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(Research Article)

Contributions to decrease noxious emissions and develop environmental sustainability in seafaring

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Abstract

Many researchers have confirmed that gasoline is taken into consideration as the primary component that causes climate change and other environmental problems. A large chunk of the greenhouse gases (GHG) that blanket the Earth and trap the sun's heat are generated through energy production by burning fossil fuels. A significant portion of the world's energy consumption, which rises annually, is caused by the transportation industry, especially the shipping industry. This study highlights the IMO regulations and the technological methods to develop environmental sustainability in seafaring. Nitrogen oxide (NOx) is one of the major components of shipping exhaust emissions. To adapt to expanding natural requests and environmental issues, the International Maritime Organization (IMO) applied restrictions to limit NOx emissions. Annex VI, NOx control requirements, apply to marine diesel engines with output power greater than 130 kW. According to IMO levels (Tiers), the Tier III controls apply only to the specified ships while operating in Emission Control Areas (ECAs) established to limit NOx emissions; outside such areas, the Tier II controls apply. The IMO's first limitation was named Tier I and was introduced in the year 2000. More recently, the stricter Tier III emission limitations have been introduced and constitute an essential step towards environmentally friendly maritime transportation. Tier III has strengthened the emissions standards, requiring NOx emissions in NOx ECAs to be less than 3.4 g/(kWh). New emission reduction technologies have to be developed to fulfil the Tier III limits. There are several promising technologies to achieve the required NOx reductions. This study focuses on the NOx formation and the technological methods to decrease the NOx emissions to achieve the standards of the IMO regulations.

Keywords: Greenhouse Gases (GHG); IMO; Maritime Transport; Nitrogen Oxides (Nox); Tier III

1. Introduction

Greenhouse gases have a significant impact on climate change and global warming (Elmallah et al., 2024; Elmallah et al., 2023). These gases, such as carbon dioxide, methane, and nitrous oxide, trap heat in the earth's atmosphere, creating a warming effect that can lead to rising global temperatures (Elmallah et al., 2024). As humans continue to burn fossil fuels and engage in other activities that release these gases into the atmosphere, the concentration of greenhouse gases has been steadily increasing over the past few decades. This increase is causing the Earth's temperature to rise, leading to a range of negative impacts such as melting glaciers, rising sea levels, and more frequent and severe weather events (Elmallah, 2024). To combat the effects of greenhouse gases, it's important to reduce emissions and convert to cleaner sources of energy (Elmallah et al., 2024). This can include things like investing in renewable energy, improving energy efficiency, and reducing reliance on fossil fuels. Doing so will slow the rate of climate change and protect the planet for future generations. Reducing greenhouse gases has become a priority in government policies and research committees

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due to the growing international collaboration regarding the adverse effects of climate change. It is crucial to comprehend the factors that affect the GHG emissions and to develop up suitable methods to decrease these emissions. In 2015, the concentrations of greenhouse gases, such as CO2, methane CH4, and nitrous oxide N2O in the atmosphere increased by 44%, 156%, and 21%, respectively, compared with these concentrations in 1750 (EPA, 2016). Water vapour, CO2, CH4, and N2O air pollutants are examples of greenhouse gases. Moreover, a number of other chemicals, such as carbon monoxide CO, nitrogen dioxide NO2, sulphur dioxide SO2, volatile organic compounds VOCs, and nitrogen oxides NOx, can have regionally varying radiative forcing effects on the earth's radiation. Figure 1 shows the global greenhouse emissions by gas.

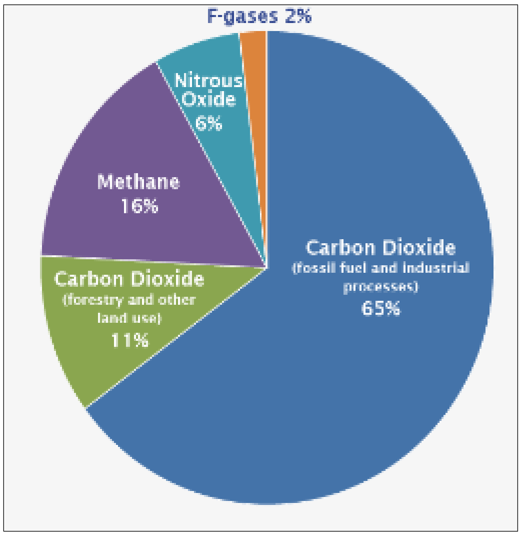

Figure 1 Global greenhouse gas emission by gas (US EPA, 2016).

According to commonly used economic sector categories, greenhouse gas emissions are distributed among major economic sectors (US EPA, 2016). The largest source of greenhouse gas emissions from human activity goes to electricity and heat production. However, the transportation sector is crucial to economic and social development and also has one of the world's fastest-rising rates of energy consumption and emissions. International shipping is one of the greatest GHG emitting industries in the world economy, and it is also predicted to have one of the quickest GHG growth rates (Gibbs et al., 2014). According to the International Maritime Organization IMO, shipping is estimated to be responsible for 2.2% of the world's greenhouse gas emissions in 2018, although this number is expected to rise sharply in the future. The IMO has put out regulations to reduce emissions from shipping, including the use of low-sulphur fuels, the use of energy-saving technologies, and the implementation of emissions monitoring and reporting requirements. Despite these attempts, the shipping sector still has a way to go in terms of decreasing its emissions, but it is still possible to minimize the consequences of climate change with the correct regulations and technologies. The maritime sector is responsible for 6.6%, 4%, and 2.6% of Nitrogen Oxide NOx, Sulfur dioxide Sox, and Carbon dioxide CO2 emissions, respectively (El-Gohary, 2012). The emission of nitrogen oxides NOx from shipping has a significant impact on the global environment and contributes to air pollution, health concerns, acid rain, and global warming. the IMO has set a target of reducing NOx emissions from shipping by at least 80% by 2050 compared to 2008 levels, by establishing emission control areas (ECAs) in designated regions, such as the Baltic Sea and the North Sea by implementing a three-tier system in NECAs (NOx Emission Control Areas). This study focuses on the technological methods to decrease noxious emissions and to develop environmental sustainability in seafaring. Methane, also known as natural gas, has been considered as a potential alternative fuel for engines in ships due to its low emissions and cost-effectiveness. The use of methane as a fuel can significantly reduce emissions of carbon dioxide CO2, nitrogen oxides NOx, sulfur oxides SOx, and particulate matter PM. This research paper provides a case study on a ship engine to demonstrate the engine efficiency and environmental effects of using methane as an alternative fuel. Table 1 shows a summary of emission mitigation methods for ships.

Table 1 Summary of Emission Mitigation Options for Ships (Han, 2010).

Measure Types	**Measure**	**Description**	**Examples**
Technological strategies	Lower sulfur fuel	- Marine residual or bunker with sulfur content at 1.5%, or below (44% Sox reduction, 18% PM reduction). - Marine distillate and gas oil with sulfur content at 0.1% or below (> 90% Sox, > 80% PM reduction).	- EU (and IMO) Sulfur Emission Control Area: Baltic Sea (2006), English Channel, and North Sea (2007). - San Pedro Harbor Maersk voluntary agreement (0.2% sulfur fuel, 2006)-California auxiliary engine rule (2007).
	Selective catalytic reduction (SCR)	- exhaust after-treatment technology providing over 90% reduction in NOx, PM, CO, and HC reduction can be obtained when SCR is combined with a PM filter and oxidation catalyst.	- Units in service starting in early 1990s in applications ranging from ferry, cruise ship, to roll-on roll-off Vessels.
Operational strategies	Vessel speed reduction	- speed within harbors is reduced to reduce engine load and NOx production (4%-8% reduction)	- Voluntary program in the Los Angeles/Long Beach harbor since 2001.
	Shore-side power	- Land based power for docked ships (100% reduction in at-port emission)	- Facilities operating in the Baltic and North Seas, Juneau (Alaska), and Port of Los Angeles.
Market-based strategies	Environmentally differentiated fee	- Fee reductions based on vessel environmental performance. - Emissions benefits depend on level of participation and implemented technologies.	- Voluntary Environmentally Differentiated Fairway Dues Program in Sweden since 1998.
	Cap and trade system	- A government or regulatory body first sets a limit or (cap) on the amount of environmental degradation or pollution permitted in a given area and then allows firms or individual to trade permits or credits in order to meet the cap.	

2. Overview of the NOx issue

Nitric oxide (NO) and nitrogen dioxide (NO2) are the two most prevalent oxides that nitrogen can produce, despite the fact that nitrogen can also form eight additional oxides. Almost 80% of the nitrogen (N2) in regular air is oxidized to NOx (NO, NO2, and N2O) during combustion. Colorless gas NO has certain negative health effects, these effects are significantly less severe than those of an equivalent dose of NO2. NO2 is created when NO combines with O2 in the atmosphere and in industrial devices. This brown gas is a significant respiratory irritant. NO and NO2 are frequently viewed as a single issue and written NOx. The majority of NOx emission rules rely their numerical figures on the supposition that all NO is transformed to NO2. NO will continue to be converted to NO2 in the atmosphere. Rain will wash away NO2, and over time, acid rain will enhance the soil's acidity. Large combustion sources like fossil fuel-fired power plants and diesel engines that burn oil mostly produce NOx into the environment. Together with acid rains, NOx is known to contribute to ozone depletion, which negatively impacts human health. All emission reduction techniques seek to reduce the thermal NOx component, which is crucial for overall emission. The temperature and oxygen concentration possess the greatest influence on the generation of NOx in the combustion chamber: the higher the temperature and the longer the temperature residence time are the more thermal NOx will be produced (Nam Dong, 2000). Thermal NOx, prompt NOx, and fuel NOx are three sources for NOx formation. NOx formation occurs by reaction between nitrogen and oxygen in the combustion air (thermal NOx), by reaction between exhaust gas hydrocarbons and combustion air oxygen (prompt NOx) and by the reaction between nitrogen bindings in fuel (fuel NOx).

3. NOx mitigation strategies

(Nam Dong, 2000), thermal efficiency and reliability have been the two main technologies used to build the diesel engine. The environment is currently a prominent theme in the development of diesel engines, and the majority of technological efforts are currently focused on this issue. In addition to focusing on improving engine performance and reliability, engine builders have to tackle environmental concerns. There are two categories of practical NOx reduction techniques for marine diesel engines: primary techniques and secondary techniques. In primary methods, reduced NOx formation during combustion is the initial goal of primary techniques. Most of these procedures have been implemented primarily to reduce the cylinder's maximum temperature. In secondary methods, NOx removal from exhaust gas is implemented by downstream treatment, The Selective Catalytic Reduction (SCR) is the most used exhaust gas treatment technique. Table 2 shows the primary methods categories.

Table 2 primary methods categories.

Modification of fuel injection	**Addition of water**	**Combustion air treatment**	**Change of engine process**
Modification of the fuel nozzle Delayed fuel injection High pressure fuel injection	Direct water injection Water emulsified fuel Stratified water injection Intake air Humidification	Exhaust gas recirculation Adjustment of inlet /exhaust valve	Compression ratio

4. Imo restrictions on NOx emissions

By implementing a three-tier system in NECAs (NOx Emission Control Areas), the goal is to cut NOx emissions from shipping by 80% since January 2021 (IMO 2017). TIER 2 was implemented in 2011 with a 20% decrease in NOx emissions from shipping compared to TIER 1, while TIER 1 went into effect in 2005 (IMO 2008). The maximum operating speed of diesel engines determines the NOx emission limits, as indicated in Figure 2 and in Figure 3. While Tier III rules only apply in NOx Emission Control Zones, Tier I and Tier II restrictions are global.

Tier	Date	NOx Limit, g/kWh		
		$n < 130$	$130 \le n < 2000$	$n \ge 2000$
Tier I	2000	17.0	$45 \cdot n^{-0.2}$	9.8
Tier II	2011	14.4	$44 \cdot n^{-0.23}$	7.7
Tier III	2016†	3.4	$9 \cdot n^{-0.2}$	1.96

† In NOx Emission Control Areas (Tier II standards apply outside ECAs).

Figure 2 primary methods categories

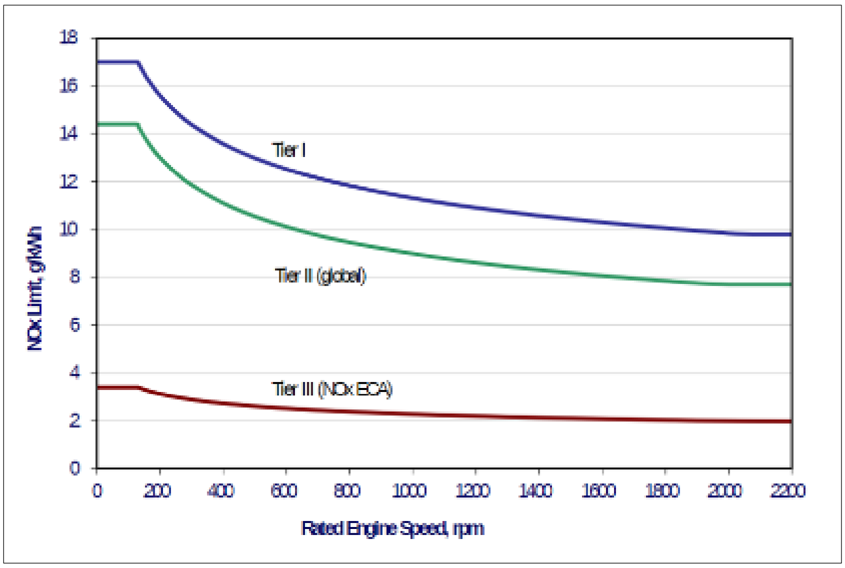

Figure 3 MARPOL Annex VI NOx emission limits.

5. Methane-Diesel Dual Fuel Engine

This paper focuses on an effective method to decrease the noxious emissions through using methane as an alternative fuel in Methane-Diesel Dual Fuel Engine. Methane is a promising marine alternative fuel for meeting current SOx and NOx regulations and reducing CO2 emissions from ship operations (Wang & Wright, 2021). The environment is harmed when methane is released into the air before it is burned. Methane affects climate change by trapping heat in the atmosphere. Methane is more effective at trapping heat than other greenhouse gases, even though its lifetime in the atmosphere is shorter than that of those gases. Although there are natural mechanisms in soil and chemical reactions in the atmosphere that help remove methane from the environment, it is crucial that all human activities that release methane into the atmosphere should be carried out in a manner that minimizes their methane emissions. This includes developing procedures to trap methane that would otherwise be emitted into the atmosphere and use it as a fuel. Methane can act as a clean renewable source of energy that complies with the IMO restrictions to decrease greenhouse emissions, despite the purification process constraints for biomethane (Li et al., 2017; Gissén et al., 2014).

6. Case study

This study focuses on a practical way to reduce noxious emissions by adding methane to diesel fuel in a Methane-Diesel Dual Fuel Engine. Using a combustion chamber and commercial CFD fluid flow (fluent), the effects of adding methane on NOX emissions were evaluated. Figure 4 shows the model description.

main dimension of combustion chamber

Chamber dimensions	
Length (chamber)	1400 mm
Diameter (chamber)	540 mm
Dimeter (nozzle)	8 mm
Length (nozzle)	12 mm

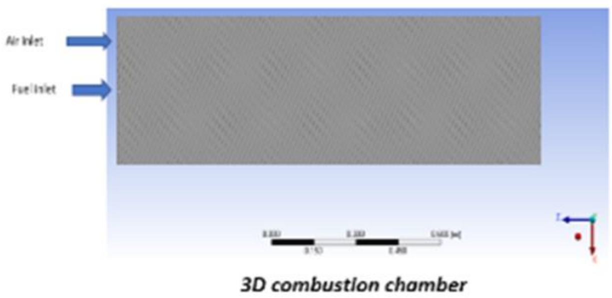

Figure 4 Model description

It is crucial to use mesh metrics to evaluate the mesh's quality, which depends in part on the mesh's skewness, aspect ratio, and softness (change in cell size). Figure 5 shows the mesh calculations.

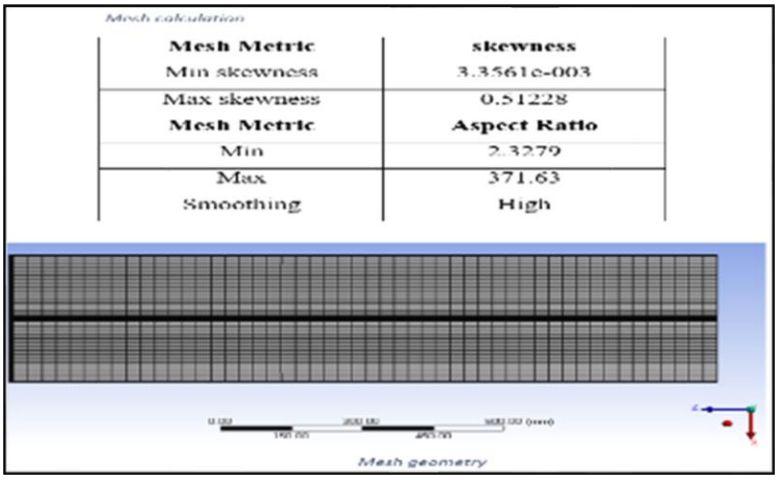

Figure 5 Mesh calculation

Figure 6 shows the CFD results of adding methane at different percentages on diesel fuel.

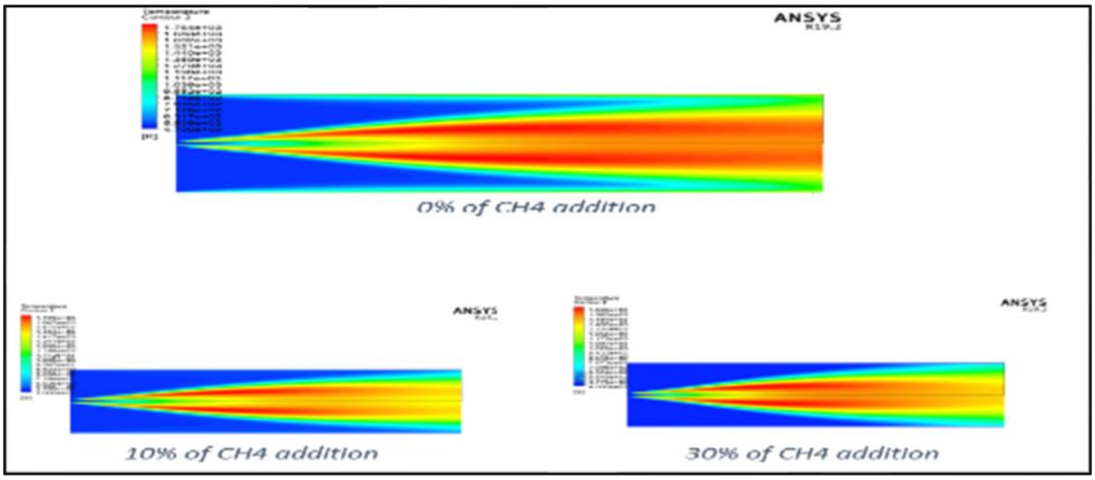

Figure 6 Methane addition at different percentages

Figure 7 shows the results of NOx reduction with respect to different percentages of methane addition to diesel fuel.

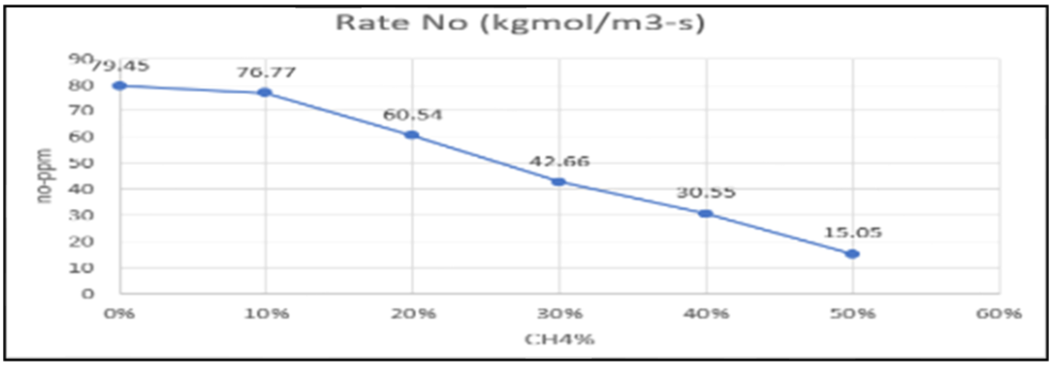

Figure 7 Relation between NOx and methane addition

7. Conclusion

This research paper provides a case study to demonstrate the environmental effects of using methane as an alternative fuel. Methane is a promising marine alternative fuel for meeting current NOx regulations. The study shows that 10% of methane addition has decreased NOx emissions by 3.3%, 20% of methane addition has decreased NOx emissions by 23.9%, and 30% of methane addition has decreased NOx emissions by 46.3%.

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