Advancements and Innovations in Marine Fuel Technology

Yimeng Liu[1] *

[1]Southampton Joint Institute of Marine Engineering, Harbin Engineering University, Harbin, 150000, China

Abstract. This paper provides a comprehensive overview of the application of three clean energy engines— Liquefied Natural Gas (LNG), hydrogen, and ammonia— in the shipping industry. The shipping industry is increasingly exploring clean energy alternatives to reduce its carbon footprint. LNG is one of the most established and widely adopted options, owing to its mature technology and reduced emissions compared to conventional fuels. However, it remains a non-renewable resource and still produces some pollution, making it a less-than-ideal solution for long-term sustainability. Hydrogen, with its high combustion efficiency and zero direct emissions, holds promise as a truly clean fuel. Nonetheless, it faces significant obstacles, including high costs related to production, storage, and transportation, as well as safety concerns due to hydrogen embrittlement and flammability. Ammonia offers the potential for zero-carbon emissions and can be produced using renewable energy sources. Yet, its use is limited by poor combustion characteristics and high corrosiveness, which pose challenges for engine design and material durability. This article delves into the advantages and limitations of these three fuels, focusing on aspects such as corrosion resistance, transportation logistics, pollution levels, friction reduction, and combustion efficiency. The paper concludes by examining future development directions for each energy source within the maritime sector, highlighting the importance of continued innovation to achieve sustainable shipping practices.

1 Introduction

98% of global shipping is almost powered by fossil-derived fuels. In 2012 the shipping industry emitted about 940 million tonnes of carbon dioxide. To provide a sense of scale, if the shipping industry were considered as a country. Globally, it would be the 6th largest CO2 emitter [1]. UNFCCC has proposed a goal of reducing carbon emissions by half until 2030[2]. Therefore, as a major energy consumer, the shipping industry has to study new strategies to improve ship efficiency and reduce fuel consumption. Clean energy engines can achieve almost zero pollution when it is running, to achieve carbon peak and carbon

* Corresponding author: yl5c22@soton.ac.uk

neutrality. However, during the operation and maintenance of clean energy engines, the problems of corrosion, transportation, pollution, friction and combustion cannot be ignored.

Currently， the clean energy engines being studied and used mainly include LNG engines, hydrogen engines and ammonia engines. Compared with HFO and MGO, the actual greenhouse gas benefits of LNG are about 8 – 20%. Hydrogen and ammonia engines don't produce greenhouse gas emissions during operation [3].

In China, the research and application of marine LNG engine technology have done a lot of effective and fruitful work. Abroad, this research and development is becoming more and more mature. In China, scientists mainly focus on the research and practical application of hydrogen fuel cell systems in hydrogen engines, while developed countries have entered the experimental application stage of hydrogen-powered ships [4]. In China, the study of marine ammonia engines is still at a preliminary stage, but some foreign companies and institutions have conducted relevant simulations and experimental research.

In summary, clean energy engines have their advantages and disadvantages. LNG engines have formed a complete set of process technologies, which are relatively mature worldwide. Hydrogen engines have a high combustion efficiency, but they are easy to leak and explode and are difficult to extract [4]. Ammonia engines are clean, but they are not easy to burn and are toxic [5].

Therefore, this article aims to review the problems of corrosion, transportation, pollution, friction and combustion in marine clean energy engines which are LNG engines, hydrogen engines and ammonia engines. Finally, the parameter and their property are summarized. It is concluded that the development of ammonia engines is a key project in the future research direction. And studying its friction problems is the key.

2 Clean Energy Ship Engine

2.1 LNG internal combustion engine

Liquefied natural gas is mainly composed of CH_4 and also contains small amounts of C_2H_6, C_3H_8, C_4H_{10} and other minute amount of gas components [5]. The liquefaction of LNG reduces the volume of natural gas by about 600 times, making it easier to store and transport.

LNG has the potential to significantly reduce carbon emissions. When burning LNG, carbon dioxide emissions are approximately 20-30% lower than when burning heavy fuel oil [5]. In addition, SO_2 and NOx produced during the combustion of LNG are also significantly lower than when burning traditional fuels. It makes LNG become a cleaner fuel. LNG is essentially a fossil fuel, so its non-renewable nature is one of its greatest limitations.

2.1.1 Technical Challenges

Corrosion: The main types of marine engine corrosion include weld corrosion, stress corrosion, seawater corrosion and so on. The main reasons are the redox reaction between oxygen, water and metal and the battery reaction between oxygen and chloride ions in seawater and metal impurity elements. LNG fuel contains a small amount of sulphur and lubricating oil, so the corrosion of ship equipment will be reduced. At the same time, LNG can also reduce the generation of water and metal corrosion.

Transportation: Transportation of LNG mainly includes pipeline transportation, sea transportation and land transportation. Multimodal transportation is to combine different modes of transportation to achieve economic and environmental benefits. However, LNG has the problem of low volume density. So LNG is stored in a specially designed energy storage system to keep LNG in a liquid state.

Pollution: From Table 1, LNG ships are cleaner and more environmentally friendly than traditional petroleum fuels such as heavy oil and diesel, but they still produce pollutants during use. The generation of major pollutants produced by LNG ships is divided into two stages: the LNG combustion stage and the LNG development and transportation stage. LNG produces a small number of pollutants after combustion, such as CH4, CO2, NOx, HC, CO, PM and SOx. During the production and transportation of LNG, it is prone to leak and cause pollution. A large amount of water is used in the refrigeration process of LNG. Chemicals will pollute the water environment and soil environment. Additionally, LNG has a role of corrosion to water quality, causing water quality to deteriorate.

Therefore, reducing the emission of these pollutants is an important research direction. EGR technology can recover the heat energy and reduce the NOx content in the exhaust gas to effectively improve the combustion and emission problems of the engines. It has the greatest applicability and economy for the combustion of LNG engines.

Friction: Due to the complex working environment of LNG engines, the environment with high temperature and high pressure causes the viscosity of lubricating oil to drop sharply, resulting in direct contact and wear between parts. In addition, some organic additives will precipitate to damage the lubricating film and aggravate the friction problem [6]. To reduce friction, lubricating oil additives or surface hardening treatments are used to reduce friction loss. Using an optimized engine cooling system is a good way to avoid lubricating oil decomposition and reduce the lubrication effect.

Table 1. Using natural gas engines reduces ship exhaust emissions compared with traditional HFO engines

Air pollutant	The percentage of emissions reduction by using LNG
SOx	Over 90%
NOx	Up to 35% for Diesel cycle compression ignition engines Up to 85% for Otto cycle engines
PM	Over 85%
CO2	Up to 29%
GHG (in CO2e)	Up to 19%

Combustion: To reduce fuel consumption, improving engine performance and reducing heat loss are crucial to improve combustion efficiency. This can be achieved by changing the injector structure parameters. LNG generally needs other fuels to ignite and requires a large-aperture injector for injection [7]. This can be achieved by using fuel control strategies, the performance of natural gas substitution rate under different loads is different. So the thermal efficiency can be improved by changing the load and substitution rate [7]. This can be achieved by using injection strategies. By changing injection timing, multiple injections, post-injection and early injection, the engine performance can be effectively improved [8].

2.1.2 Application Cases

In Finland, for its European shipping business UPM company purchased seven LNG ships equipped with dual-fuel engines in 2022. The average carbon emissions per ton of cargo were reduced by 26% compared to the average carbon emissions in previous years. During the initial commissioning of these ships, the investment costs of LNG ships were higher, but they ultimately showed good long-term benefits. The use of LNG reduced port emission charges and related expenses. It also improved the public reputation and image [9].

2.1.3 Pros and Cons

Compared with traditional energy ships, the advantage of LNG ships is that the pollutants produced by combustion are significantly reduced [3]. In addition, the storage and transportation of LNG are safer than other clean energies.

However, the public still has concerns about the high cost of LNG ships in its early developed stage, energy leakage and other safety issues. In addition, with the increasing environmental pressure and the development of various new energy sources in the future, LNG ships need to continue to innovate. Therefore, researching the technologies for reducing propulsion and cooling fuel consumption, focusing on the optimization of the power system and popularizing new engines are important. In addition, the exhaust emission system needs to be improved. To improve it can use new technologies such as EGR and selective catalytic reduction systems to reduce pollution generated by ships.

2.2 Hydrogen internal combustion engine

Under standard temperature and pressure, hydrogen is a colourless, odourless and non-toxic gas. It is highly flammable. When burned, it reacts with oxygen to form water and at the same time releases a large amount of energy. Hydrogen fuel is considered a clean energy because it produces no greenhouse gases when burned and only emits water vapour. Therefore, hydrogen has significant potential to reduce carbon emissions compared to traditional fossil fuels.

2.2.1 Technical Challenges

Corrosion: The presence of hydrogen in the air will cause a chemical reaction between the surface of the metal and the air, causing the metal to produce " hydrogen embrittlement". This problem can be solved by coating [10]. In addition, in the electrolyte solution, the anode and cathode on the metal surface are prone to electrochemical reactions, forming battery corrosion. Protective silicone can be added to the seal around the turbocharger. And coating selection can be performed [11].

Transportation: Hydrogen-powered ships mostly use high-pressure gaseous hydrogen storage. A small number of ships use metal hydride hydrogen storage. However, hydrogen is a high-pressure and explosive gas. So a series of safety measures need to be taken during transportation, such as increasing the thickness of the container wall, using advanced pressure relief valves and safety valves and other technical measures to reduce transportation risks.

Pollution: The production and use of hydrogen will cause pollution. Hydrogen can be produced by a variety of methods. The most widely used method is steam methane reforming, but it will emit a large amount of carbon dioxide. Another method is coal gasification, but the production efficiency is low [10]. Therefore, it is imperative to produce "green hydrogen". The hydrogen production process uses renewable energy and adopts advanced technologies and equipment such as water electrolysis, biomass gasification, biomass-derived liquid reforming or microbial biomass conversion [12].

Friction: Hydrogen causes problems such as deterioration of the operating state of the engine friction pair, emulsification of lubricating oil and abnormal wear of the engine. Researchers at home and abroad are studying the influence of lubricating oil characteristics in a zero-carbon environment on the film formation, wear and corrosion characteristics of the interface of equivalent small sample specimens based on typical friction pair geometry and operating conditions. This research can support the improvement of lubricating oil and surface treatment of friction pairs under low-carbon and zero-carbon fuels.

Combustion: Hydrogen engines generally use hydrogen-air mixture combustion, but hydrogen has the characteristics of high flame speed, wide flammability limit, short flameout distance and instability. Therefore, it is necessary to prevent abnormal combustion and flashback. To deal with these, direct injection and special injection strategies to eliminate backflow, increase air dilution, DI combustion mode and laser ignition are generally used.

2.2.2 Application Cases

In 2015, Stena Line applied hydrogen fuel cell technology to its cargo ship " M/S Stena Germanica" in Sweden. The application of hydrogen fuel cells on ships successfully reduced emissions during navigation and demonstrated the reliability of hydrogen fuel cell systems. However, there are still problems in the application process, such as the complexity of hydrogen storage and supply, the need to build hydrogen infrastructure and compatibility with traditional power systems [13].

2.2.3 Pros and Cons

Hydrogen as a fuel can significantly reduce greenhouse gases and harmful emissions produced by ships during operation. Hydrogen has high combustion efficiency. And it is renewable. It has diverse production methods and is rich in resources. Therefore, it has significant benefits for reducing emissions and promoting sustainable shipping.

However, hydrogen is expensive to produce, store and transport, especially green hydrogen [12]. The energy efficiency of hydrogen production and combustion is lower than some traditional fuels. Hydrogen embrittlement can easily lead to corrosion damage to ship structures and components [10]. Hydrogen is highly flammable. So, it poses safety challenges.

2.3 Ammonia internal combustion engine

Ammonia is a colourless gas with a pungent odour at room temperature and pressure. It does not produce carbon dioxide during combustion. So, it has great potential for reducing carbon emissions. However, ammonia combustion may produce a small amount of nitrogen oxides [14]. In addition, by using renewable energy to produce ammonia, its renewable nature can be achieved.

2.3.1 Technical Challenges

Corrosion: Ammonia is highly acidic and alkaline. So, it can easily form corrosion layers such as nitrides and oxides on metal surfaces. Metal materials in lubrication systems are susceptible to corrosion by ammonia, resulting in a decrease in lubricant quality. In addition, the water produced by the combustion of ammonia can cause the hydrolysis of ammonium ions, making the metal susceptible to passivation, corrosion, fracture, and other problems [15]:

$$NH_4^{+}+2H_2O==NH_3{\cdot}H_2O+H3O^{+} \quad (1)$$

$$NH_4^{+}+2H_2O== NH_3{\cdot}H_2O+H^{+} \quad (2)$$

$$2H^{+}+Fe==Fe2^{+}+H_2 \quad (3)$$

To reduce ammonia corrosion, using corrosion-resistant materials is the most direct method. In addition, applying anti-corrosion coatings can provide additional protection. Ammonia fuel can also be purified to reduce impurities.

Transportation: Ammonia is processed to obtain liquid ammonia by cooling at normal pressure and liquefied under pressure, which is then stored in special pressure vessels or cryogenic tanks. The storage container must have good insulation and sealing properties. The temperature and pressure must be strictly controlled during transportation to prevent leakage and explosion risks. In addition, when storing and transporting ammonia, a leak detection system must be installed to ensure that ammonia leaks are discovered and handled timely.

Pollution: The production of Ammonia uses fossil fuels such as natural gas or coal, resulting in large amounts of CO2 and other greenhouse gas emissions, as well as other pollutants such as SOx, NOx, and nitrous oxide [16]. It can use alternative sustainable ammonia production pathways, including electrochemical and biological pathways. During use, incomplete combustion of ammonia may lead to increased NOx emissions. It can use in-cylinder reformate recirculation technology to improve the thermal efficiency of pilot-ignition diesel ammonia combustion engines and reduce unburned NH3, NOx, and N2O emissions [14].

Friction: Ammonia as a fuel does not have good lubrication properties. It is easy to produce dry combustion byproducts during combustion. And it produces highly corrosive nitrogen oxides. Even trace concentrations of ammonia can seriously affect the deposit formation characteristics and stoichiometric concentration [17].

Therefore, domestic and foreign researchers have conducted research on the composition and working conditions of lubricating oils in a zero-carbon environment [16]. At the same time, high-temperature-resistant and corrosion-resistant alloy materials are selected as the materials for key friction parts of the engine and friction and wear tests are carried out on the moisture produced by the combustion of ammonia fuel. Oil manufacturers need to consider the impact of ammonia when developing new additive packages. Moreover, when using ammonia as a fuel, appropriate chemical analysis procedures are required [17].

Combustion: The challenge of using ammonia as a marine fuel lies in the poor combustion characteristics of ammonia and the related engine combustion technology. Therefore, to overcome the inherent disadvantages of ammonia, such as high ignition energy, narrow flammability limit and slow propagation speed, HPDF and LPDF are the two main modes [18, 19]. At the same time, to solve the problem of excessive unburned ammonia emissions, EGR is usually used to control NOx emissions. The new concept of in-cylinder reformed gas recirculation (IRGR) can also be used to improve the indicated thermal efficiency and reduce unburned NH3, NOx, N2O and GHG emissions [14].

2.3.2 Application Cases

C-Job Naval Architects designed a zero-emission ship using ammonia fuel to ensure that ammonia can be stored and transported safely and efficiently, achieving the goal of zero carbon emissions. However, it also faces many difficulties. The storage and transportation of ammonia requires a low-temperature and high-pressure environment, which increases the complexity and cost of ship design. And ammonia has a greater risk of leakage in the marine environment. With the continuous advancement of technology, ammonia fuel is expected to play a key role in more fields in the future.

2.3.3 Pros and Cons

Ammonia does not produce greenhouse gas emissions during operation, which can effectively meet the pressure of the global shipping industry to reduce greenhouse gas emissions. In addition, ammonia can be produced through renewable energy, electrolyzing water to produce hydrogen, and then synthesizing it with nitrogen. The use of renewable energy to produce ammonia can achieve sustainable development. And compared with hydrogen, ammonia is relatively easier to store.

However, full decarbonization of ammonia fuels relies on low-carbon energy inputs and feedstock materials. And “green” hydrogen and ammonia from renewable sources are currently not available in the quantities required by the maritime industry [20]. Ammonia is corrosive and can corrode metal components of marine engines by used for a long time, increasing maintenance costs[15]. For ammonia-fueled shipping to become a reality, poor combustion performance and toxicity risks must be overcome, as well as infrastructure development. However, the means to overcome these challenges may be beyond the scope of the maritime sector itself [20].

3 Results and Discussion

Table 2. Performance comparison between the marine clean energy engines

	LNG	Hydrogen	Ammonia
Corrosion	LNG reduces moisture generation. It contains sulfur and lubricating properties. It has less corrosivity.	It will cause hydrogen embrittlement and easily cause battery corrosion. So, it will cause strong corrosion to the equipment.	It has a high corrosivity. Metals are prone to passivation, corrosion and fracture when contacting ammonia.
Transportation	The transportation cost is high. And the transportation pollution problem needs to be solved urgently.	High-pressure gaseous hydrogen storage is used, but a series of safety measures need to be taken. So, transportation is complicated.	It is stored in special pressure vessels or low-temperature tanks for transportation, but the risk of leakage and explosion must be prevented.
Pollution	It is clean and environmentally friendly, but during combustion and transportation, it will produce small amounts of pollutants. And the risk of methane leakage is the greatest.	The combustion products are completely environmentally friendly. However, production will cause pollution. So the production of "green hydrogen" is crucial.	It produces NOx emissions to cause pollution. So additional equipment is needed to reduce pollution.
Friction	The impact of friction is small. However, it will reduce the viscosity of the lubricating oil and cause the organic additives to precipitate, generating friction.	It causes problems such as deterioration of the operating condition of the engine friction pair, emulsification of lubricating oil and abnormal engine wear.	It does not have good lubricity. It produces dry by-products and NOx with high corrosivity.
Combustion	It has stable energy output, but the LNG combustion efficiency needs to be improved.	It uses a style of hydrogen-air mixture for combustion, which has extremely high combustion efficiency. But this style poses a safety hazard.	The poor combustion characteristics of ammonia and related engine combustion technology.

In summary, according to the table 2, LNG has high combustion efficiency, less pollution and mature technology. However, LNG engines have a high risk of methane leakage and high transportation and storage costs. Normally it is suitable for large ships. Hydrogen has high energy density and low pollutant emissions. However, it is difficult to store and transport. It has high investment costs. And there is uncertainty in fuel supply. It is suitable for short-distance and light ships. Ammonia is easy to store and distribute. And it has no carbon emissions. However, it has poor combustion performance. And there is a risk of toxicity. It is suitable for medium and long-distance transportation.

4 Summary and Conclusion

The article mainly discusses the urgency of reducing carbon emissions in the shipping industry and the application prospects and technical challenges of clean energy engines. The article points out that the use of traditional fossil fuels in ship transportation results in serious carbon emissions. Thus, this phenomenon promotes the development of clean energy engines. The article focuses on three clean energy engines: LNG engines, hydrogen engines and ammonia engines. LNG engine technology is relatively mature, which can significantly reduce carbon emissions and have low pollutant emissions. But its storage and transportation costs are high. And there is a risk of methane leakage. Hydrogen has high combustion efficiency as a fuel. And its combustion product is only water, making it extremely environmentally friendly. But production and storage costs are high. Ammonia engines have huge potential to reduce emissions and are relatively easy to store and transport. However, ammonia has poor combustion characteristics and high corrosivity. And it has certain toxicity risks. Therefore, the potential of ammonia engines has attracted widespread attention at home and abroad. It is predicted that ammonia engines will be a key project in the future ship research direction of various countries.

At present, the research about ammonia engines at home and abroad is in its infancy. And there is no mature and effective solution to solve the problems of ammonia engines. In the future, efforts should be made to develop efficient combustion technology, the safety of transportation and storage and research on mixed-use with other renewable energy sources. Among them, the friction problem is the key part of improving efficiency. The friction problem can be studied from the aspects of low-carbon environment lubricating oil analysis and testing, low-carbon environment interface tribological characteristics test research, low-carbon environment interface friction and wear detection and so on. At the same time, some parameters such as lubricating oil type, viscosity and water content also have a certain impact on the friction.

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