Combustion efficiency and emission control of ships with liquefied natural gas internal combustion engines

Yujie Ruan[1*],
[1]Dalian Maritime University, Department of Naval Architecture and Ocean Engineering College, Dalian, China

Abstract. Due to the increasingly serious environmental pollution, new energy technology has received more and more attention. Among the many new forms of energy, liquefied natural gas (LNG) stands out because of its relatively mature technology and sufficient reserves. Its many advantages also make it very suitable for Marine fuel. Liquefied natural gas (LNG) internal combustion engine ships have received more and more attention in the current environment, but due to the technical monopoly and high research and maintenance costs, there are still some deficiencies in combustion and emissions, which have caused some obstacles to the promotion of LNG internal combustion engine. This paper introduces and summarizes some technical solutions in the field of combustion emission of LNG ships, analyses some successful cases of commercial ships, and summarizes part of the development process of LNG internal combustion engine ships, hoping to be helpful to the development of LNG internal combustion engine ships.

1 Introduction

Since the Industrial Revolution took place in the United Kingdom, the demand for and use of fuel in human society has increased dramatically. In the Second Industrial Revolution, the invention of the internal combustion engine made fossil fuels a very important part of modern industry. Nowadays, the vast majority of vehicles, ships, etc., still use the internal combustion engine as the main power source. However, the traditional fuel combustion process will inevitably produce a lot of pollution. With time, the pollution problem caused by the exhaust gas from the burning of traditional fossil fuels has become more and more serious. Climate change such as global warming has caused a great impact on the ecological environment, and natural disasters such as acid rain are becoming more frequent. Because of the increasing environmental pressure and the continuous improvement of public awareness of environmental protection, the research and utilization of new energy have been paid more and more attention. Since the United States first used liquefied natural gas (LNG) for ship fuel, LNG has become one of the most competitive new energy fuels because of its characteristics of less pollution and large reserves. The main component of LNG is CH4.

* Corresponding author: be21120903@dlmu.edu.cn

Studies have shown that using liquefied natural gas (LNG) as a fuel can significantly reduce emissions compared to conventional fuels. Specifically, carbon dioxide (CO_2) emissions are reduced by about 20-30%, nitrogen oxide (NO_x) emissions are reduced by 70-90%, while sulfur oxide (SO_x) can be almost eliminated. These significant emissions reductions make LNG a more environmentally friendly alternative. Therefore, LNG is a new energy fuel that is friendly to the environment. However, if LNG is not fully burned, it will produce a large number of polluting gases such as carbon monoxide. Therefore, it is very important to improve the combustion efficiency of LNG and allow it to be fully burned. At the same time, the harmless treatment of the exhaust gas after combustion is also an important goal of current research. In recent years, engineers all over the world have been deeply studying the combustion efficiency of internal combustion engines for LNG ships, and have developed and put into use improved equipment such as pure gas fuel engines, spark ignition engines and dual-fuel engines. In terms of emission, waste gas recirculation, catalytic reduction and low-temperature separation are used to deal with the harmful gases emitted. This paper hopes to help the development of LNG energy by summarizing and comparing the combustion improvement measures and emission control technologies of the current mainstream LNG internal combustion engine ships and summarizing the development of LNG internal combustion engine ships [1-3].

2 Combustion characteristics, exhaust gas types and environmental impacts of LNG in internal combustion engine ships

2.1 Combustion efficiency optimization

Under normal circumstances, liquefied natural gas is first converted into gas in the intake pipe of the internal combustion engine and burned as fuel, which releases a large amount of heat to power the engine. The exhaust gas produced by LNG in the case of complete combustion is only carbon dioxide and water, which has little impact on the environment except for the greenhouse effect. However, if LNG is not completely burned, it may produce a large number of pollutants, resulting in various exhaust gases that have a significant negative impact on the atmospheric environment. Table 1 shows the comparison of pollutants under different combustion conditions of LNG.

Table 1. Different combustion degrees of liquefied natural gas produce pollution comparison

Contaminant	Complete combustion	Incomplete combustion
Carbon dioxide	High	Low
Carbon monoxide	None	High
Volatile organic compounds	None	High
Particulate matter	None	High
Nitrogen oxide	Low	High
Steam	High	Low

Therefore, improving combustion efficiency is very important to improve the competitiveness of LNG internal combustion engines.

2.1.1 Optimization method of fuel feeding system

At present, there are many methods to improve the combustion efficiency of LNG internal combustion engines, and one of the more common and widely used methods is fuel injection system optimization. LNG is burned differently from other conventional fossil fuels, although it is called liquefied natural gas, which is ultimately burned as a gas. Before entering the combustion chamber, the LNG needs to be mixed with air to enter the internal combustion engine for combustion. During the operation of an internal combustion engine, a mixture of fuel and air enters the combustion chamber, which then causes combustion through compression and ignition and does work to the engine. The mixture of LNG and air is called the air-fuel ratio, which determines the efficiency and emission characteristics of combustion. Therefore, if the air-fuel ratio can be accurately controlled, the combustion efficiency of LNG can be well improved. Optimization of the fuel injection system allows precise control of injection timing: Precise control of the fuel injection timing through the electronic control unit (ECU) ensures adequate mixing of fuel and air, reducing fuel waste and thereby increasing combustion efficiency. In addition, properly controlled fuel injection can also ensure that the natural gas mixture in the combustion chamber is fully consumed before the next round of intake, which can reduce the accumulation of unburned fuel during the combustion process, thereby reducing emissions. While the LNG may lose heat in the pipeline leading to energy loss before the fuel enters the combustion chamber, Direct injection systems (DI) can inject the fuel directly into the combustion chamber, reducing waste while improving the response time and efficiency of the combustion process. Viking Energy, owned by Norwegian company Eidesvik Offshore and the world's first supply vessel powered by LNG, has improved its combustion efficiency by around 1.9% following improvements to its fuel feed system, such as optimized injection technology. This has helped it meet International Maritime Organization (IMO) emissions requirements [4-5].

2.1.2 Optimizing the Combustion Chamber

Unlike oil and other general liquid fog in the combustion chamber pressure combustion, gas combustion of LNG in the combustion chamber design is also different from the traditional energy emphasis. Because there is no need to consider the partial situation of the liquid, the vortex combustion chamber is an effective optimization direction. Through the design of the combustion chamber that can trigger air swirl, the gas will be affected by the special shape of the fuel chamber when entering the spiral motion and constantly mixed with the newly entered gas, which will enhance the mixing of fuel and air, fully improve the air-fuel ratio, and make the heating of each part of the mixed gas more uniform, which is conducive to improving the combustion uniformity and efficiency; Precombustion chamber technology is also a design scheme that can effectively improve combustion efficiency. This method will set up an additional combustion space outside the main combustion chamber. The LNG mixture is first ignited in the precombustion chamber to generate a high-speed flame, which then travels to the main combustion chamber to accelerate the combustion process. At present, the most common combustion chamber optimization technology for LNG internal combustion engines is dual-fuel engines. The fuel for such engines is usually a combination of LNG and conventional diesel or other liquid fuels. In dual-fuel engines, LNG is primarily responsible for combustion to provide most of the energy, while conventional fuels (such as diesel) are primarily placed at the bottom of the combustion chamber for ignition. Due to the high compression ratio of traditional fuels such as diesel, they can ignite themselves by compressed air, generating a large amount of heat in an instant, which in turn ignites a natural gas mixture to generate a large amount of energy. This method takes into account the advantages of easy ignition of traditional energy and high heat and less pollution of LNG energy combustion, reduces the energy loss in the combustion process, and greatly improves the combustion efficiency of LNG. In addition, based on the characteristics of the ship's ocean sailing is not easy to replenish fuel, the dual-fuel engine can also completely use diesel as an emergency fuel when necessary, which improves the flexibility of navigation. Norwegian shipowner Fjord1's LNG ferry "Kvitebjørn" has a dual-fuel engine, powered primarily by LNG combustion, with diesel used for ignition. The ship sets an example in the ferry market of an environmentally friendly and economically efficient energy transition, significantly reducing emissions while minimizing the economic impact [6-7].

2.2 Optimization of the emission system

In addition to minimizing the generation of pollutants during the combustion phase, the optimization of the exhaust gas emission phase is also critical. Effective and improved discharge systems can significantly reduce the emission of hazardous substances. A common technology for reducing nitrogen oxide (NO_x) emissions is exhaust Gas recirculation technology (EGR). Through EGR technology, the exhaust gas that should have been directly discharged after partial combustion will enter the intake pipe again and mix with the unburned gas, which will then enter the combustion chamber together. At this time, in addition to LNG gas, there are non-combustible gases such as water vapour in the mixed gas, which will reduce the combustible content in the mixed gas and thus reduce the reaction rate, and then reduce the temperature of the combustion chamber. In addition, due to the addition of waste gas, the oxygen content of the mixed gas in the intake pipe is also reduced, which reduces the concentration of oxygen in the combustion chamber and reduces the intensity of combustion. The formation of nitrogen oxides depends on the high-temperature environment, and through the EGR system, the temperature peak of the combustion chamber can be reduced, thus reducing the generation of NO_x and reducing exhaust gas pollution [8-11].

Selective catalytic reduction systems (SCR) are also common ways to optimize emission systems. As an advanced and relatively mature exhaust gas treatment technology, SCR systems are widely used in internal combustion engine ships including diesel and natural gas fuels. The SCR system converts NO_x into two harmless substances, nitrogen (N_2) and water vapour (H_2O), through a chemical reduction process, and then emits it, greatly reducing the pollution caused by LNG combustion. The SCR system is essentially a catalytic reaction. First, the urea-based reducing agent will be sprayed into the exhaust pipe and decomposed into ammonia gas; Subsequently, the exhaust pipe through rotation and other effects, so that ammonia gas and combustion exhaust gas are fully mixed; Eventually, under the action of the catalyst, the ammonia will react with the nitrogen oxides in the combustion exhaust gas to form water and nitrogen. Nitrogen oxides react with ammonia as follows：

$$4NO+4NH_3+O_2 \rightarrow 4N_2+6H_2O \quad (1)$$

$$6NO_2+8NH_3 \rightarrow 7N_2+12H_2O \quad (2)$$

The SCR system has good stability and can work under different load conditions, especially suitable for ships with long time and high load operation. In addition, the selective catalytic reduction system is very effective in the treatment of nitrogen oxides and generally can reduce NO_x emissions by more than 90%, which makes the application of the technology more easily meet the International Maritime Organization (IMO) emissions standards and favoured. However, the SCR system is more dependent on a high-temperature environment, low temperature will affect the reaction efficiency of SCR, resulting in increased cost. Due to the low combustion temperature of LNG internal combustion engines, the SCR system needs to be more suitable for low-temperature design when applied in LNG internal combustion engine ships, or combined with an exhaust gas preheating device in the exhaust system to improve its working efficiency.

2.3 Application of LNG technology improvement in internal combustion engine ships

As one of the most competitive forms of new energy, LNG vessels have experienced a fairly rapid development stage since the combustion engine fueled by it was first used in ship power systems by the Norwegian Gas Company in 2000. Since 2015, LNG internal combustion engines have experienced many technological improvements and good and rapid progress has been made in the field of combustion efficiency improvement and exhaust gas emission control. In terms of combustion chamber optimization, since 2015, the combustion chamber design of LNG internal combustion engines has gradually developed from a traditional structure to an efficient combustion direction. By improving the shape and material of the combustion chamber, the mixture of air and fuel is enhanced, making the combustion more complete, reducing the byproducts of incomplete combustion, which reduces the production of waste gases and improves the utilization of fuel. MAN Energy Solutions, for example, launched a new combustion chamber for LNG fuel based on an EGR system in 2019. By optimizing the flow rate, fuel injection Angle and pressure of the intake pipeline, LNG fuel achieves higher combustion efficiency and significantly reduces the level of nitrogen oxide emissions. This technology has been applied to modern LNG ships with remarkable results. In recent years, the combustion chamber adapted to the LNG combustion environment has been updated continuously, and major ship research institutes are committed to further optimizing the structure of the combustion chamber to maximize the combustion efficiency of LNG.

Engine optimization is mainly focused on the mixed fuel system. One example is the dual-fuel engine. This engine can use LNG as the main fuel and traditional heavy oil for ignition and emergency energy supply, and flexibly switch fuels. The introduction of LNG gives the engine obvious advantages in reducing emissions (such as SO_x, NO_x, and CO_2) while maintaining stable performance during fuel switching. Coupled with the high combustion temperature of traditional fossil fuels, the combustion chamber can be quickly preheated to further improve combustion efficiency. MAN, Energy Solutions' ME-GI engine, which went into service in 2015, is an example of a dual-fuel engine. This is the world's first LNG dual-fuel low-speed engine with high-pressure direct injection technology. The design of the ME-GI engine allows the use of LNG as the primary fuel, supplemented by a small amount of fuel oil for ignition. This engine can significantly improve fuel efficiency without increasing emissions and reduce methane leakage. It can effectively utilize the ship's natural gasification gas (BOG) during the voyage to achieve optimal fuel consumption and efficiency. Since 2015, more than 70 LNG vessels equipped with ME-GI systems have been put into service, demonstrating significant fuel efficiency and energy-saving advantages over conventional LNG carriers. In addition, MAN Energy Solutions has integrated exhaust gas recirculation (EGR) technology on its ME-GI engine platform. The application of this technology significantly reduces NOx and methane leaks while improving fuel efficiency. The system helps the engine comply with the increasingly stringent emission requirements of the International Maritime Organization and does not require additional exhaust treatment systems, which greatly saves the economic cost of emissions. In 2023, the ME-GA opti system was introduced to further improve the ME-GI engine. This control system maximizes combustion efficiency by precisely controlling the combustion process of each cylinder, further improving fuel economy and reducing emissions [12].

3 Conclusion

As one of the most competitive new forms of energy, LNG has attracted much attention and developed rapidly since its first commercial use. At present, the optimization of LNG internal combustion engines by major energy companies and research institutes mainly focuses on improving combustion efficiency and improving emission systems. By improving the combustion chamber, such as optimizing the shape of the combustion chamber, adopting a dual-fuel engine and reforming the feed system, LNG can be more fully burned in the combustion chamber at a lower temperature and reduce the generation of pollutants. In the process of exhaust gas emission, low-pressure fuel gas supply systems (FGSS), the EGR, and

SCR systems are used to treat and reuse the exhaust gas, which can further reduce unnecessary pollution emissions. Under the guidance of the policy, major energy and shipping companies have carried out a lot of research and optimization on the LNG internal combustion engine system, which has significantly reduced the emissions of nitrogen oxides and carbon dioxide since 2015. In the future, LNG internal combustion engine ships will pay more attention to methane leakage control technology. Methane has about 25 times more greenhouse potential than carbon dioxide. During combustion, unburned methane escapes into the atmosphere, undermining LNG's climate advantage as a clean fuel. While current technologies such as EGR have significantly reduced methane leakage, further controlling and reducing such emissions remains a key challenge for LNG applications. Since LNG requires low-temperature combustion, low-temperature combustion technology will continue to develop, so that LNG can burn fuel more evenly to reduce NOx generation. The combination of LNG and other low-carbon energy sources is also a hot spot for future development. While LNG is currently a relatively clean fuel, it may be combined with more environmentally friendly fuels such as hydrogen and ammonia in the future. In addition, the current full promotion of LNG internal combustion engine ships is still subject to its higher technical requirements. Most of the production research data are still monopolized by developed countries and some large companies, which makes its promotion subject to certain restrictions. The operation and maintenance of LNG fuel technology requires a high level of technical support and personnel training, which makes the operating cost of LNG internal combustion engine ships high, to a certain extent, reducing the enthusiasm of shippers to invest. In this case, some shipping companies and government organizations have begun to share technology to a certain extent in the international scope. In general, LNG internal combustion engine ships are still facing certain problems due to technical problems, which affects the effect of reducing pollution. However, through continuous improvement and optimization over the years, the LNG internal combustion engine has greatly reduced pollutant emissions and reflected huge commercial value, and LNG will continue to get more attention and development as one of the most competitive new energy methods in the future.

References

1. Paul Balcombe, Iain Staffell, Ivan Garcia Kerdan, Jamie F. Speirs, Nigel P. Brandon, Adam D. Hawkes, How can LNG-fuelled ships meet decarbonisation targets? An environmental and economic analysis, Energy, Volume **227**, (2021), https://doi.org/10.1016/j.energy.2021.120462
2. Fabio Burel, Rodolfo Taccani, Nicola Zuliani, Improving the sustainability of maritime transport through the utilization of Liquefied Natural Gas (LNG) for propulsion, Energy, Volume **57**, (2013), https://doi.org/10.1016/j.energy.2013.05.002
3. O. Schinas, M. Butler, Feasibility and commercial considerations of LNG-fueled ships, Ocean Eng., Volume **122**, (2016), https://doi.org/10.1016/j.oceaneng.2016.04.031
4. Boretti, A. Advances in Diesel-LNG Internal Combustion Engines. Appl. Sci. 2020, **10**, 1296. https://doi.org/10.3390/app10041296
5. Shou-guang Yao, Zijing Zhang, Yue Wei, Rui Liu, Integrated design and optimization research of LNG cold energy and main engine exhaust heat utilization for LNG powered ships, Case Stud. Therm. Eng., Volume **33**, (2022), https://doi.org/10.1016/j.csite.2022.101976
6. Ruiz Zardoya, A.; Oregui Bengoetxea, I.; Lopez Martinez, A.; Loroño Lucena, I.; Orosa, J.A. Methodological Design Optimization of a Marine LNG Internal Combustion Gas Engine to Burn Alternative Fuels. J. Mar. Sci. Eng. 2023, **11**, 1194. https://doi.org/10.3390/jmse11061194

7. Jiehui Li, Bingbing Wu, Gongping Mao, Research on the performance and emission characteristics of the LNG-diesel marine engine, J. Nat. Gas Sci. Eng., Volume **27**, Part 2, (2015), https://doi.org/10.1016/j.jngse.2015.09.036
8. Medhat Elkelawy, E.A. El Shenawy, Sherif A. Mohamed, Mostafa M. Elarabi, Hagar Alm-Eldin Bastawissi, Impacts of using EGR and different DI-fuels on RCCI engine emissions, performance, and combustion characteristics, ECMX, (2022), https://doi.org/10.1016/j.ecmx.2022.100236
9. Hua Xu, Dong Yang, LNG-fuelled container ship sailing on the Arctic Sea: Economic and emission assessment, Transportation Research Part D: Transport and Environment, Volume **87**, (2020), https://doi.org/10.1016/j.trd.2020.102556
10. Paul Balcombe, Dalia A. Heggo, Matthew Harrison,Total Methane and CO2 Emissions from Liquefied Natural Gas Carrier Ships: The First Primary Measurements, Environmental Science & Technology, Volume **56**, (2022), https://doi.org/10.1021/acs.est.2c01383
11. Maria Anderson, Kent Salo, Erik Fridell, Particle- and Gaseous Emissions from an LNG Powered Ship, Environmental Science & Technology, Volume **49**, (2015), https://doi.org/10.1021/acs.est.5b02678
12. E. Ekanem Attah, R. Bucknall, An analysis of the energy efficiency of LNG ships powering options using the EEDI, Ocean Eng, Volume **110**, Part B, (2015), https://doi.org/10.1016/j.oceaneng.2015.09.040