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, as well as the development and research status of relevant technologies, including standardized specification of hydrogen fuel cell power, the safety of hydrogen system and production and storage of hydrogen. Based on the current research in various countries, the challenges faced by the development of hydrogen fuel cell-powered ships are put forward. According to the research survey, the number of hydrogen fuel-powered ships in the world is limited, and most of them are small passenger ships in inland rivers and lakes. The formulation of relevant standards and specifications for hydrogen fuel cell-powered ships is still in development. Hydrogen fuel cell is the safest and most environmentally friendly way to apply hydrogen fuel to ship power. Hydrogen fuel storage can be optimally installed on a ship using a combination of different methods.

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

Introduction
In my opinion, hydrogen fuel cells are the most promising development prospects in the 21st century and one of the most promising power sources to replace traditional fossil fuels because of their low cost, diverse access methods, high safety, and zero environmental pollution. As an important means of transport in the world, ships greatly impact the economic development of almost all countries. Nowadays, many countries are becoming increasingly environmentally friendly; traditional ships, however, produce lots of greenhouse gases and atmospheric contaminants such as CO2, NOx, SOx, CO, and particulate matter when they operate. At present, diesel and other fossil fuels are still the main source of power for marine engines. However, the amount of fossil energy is limited and non-renewable, with lots of constraints and confined development potential. As a result, many countries have begun to focus on developing ships powered by clean energy. Hydrogen power, a sustainable carbon-free energy type with high conversion efficiency, is the most promising clean energy in the 21st century.

A hydrogen fuel cell system is one of the ideal applications of hydrogen energy in marine power systems, which has the advantages of simple structure, low vibration noise, and easy maintenance. There are quite a few companies and countries studying the application of hydrogen fuel cell systems, such as Siemens AG, Honeywell, Plug Power, etc. Furthermore, countries and regions have formulated diversified hydrogen energy development policies. For example, in the “13th Five-Year Plan,” “Energy Production and Consumption Revolution Strategy (2016-2030),” and other government-released publications, China has pointed out the importance of developing 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, German Navy 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
Green hydrogen could play a crucial role in the maritime industry’s journey towards decarbonization. Produced through electrolysis, hydrogen is emission-free and could
be widely available globally – as a marine fuel or a key enabler for synthetic fuels. Many shipping companies recognize hydrogen’s potential as a fuel, but the barriers to realizing this are substantial.

Handbook for Hydrogen-fuelled Vessels’ offers a road map towards safe hydrogen operations using fuel cells. It details how to navigate the complex requirements for design and construction, and it covers the most important aspects of hydrogen operations, such as safety and risk mitigation, engineering details for hydrogen systems, and implementation phases for maritime applications based on the current regulatory Alternative Design process framework. (DNV, 2021)

At the same time, the other standard from the Chinese government specifies the safety technical requirements of gaseous hydrogen in the use, replacement, storage, compression, filling (filling), discharge process, fire and emergency management, and safety protection. This standard applies to all working places on the ground after gaseous hydrogen production and does not apply to liquid hydrogen, gaseous hydrogen on water, aviation hydrogen sites, and vehicle hydrogen supply systems. The corresponding steps in hydrogen production can be followed. (Chinese National Safety production standardization Technical Committee and Chemical Safety standardization Sub-technical Committee, GB 4962—2008)

With the implementation of hydrogen fuel cell vehicle demonstration projects around the world, the supporting hydrogen energy infrastructure - hydrogen refueling stations are also developing rapidly worldwide. 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. The main controversy on the risk assessment of hydrogen refueling stations in the world is the determination of damage limit and risk acceptance criteria. By reviewing the research status and progress of the risk assessment of hydrogen refueling stations abroad, this paper summarizes the risk assessment methods of hydrogen refueling stations from risk identification, probability analysis, consequence evaluation, and risk measurement. It analyzes hydrogen energy safety, such as hydrogen behavior and its consequences, which is the basis of the risk assessment of hydrogen energy facilities. On this basis, the recent international research in this field is further reviewed to Study the progress made. (Li Zhi-yong, et al, 2009)

In this essay, the main storage technology 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 were introduced. In particular, the practical application of hydrogen storage materials in large-scale wind energy storage is described. (Gao Jin-liang, et al, 2016)

The focus of this review is different storage methods, and in this work, we discuss the storage of hydrogen at high pressure, in the liquefied form at cryogenic temperatures, and bound to liquid or solid-state carriers. In this work, a theoretical introduction to different hydrogen storage methods precedes an analysis of the carriers’ energy-efficiency and practical storage density. In the final section, the major challenges and hurdles for the development of hydrogen storage for the maritime industry are discussed. The most likely challenges will be developing a new bunkering infrastructure and suitable safety monitoring to ensure the safe operation of these hydrogen carriers on board the ship. (Van Hoecke L, et al, 2021)

Chapter 1 Standards for hydrogen fuel cell power

The standardized specifications for hydrogen fuel cell power are the basis for promoting and applying hydrogen fuel cell power ships. The following are some regulations related to hydrogen fuel cell power in China and other countries, mainly related to fuel cells, hydrogen injection storage, supply systems, and hydrogen safety.


It provides guidance and reference for designing, evaluating, and establishing auxiliary support systems for Marine fuel cells and defines the types of ships that can use fuel cells.


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


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

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

As seen from above, the development of hydrogen fuel cell-powered ships is still in its initial stage, and the relevant specifications are still relatively few, most of which are general standards. The only example of hydrogen fuel cell-powered vessels is the Handbook for Hydrogen-Fuelled Vessels, published by DNV. DNV mainly focuses on the safety of hydrogen fuel cell-powered vessels in the Handbook for Hydrogen-Fueled Vessels. It clarified the relevant safety regulations and standards for hydrogen as a ship fuel and the risk assessment methods and disposal measures required regarding safety issues. This handbook clarifies the requirements for constructing hydrogen fuel cell-powered ships from four different aspects: designing, manufacturing, commissioning, and operation and maintenance. Then, combined 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), the energy conversion of fuel cells and hydrogen storage on board is restricted. Finally, it discusses the risk judgment analysis method and the corresponding risk control measures in 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 complete, such as “Fuel cell electric vehicle fuel cell stack safety requirements” (GB/T 36288—2018), “Fuel cell electric vehicle safety requirements” (GB/T 24549—2009), etc. Without 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 its safety one of the important factors affecting the application and commercialization of hydrogen fuel cell-powered vessels.


1.1 Leakage and Diffusivity of Hydrogen

The density of hydrogen is low (about 1/14 of the density of air), the molecule is small, and the viscosity is low, so it is easy to leak from the hole/gap. The diffusion rate of hydrogen is extremely high; its speed going through the same hole/gap is 1. 2-2. 8 times that of natural gas, but when hydrogen leaks, it can also spread rapidly in more directions compared to natural gas, so the concentration can be reduced, which can reduce the possibility of hydrogen explosion to a certain extent.

1.2 Flammability and Explosive of Hydrogen

The ignition energy of hydrogen is low, the combustion range is wide (4%~75%), the flame propagation speed is fast, and the density of hydrogen is low, resulting in the flame rising fast 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 a relatively dangerous gas, and we need to pay extra attention 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 absorption will occur, deleting the metal materials’ mechanical properties and leading to hydrogen embrittlement. Once hydrogen embrittlement occurs, it is not reversible, so it needs to be prevented. Surface treatment technologies, such as surface coating and surface modification technology can prevent hydrogen embrittlement on the surface of metal materials. 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, ease people’s minds 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. Hydrogen safety Risk analysis is mainly divided into Rapid Risk Ranking
capacity ratio is low, and the safety is poor; the most
transportation and simple operation, but the volume
resistant vessels. Its technology is mature, with convenient
pressure gaseous hydrogen storage, using high-pressure
most widely used hydrogen storage technology is high-
endurance of hydrogen fuel cell-powered ships is closely
Because PEMFC must use high-purity hydrogen, the
highly corrosive liquid leads to complex system operation,
AWE electrolysis technology is the most mature, but the
Hydrogen rarely occurs in nature as an elementary
Hydrogen production from renewable sources is a minority. Currently, most hydrogen
produced is Gray/Blue Hydrogen (extracted from coal
and natural gas, respectively), while the electrolysis
of water produces Green Hydrogen. 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 that are 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,
from the anode and cathode of the electrolytic cell. The
different electrolytes it is mainly divided into Alkali 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,
maintenance, and high cost. PEM water electrolysis
technology has developed rapidly in recent years and
mainly has the advantages of flexible operation, stability,
and low operation and maintenance costs. The technology
of SOE and AEM electrolysis is in the initial stage.
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. Its technology is mature, with convenient
transportation and simple operation, but the volume
capacity ratio is low, and the safety is poor; the most
Hydrogen production by electrolytic water refers to

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. Hydrogen production from
renewable sources is a minority. Currently, most hydrogen
produced is Gray/Blue Hydrogen (extracted from coal
and natural gas, respectively), while the electrolysis
of water produces Green Hydrogen. Therefore, we
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pressure gaseous hydrogen storage, using high-pressure
resistant vessels. Its technology is mature, with convenient
transportation and simple operation, but the volume
capacity ratio is low, and the safety is poor; the most
concerning issue is the hidden dangers of leakage and
explosion. At the same time, metal alloy hydrogen storage
technology is also being studied, and its performance is
excellent in all aspects: good safety, high volume capacity
ratio, very convenient transportation, and relatively
mature technology. However, this technology is still in the
stage of technical research, and it needs to be developed
more maturely before it can be gradually promoted. GAO
Jin-liang, YUAN Ze-ming, SHANG Hong-wei, et al.
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The high-pressure gas hydrogen storage technology is
mature, and it is a good choice to achieve large-scale
commercialization of hydrogen fuel cell powered ships
in the short term. But 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
energy. And because this storage method is easy to leak,
to ensure the ship’s safety, the high-pressure hydrogen
storage tank is not suitable for placement in the ship’s
cabin but should be fixed on the deck. Metal hydrogen
storage technology, that is, adsorption hydrogen storage
technology, in which the hydrogen storage carrier cannot
be used as a fuel directly for hydrogen fuel cells, and the
hydrogenated hydrogen 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.
To sum up, each hydrogen storage method has its
advantages and disadvantages, and no way is without
disadvantages. Based on the statistics of VAN HOECKE
L, LAFFINEUR L, CAMPE R, et al. Challenges in the
use of hydrogen for maritime applications[J]. Energy
and Environmental Science, 2021, 14: 815-843, high-
pressure gaseous hydrogen storage requires the least
energy. Although adsorption hydrogen storage has
many advantages, it is necessary to set up extra space
on the ship to store the hydrogen storage carrier after
dehydrogenation.

Chapter 4 Challenges

In recent years, various industries related to hydrogen
energy have been vigorously promoted by countries
worldwide, and various technologies related to it have also
made great progress. However, there is still a lot of room
for improvements in the application and standardized
specifications of some related technologies for hydrogen
fuel cell powered ships, and here are some challenges the
project faces.
First and foremost, there is still a lack of standardized specifications for hydrogen fuel cell-powered vessels, and in the cases mentioned above, only DNV-issued HHFV is a targeted standardized specification. In addition, most of the existing standards for hydrogen fuel cell powered ships mainly put forward relevant technical requirements for Marine hydrogen fuel cells and did not include specific standards for fuel storage and ship operation safety. Furthermore, the experiments and simulations on hydrogen safety are mainly about hydrogen fuel cell vehicles. In contrast, 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 further improvement.

Last, there is no unified standard 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, are very demanding on hydrogen fuel, and the number and volume of tanks used for high-pressure gaseous hydrogen storage need to be more and larger, so it is faced with the hydrogen storage tank occupying too large volume on board and difficult to arrange. In addition, high-pressure gaseous hydrogen storage tanks are generally 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 attach great importance to the research of hydrogen energy as a power source due to the increasing concerns about clean energy and environmental protection. 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 concise 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 prospect of hydrogen fuel cell-powered ships is bright and will make great contributions to the development of the human transportation industry.

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