affect its safety. Therefore, the safety risk analysis standards and methods for hydrogen fuel cell-powered ships are still incomplete.

In addition, the mainstream hydrogen production method in the world is still coal hydrogen production, and the cost of various key components in renewable hydrogen production, such as electrolytic water, is too high. Compared with coal hydrogen production, the energy density is low, the stability is poor, and the hydrogen production efficiency still needs to be further improved.

Lastly, there is no unified standard for hydrogenation equipment in ports of various countries. The analysis of various current hydrogen storage methods shows that high-pressure gaseous hydrogen storage is the most suitable and widely used hydrogen storage method. However, ships, especially large ocean-going ships, have a high demand for hydrogen fuel, and the number and volume of tanks used for high-pressure gaseous hydrogen storage would need to be larger, so it faces the challenge of hydrogen storage tanks occupying too large a volume on board and being difficult to arrange. In addition, high-pressure gaseous hydrogen storage tanks are typically metal, and long-term exposure to hydrogen increases the risk of hydrogen embrittlement.

Epilogue

According to the current development of hydrogen fuel cell-powered ships, countries are placing great importance on the research of hydrogen energy as a power source due to increasing concerns about clean energy and environmental protection. The transition to hydrogen fuel cell-powered ships is not without its economic and environmental considerations. Evidences offered above provided a balanced view of the benefits and hurdles in adopting hydrogen fuel cells. This perspective is crucial for policymakers and industry stakeholders to formulate strategies that support sustainable maritime transportation. As an environmentally friendly type of fuel, hydrogen fuel cells are the perfect fit to provide more power than existing fuels since they will not produce any greenhouse gas or pollution emissions. However, we still need to conduct more rigorous research on hydrogen production and storage technology, and countries and institutions still need to introduce and issue more relevant favorable policies and standards for hydrogen fuel cell-powered ships. The development prospects of hydrogen fuel cell-powered ships are bright and will make significant contributions to the development of the human transportation industry.

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