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DEVELOPMENT OF STRATEGIES FOR REDUCING NITROUS OXIDE EMISSIONS FROM MARINE DIESEL ENGINES

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Abstract

This paper provides a comprehensive review of current strategies and technologies aimed at reducing nitrogen oxide (NOx) emissions from marine diesel engines and serves as a mechanism to summarize existing solutions. The scientific value of the paper lies in the comprehensive analysis of the approaches and offers new insights and an integrated framework that improves the scientific understanding and practical application of these technologies. The study synthesizes different approaches to NOx emission reduction, including selective catalytic reduction (SCR), exhaust gas recirculation (EGR), and fuel switching, into a single system. This holistic perspective emphasizes the synergistic benefits of combining these techniques, offering a more effective strategy for implementation in real-world settings. It addresses the practical challenges associated with these technologies, such as economic, logistical, and regulatory considerations, and proposes potential solutions. Thus, it bridges the gap between theoretical research and practical application, making its findings highly relevant to industry stakeholders. Alongside the review of existing technologies, the paper also proposes new ideas and integrated approaches that contribute to the scientific understanding and practical application of NOx reduction strategies in maritime transport, which is essential for promoting environmental sustainability in the industry.

Keywords: NO_x Reduction Strategies; Maritime Transportation; Marine Diesel Engines; Merchant Ships; Regulatory provisions; Fuel Switching; Sulfur Content; Air Quality; Environmental Impacts; Greenhouse Gas Emissions; Shipping Technologies.

РОЗРОБКА СТРАТЕГІЙ СКОРОЧЕННЯ ВИКИДІВ ОКСИДІВ АЗОТУ З СУДНОВИХ ДИЗЕЛЬНИХ ДВИГУНІВ

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Анотація

Дана стаття містить всебічний огляд сучасних стратегій і технологій, спрямованих на зменшення викидів оксиду азоту (NO_x) від суднових дизельних двигунів. У статті синтезовано різні підходи до скорочення викидів NOx, включаючи селективне каталітичне відновлення (SCR), рециркуляцію вихлопних газів (EGR) і перехід на інше паливо, в єдину систему. Така цілісна перспектива підкреслює синергетичні переваги поєднання декількох методів, пропонуючи більш ефективну стратегію для впровадження в реальних умовах. У роботі також розглядаються практичні виклики, пов'язані з новими технологіями, такі як економічні, логістичні та регуляторні питання, також пропонуються потенційні рішення що здатні подолати розрив між теоретичними дослідженнями і практичним застосуванням, окреслюючи актуальність для зацікавлених сторін галузі. Поряд з розглядом існуючих технологій, в роботі також пропонуються нові ідеї та інтегровані підходи, які сприяють науковому розумінню і практичному застосуванню стратегій скорочення викидів NO_x на морському транспорті що має важливе значення для просування екологічної стійкості в галузі.

Ключові слова: стратегії скорочення викидів NO_x; морський транспорт; морські дизельні двигуни; транспортні судна; нормативні положення; перехід на інше паливо; вміст сірки; якість повітря; вплив на навколишнє середовище; викиди парникових газів; судноплавство.

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Introduction

Shipping plays a pivotal role in the global economy, facilitating over 80% of worldwide trade and contributing 1–3% to the global gross domestic product (GDP). Throughout human history, billions of tons of cargo, ranging from solid goods to liquids and bulk materials, have traveled the oceans. This large-scale maritime activity contributes to the economies of many countries by increasing the availability of essential commodities such as food and raw materials.

Nevertheless, the shipping industry faces the most serious challenge in terms of sustainable development - environmental protection. According to S&P Global Platts Analytics, the shipping sector currently accounts for 2 to 3 % of global CO_2 emissions. Without decisive action, this share could rise to 17 % by 2050. This underscores the urgent need to reconcile climate change goals with the environmental impact of maritime shipping.

Furthermore, the industry's emissions of sulfur oxide (SO_x), nitrogen oxide (NO_x), particulate matter (PM), and soot are garnering increased attention due to their adverse effects on human health and the environment, especially at the local level. There is a clear and immediate demand for effective and practical solutions to address the pressing environmental issues associated with the shipping sector. In the transport sector, this problem is solved in different ways.

Maritime transportation is widely recognized for its efficiency in terms of air pollution, making it a preferred method for transporting heavy loads across long distances, especially when compared to air travel. However, despite its inherent advantages, the sheer scale of global maritime transportation, responsible for a substantial portion of annual cargo tonnage, results in significant pollution emissions. One of the primary challenges stems from the rapid growth in the number of sea shipments, which often outpaces efficiency improvements, such as those achieved through slower travel speeds or the integration of sails.

Over the past years, the growth in ton-miles of maritime transportation has been significant, averaging about 4 % per year since the end of the last century. Currently, the maritime industry is booming, with more than one handred thousand ships in operation, and paradoxically, the favorable tax incentives associated with maritime transportation are unwittingly contributing to increased emissions.

A review of key literature addressing the complex issue of nitrogen oxide (NO_x) emissions in the maritime sector while striving for environmental sustainability reveals several noteworthy findings. A study in [2] provides insights into the implementation of the Energy Efficiency Design Index (EEDI) as a mechanism to enhance energy efficiency in shipping. A technical paper in [3] comprehensively explores gas fuel supply processes and their impact on emission reduction in low-speed gas-diesel engines. The Third IMO GHG report [4] offers a comprehensive overview of the maritime sector's role in greenhouse gas emissions. It serves as a valuable resource for policymakers, industry stakeholders, and researchers, guiding discussions and initiatives aimed at steering the maritime industry towards a more sustainable future. A scholarly article in [5] examines the feasibility and advantages of adopting natural gas as a marine fuel, shedding light on its potential contributions to emission reduction. The research [6] focuses on the life cycle impacts and environmental comparison of marine fuels, particularly in the context of the IMO 2020 Sulphur Cap. An official publication in [7] consolidates articles, protocols, annexes, and unified interpretations of the international convention for the prevention of pollution from ships, providing a comprehensive framework for addressing pollution issues in the maritime industry. The conference presentations in [8; 9] detail the innovative aspects of the Wärtsilä low-speed, low-pressure dual-fuel engine, shedding light on its potential impact on emission reduction. It also highlights Wärtsilä's 2-stroke dual-fuel technology and its role in advancing maritime emission reduction strategies.

While [10] investigates the environmental impact of biodiesel on automotive emissions, its findings may extend to eco-friendly maritime propulsion systems, in [11], effective strategies such as SCR and EGR to reduce NOx emissions in marine diesel engines are highlighted, reinforcing the relevance of these technologies for marine applications. The sources [12; 13] contribute to advanced detection methods for environmental monitoring applicable to emission control in marine diesel engines and explore lightweight polyolefins for the aerospace industry, offering ideas for improving marine vessel efficiency and reducing emissions through material innovation. The works [14; 15] focused on an integral approach to vulnerability assessment of ship critical equipment and information security risks

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in maritime transportation, addressing a critical safety aspect. The sources [16; 17] are applied to improve maritime cargo delivery processes, which is relevant to the maintenance of maritime infrastructure, providing a holistic view of the factors affecting the safety, efficiency and sustainability of maritime transportation.

Scholarly work [18] focuses on simulation-based investigations of marine dual-fuel engines, offering valuable insights into their potential role in reducing NO_x emissions. The work [19] is devoted to the prediction of air pollution using classification models in the Gulf of Algeciras (Spain). The study examines the application of classification models to predict the level of air pollutants in this region. In [20], the possibility of using methanol as a marine fuel for clean shipping is investigated. The study presents a case study involving a tanker ship to evaluate the viability of methanol as a clean fuel. A study [21] investigates the effect of plasma torch on NO_x reduction and catalyst regeneration in a marine selective catalytic reduction (SCR) system. The study evaluates the effectiveness of plasma torch in NO_x reduction and catalyst regeneration. In [22], presented a survey on the efficiency of magnetic hydrocyclones for purifying marine engine oil and hydrophobic substances. In [23], an economic-comparative study on achieving carbon neutrality in ship docking and harbor operations is presented. The study evaluates ways to decarbonize maritime sector operations in these operational phases. The source [24] compares carbon capture systems for on-board applications and investigates their impact on voyage efficiency. The study evaluates different carbon capture methods and their emission reduction potential. The paper [25] examines the role of cold iron in reducing emissions in marine transportation. The study focuses on the effect of shore power (cold ironing) on emission reduction during ship mooring. In [26] assessed the health impacts of air pollution caused by shipping and ports on a global scale. The study provides a literature review on the assessment of the health effects of air pollution from shipping activities. Works [27; 28] examine the international law of the sea related to the management of environmental issues, with a special focus on the Indian Ocean. The study reviews the legal framework for addressing environmental problems in maritime activities and discusses the potential of TROPOMI to understand NO_2 changes over the Iberian Peninsula, probably based on the previously mentioned study. In [29], emissions and environmental costs associated with ferry operations in Lake Van are estimated. The study evaluates the environmental impacts and costs associated with the operation of ferries in the mentioned region. The paper [30] analyzes the role of maritime transport in the economic growth of the European Union using a panel data analysis approach. In [31], data on NO_x emissions from maritime transportation over the seas of China using satellite observations are obtained, which contributes to the understanding of the sources of air pollution in the region. A study [32] presents an inventory of anthropogenic emissions and spatial analysis of greenhouse gases and pollutants for the Galapagos Islands, which sheds light on the environmental challenges of this unique ecosystem.

The work [33] focuses on determining energy-efficient operation modes of the propulsion electrical motor in autonomous swimming apparatus, addressing energy efficiency in maritime technology. The papers [34; 35] present a simple methodology for ship model parameterization and ship acquisition and operation projects, offering a practical approach to process modeling for various applications. The article [36] explores the environmental efficiency of ship operation concerning freight transportation effectiveness, highlighting the importance of eco-friendly practices in maritime logistics. The works [37–43] consider fundamental aspects of shipping safety, provide insight into safety measures and practices in the maritime industry and discuss measures to improve environmental safety and operational pollution reduction, emphasize the industry's commitment to environmental sustainability. A comprehensive integrated study and evaluation of ship energy efficiency and environmental safety management measures, ship energy efficiency and environmental safety management measures, ship energy efficiency and environmental safety management measures, the most important aspects of maritime sustainability are considered.

The literature review on the research topic also covered various issues related to maritime safety, environmental liability, legal aspects and technological advances. It included studies on predicting centrifugal compressor instability in internal combustion engines [44], shipowners' liability for marine pollution [45], legal implications of ocean change [46], highlighting legal implications for marine conservation [47], and the impact of biofuels on marine diesel engines [48; 49]. A comparative analysis of Tier III

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compliant gas engines [50], involvement of seafarers in energy efficient ship operation [51], assessment of the impact of marine emissions and application of combinatorial configurations in innovative devices [52; 53].

The article [54] presents a Markov-Model approach to assess navigational safety, highlighting its importance for maritime operations, while [55] explores methods for identifying mistuning in turbocharger impellers, critical for optimizing engine performance and reducing emissions. The authors in [56] introduced an acoustic method for detecting mistuning, enhancing engine diagnostics and lowering emissions. The study [57] proposes an algorithm for vibration monitoring of turbomachines, essential for maintaining engine reliability and reducing emissions. In [58] discussed renewable energy applications in shipping, highlighting their potential to reduce emissions and supporting our focus on environmental sustainability. The papers [59; 60] propose a preliminary assessment of NOx pollution using satellite data, propose innovative methods for monitoring emissions, and provide detailed inventories of shipping emissions in China, which emphasizes the need for targeted strategies to reduce NO_x emissions. explore different aspects of project management and application of genetic approaches in computer sciences and information technologies. The articles [61; 62] focus on the application of genetic approaches and the creation of a project genetic model and discuss the development of a method for managing product configuration within an eco-logistics system project.

Taken together, these sources provide valuable insights into the multifaceted aspects of the maritime industry and their contribution to maritime environmental safety. This literature covers a wide range of research topics in the field of maritime transport and environmental sustainability, touching on important areas such as ship safety, energy efficiency, emission reduction and organizational dynamics, reflecting the multifaceted nature of sustainability issues in the maritime industry.

One of the most important topics in this body of work is the urgent need to reduce nitrogen oxide (NO_x) emissions from ship engines. This is not only an environmental issue, but also a serious human health concern. Various techniques and approaches, including fuel switching, exhaust after treatment systems and the introduction of alternative fuels, are presented in the studies, demonstrating the industry's commitment to tackling this complex problem. While progress has been made in understanding and reducing NOx emissions, it is clear that more research is needed to develop innovative strategies, advanced technologies, and integrated policies to better address this issue. Achieving a sustainable future for maritime transport requires continued collaboration between researchers, stakeholders and policy makers to make meaningful changes and minimize the environmental footprint of this vital global industry.

The objective of this study is to develop and evaluate effective strategies to reduce nitrogen oxide (NO_x) emissions from marine diesel engines of merchant ships. The study aims to analyze existing technologies and methods such as switching to alternative fuels, engine modifications, use of exhaust gas cleaning systems and other innovative approaches. The main objective is to identify best practices and integrated solutions that can be applied in real-world shipping environments to achieve significant NO_x emission reductions, improve environmental sustainability and meet international environmental standards.

Materials and methods

The original strategy developed by the International Maritime Organization (IMO) in 2018 aimed to reduce carbon dioxide emissions by at least 40 % from 2008 levels by 2030. It also aimed to achieve an overall reduction in greenhouse gas emissions from the shipping sector of at least 50 % by 2050. However, this strategy fell short of the targets set out in the 2015 Paris Agreement, which aims to limit global warming to well below 2 °C and continue efforts to limit temperature rise to 1.5 °C.

Recognizing the need for a more ambitious approach, the IMO has set a deadline to reach consensus on a series of medium-term measures to support greenhouse gas emission reductions by 2025. These measures are expected to include the introduction of a target standard for marine fuels that would govern the phasing in of emission intensity reductions. They may also include the introduction of an emissions pricing mechanism for the shipping industry. The impact of each proposed measure will be carefully evaluated from this summer to next fall. These selected measures are expected to be formally adopted at the UN Environment Committee meeting in the fall of 2025.

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Although the revised strategy is not legally binding, measures implemented under it may carry legal obligations. For example, following the adoption of the original strategy to reduce greenhouse gas emissions, the IMO approved short-term measures to regulate emissions. Among these measures, two entered into force in 2023: the Energy Efficiency Index for Existing Ships (EEXI) and the Carbon Emission Intensity Indicator (CII). These measures are legally enforceable as they are included in an international treaty, the International Convention for the Prevention of Pollution from Ships (MARPOL).

Reducing nitrogen oxide (NOx) emissions from marine internal combustion engines is a critical concern for the maritime industry due to the environmental and health impacts of NOx pollution. Several strategies and technologies have been developed and implemented to address this issue. Here are some key strategies (Table 1);

Table 1

Strategies and technologies to reduce nitrogen oxide (NO_x) emissions from marine engines

Strategy	Designation	Advantages
Selective Catalytic Reduction (SCR)	SCR systems inject a urea-based solution (often called AdBlue or DEF) into the exhaust stream, where it reacts with NOx in the presence of a catalyst to form harmless nitrogen and water	SCR technology is widely used in large marine engines to significantly reduce NOx emissions
Exhaust Gas Recirculation (EGR)	EGR systems recirculate a portion of the engine's exhaust gases back into the combustion chamber, reducing the oxygen concentration	Consequently lowering the combustion temperature, which leads to reduced NO_x formation
Low-NOx Engine Design	Modern marine engine designs incorporate various features like optimized combustion chambers, advanced fuel injection systems	Improved air management to minimize NO_x emissions during combustion
Fuel Switching	Using cleaner-burning fuels, such as LNG (liquefied natural gas) or low-sulfur diesel, can reduce NOx emissions	LNG produces significantly lower NO_x emissions compared to traditional marine fuels
Hybrid and Electric Propulsion	Electric and hybrid propulsion systems, including battery-electric and fuel cell technologies, can help reduce NO_x emissions	Eliminating the need for internal combustion engines during certain operational phases
Exhaust Gas Cleaning Systems (Scrubbers)	Exhaust gas cleaning systems, or scrubbers, remove pollutants, including NOx, from the exhaust gases before they are released into the atmosphere	These systems are often used to comply with emissions regulations
Optimized Operation and Maintenance	Regular maintenance and optimal engine operation can ensure that engines run efficiently, reducing NO_x emissions	This includes proper tuning, timely maintenance, and efficient load management
Regulatory Compliance	Compliance with international and regional emissions regulations, such as the International Maritime Organization's (IMO) MARPOL Annex VI, is crucial	These regulations set limits on NO_x emissions and require the use of technology like SCR or EGR to meet these limits
Research and Development	Ongoing research and development efforts focus on developing advanced technologies and alternative fuels	Further reduce NO_x emissions from marine engines
Education and Training	Proper training and education of ship operators and crew members on the importance of NO_x reduction and the use of emission control technologies	Ensuring effective implementation

NO_x emission reduction strategies should be tailored to the specific operational needs and regulatory requirements of each ship. Ship owners and operators should consider the most appropriate combination of technologies and operating practices to achieve NO_x emission reductions while maintaining operational efficiency. In addition, regulatory requirements and technological advances in the maritime industry continue to evolve, so it is critical to stay abreast of the latest developments for an effective NOx reduction strategy.

One of the key areas of emission reduction in maritime transportation is to improve the energy efficiency of ships. This can be achieved through a number of measures such as optimizing ship design, increasing engine power and reducing cargo weight. The IMO has set a number of Energy Efficiency Design Index (EEDI) requirements for new ships, which aim to encourage the use of energy efficient technologies and reduce emissions.

Reducing emissions from maritime transportation is a multifaceted challenge, and several strategies are being explored to address it (Fig. 1).

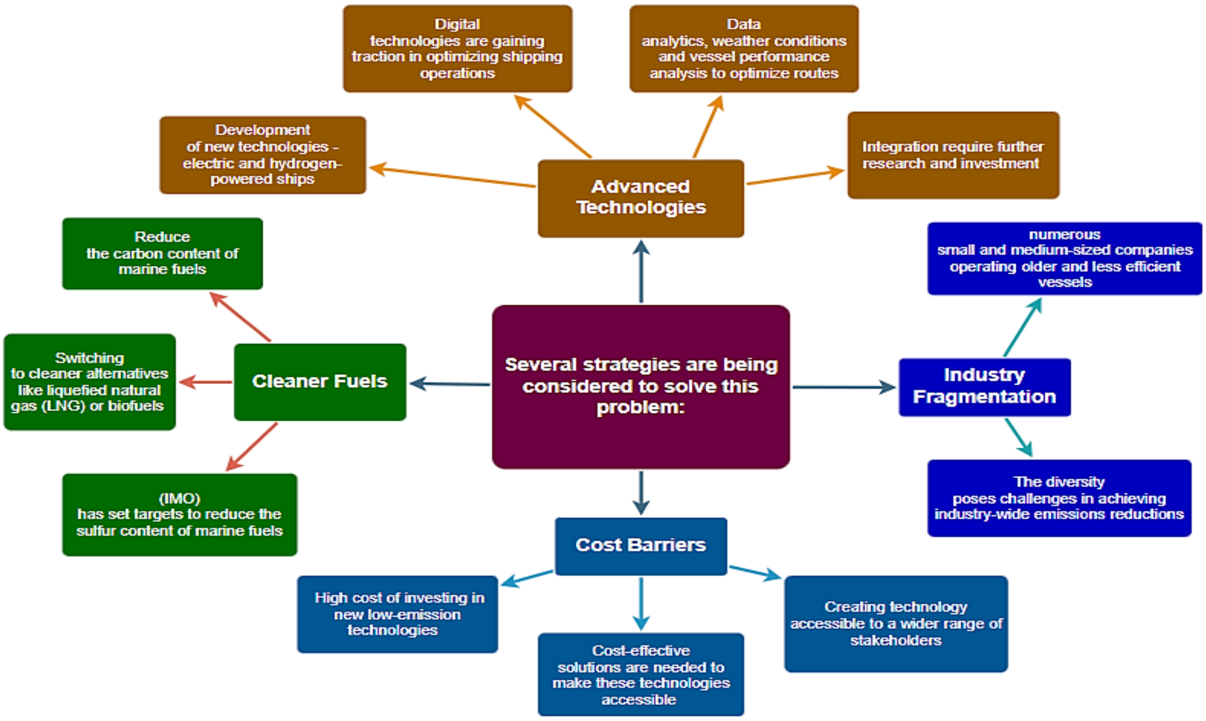

Fig. 1. Analysis of emission reduction strategies in maritime transportation (Authors)

One approach is to reduce the carbon content of marine fuels. Switching to cleaner alternatives such as liquefied natural gas (LNG) or biofuels can significantly reduce emissions. In addition, the International Maritime Organization (IMO) has set targets to reduce the Sulphur content of marine fuels, which helps improve the environment. The development of new technologies, such as electric and hydrogen-powered ships, holds promise for reducing emissions. However, these technologies are still in their early stages and have not been widely adopted by the industry. Their successful integration will require further research and investment. Digital technologies are increasingly being used to optimize shipping operations. For example, data analytics can analyze weather conditions and vessel characteristics to optimize routes, ultimately leading to reduced fuel consumption and emissions. Despite these efforts, reducing emissions from maritime transportation remains a significant challenge. The industry is highly fragmented, with many small and medium-sized companies operating older and less efficient vessels. This diversity creates challenges to achieving industry-wide emission reductions. Investing in new low-emission technologies can be costly, especially for smaller companies with limited resources. Cost-effective solutions are needed to make these technologies available to a wider range of stakeholders. Addressing emissions from maritime transportation will require a comprehensive approach that includes: Implementation and enforcement of regulations that incentivize emissions reductions and compliance with environmental standards. Continued research and development to improve existing technologies and create new efficient and cost-effective solutions. Joint efforts of states, organizations and stakeholders to develop common standards and goals for emission reductions. While progress has been made, there is still a long way to go to achieve IMO's goals and ensure a sustainable future for the maritime industry. Effective strategies and a collective commitment to reduce emissions will be essential to achieving these goals.

Diesel engines are known for their high power, thermal efficiency and low speed. However, they are notorious for their significant emissions of nitrogen oxides (NO_x) – harmful pollutants that contribute to smog, acid rain and poor health. In marine low-speed engines, NO_x emissions come from a variety of sources and depend on a multitude of factors. The primary source of NO_x is the combustion process in engine cylinders, where fuel and air are mixed and ignited by spark or compression, creating high temperature and pressure, causing nitrogen and air oxygen to react and form various nitrogen oxides, including

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nitrogen oxide (NO) and nitrogen dioxide (NO_2). The amount and composition of NOx emissions depend on various combustion-related factors such as fuel-to-air ratio, ignition timing, combustion chamber design, air movement, and turbulence levels. For example, rich fuel may decrease NO_x emissions but increase hydrocarbon and carbon monoxide emissions, and poor fuel may decrease hydrocarbon and carbon monoxide emissions but increase NO_x emissions. Engine operation, which includes load and speed changes, cleaning process, turbocharging, supercharging, and exhaust gas recirculation (EGR), also affects NO_x emissions. High engine load and speed can increase combustion temperature and pressure, thereby increasing NO_x emissions, while EGR reduces NO_x emissions by recirculating a portion of the exhaust gas into the engine cylinders, diluting the oxygen concentration and reducing combustion temperature and pressure. Fuel characteristics, including sulfur and nitrogen content, viscosity, density, and heating value, also affect NO_x emissions. High sulfur fuels can produce sulfur compounds that interact with ammonia in the exhaust, reducing its availability for the selective catalytic reduction (SCR) process (Table 2);

Table 2

Impact of Nitrogen Oxide Emissions on Health and Environment

Health Effects of Nitrogen Oxide Emissions	Impact on Air Quality	Impact on Water Quality
Nitrogen oxide (NO_x) emissions, primarily from combustion processes in transportation and industry, have been extensively studied for their health effects. Exposure to NO_x can lead to respiratory issues, cardiovascular problems, neurological disorders, reproductive and developmental impacts, and an elevated cancer risk. Vulnerable populations like children, the elderly, and individuals with existing health conditions are particularly susceptible to these adverse effects.	NO_x emissions can contribute to the formation of ground-level ozone, a primary component of smog. Ozone exposure can lead to respiratory illnesses, especially in children and individuals with asthma or other lung disorders. NO_x emissions also play a role in the creation of fine particulate matter, which can deeply penetrate the lungs, resulting in various health issues, including heart attacks, strokes, and lung cancer. Furthermore, emissions of nitrogen oxides can contribute to the occurrence of acid rain, which can inflict damage on crops, forests, and bodies of water.	NO_x emissions can lead to the generation of nitric acid, which may be deposited in water bodies and soil, leading to acidification. Acidification can have detrimental effects on aquatic life and ecosystems, affecting fish, plants, and microorganisms. Additionally, NO_x emissions can contribute to eutrophication, characterized by excessive growth of algae and aquatic plants, leading to oxygen depletion in the water and harm to fish and other aquatic organisms.

Results and discussion

Fuel switching is a strategy to reduce NO_x emissions in marine engines by switching from high sulfur fuels such as heavy fuel oil (HFO) to low sulfur alternatives such as marine gas oil (MGO) or ultra-low sulfur diesel (ULSD). This choice is due to the direct correlation between the sulfur content of the fuel and the generation of NO_x emissions.

The combustion of high sulfur fuel reacts with atmospheric oxygen to produce sulfur dioxide (SO_2). SO_2 emissions contribute to particulate matter and acid rain, and reduce the effectiveness of NOx reduction technologies such as selective catalytic reduction (SCR), which can lead to further NO_x emissions. Switching to low sulfur fuels significantly reduces SO_2 emissions, resulting in reduced NO_x emissions.

However, it must be recognized that while fuel switching is an effective strategy to reduce NO_x emissions, it does not address other environmental issues associated with marine fuels, such as greenhouse gas emissions and oil spill risk. Therefore, an integrated approach is needed to reduce the overall environmental impact of marine transportation, which may involve a combination of strategies including fuel substitution, engine modification, and alternative fuel sources.

Disadvantages associated with fuel substitution include:

- increased fuel costs associated with the use of low-sulfur fuels;
- potential logistical problems associated with fuel storage and transportation;
- limited availability of low-sulfur fuel in some regions, potentially limiting the feasibility of fuel substitution for some vessels.

The below expression calculates the percentage reduction in NOx emissions (also achieved by switching to an alternative fuel), considering the exhaust gas consumption and the efficiency of the treatment system:

$$FS = (1 - \frac{E_{sw}}{E_{in}} \times (\frac{Q \times \eta}{ECSE_{ff}})) \times 100\% \quad (1)$$

Where: FS – percentage reduction in NO_x emissions achieved by switching to an alternative fuel (dimensionless), E_{in} – initial NOx emissions from the original high-sulfur fuel, E_{sw} – NO_x emissions after switching to a low-sulfur or alternative fuel (grams per kilowatt-hour), η – (NO_x Reduction Efficiency) – the efficiency of the emission control system in reducing NOx emissions (dimensionless), Q (Exhaust Gas Flow Rate) – the rate at which exhaust gases are produced by the engine (liters per second or cubic meters per second), $ECSE_{ff}$ (Emission Control System Effectiveness) – efficiency of the emission control system, including SCR or other technologies, functions in reducing NO_x emissions (dimensionless).

The above formula also ensures dimensional consistency and accurately reflects that NO_x reduction is a result of the combined effect of the emission reduction technology and the control system, independent of the fuel type used.

The percentage reduction in NO_x emissions achieved by switching to an alternative fuel is calculated. This compares the difference between the initial NO_x emissions and the emissions after switching to the alternative fuel with respect to the initial emissions and expresses this reduction as a percentage.

Selective catalytic reduction technology. Selective Catalytic Reduction (SCR) is an advanced emission control technology used in a variety of industries, including automotive and marine, to reduce nitrogen oxide (NO_x) emissions from internal combustion engines and other sources. SCR is particularly effective in reducing NO_x emissions from diesel engines, which are known for their high NO_x levels.

With this system, urea or ammonia is injected into the exhaust gases before passing through a special catalyst bed at temperatures between 300 and 400 degrees Celsius. The chemical reaction between urea/ammonia and NO_x in the exhaust gases converts the NO_x (NO and NO_2) into N_2. The SCR unit is installed between the exhaust manifold and the turbocharger (Fig. 2).

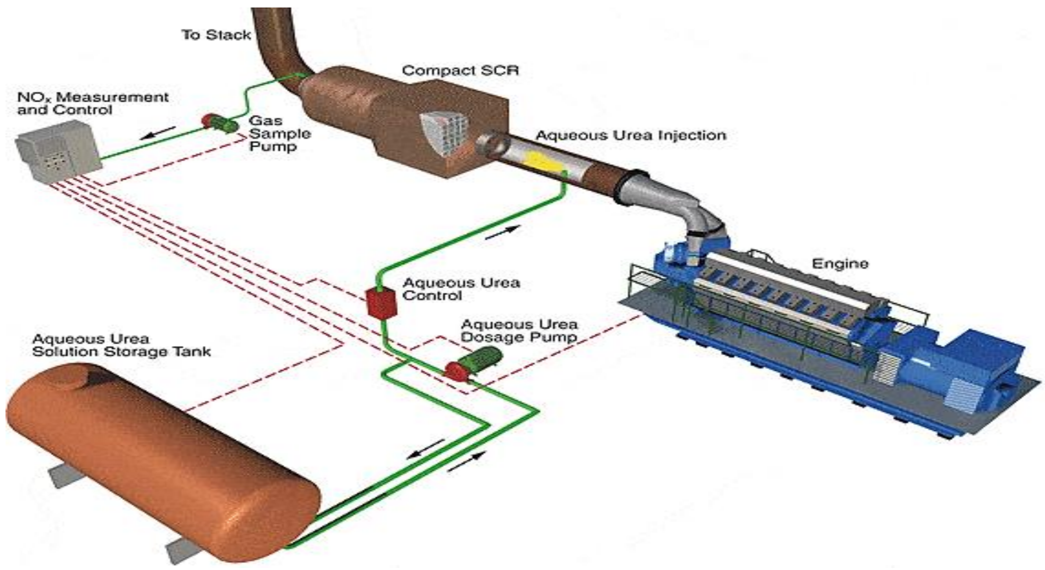

Fig. 2. The application scheme of the selective catalytic reduction system (Source: mcseatec.com)

In order to sustain optimum system efficiency, a high-performance turbocharger is required due to the pressure drop across the SCR unit. It is essential that the engine is operated at 40% load and above. This load range lies within the temperature range of 300 to 400 degrees Celsius, at which the conversion of NO_x to N_2 occurs most efficiently.

However, if the temperature exceeds 400 degrees Celsius, the ammonia will tend to burn rather than react with NO, resulting in reduced system efficiency. On the other hand, if the temperature drops below 270 degrees Celsius, the reaction rate is greatly reduced and the formation of ammonium sulfates can damage the catalyst.

Some engine types, including some B&W and Wartsila engines, have $DeNO_x$ or SiNOx systems that utilize SCR technology. In addition, Wartsila engines are equipped with NOR (NOx Reduction) systems utilizing SCR technology. The application of SCR technology allows achieving a reduction of NO_x emissions in exhaust gases by more than 90%.

It is important to note that this representation of the chemical process is simplistic and does not

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cover all the variables and complexities associated with SCR technology. The actual reaction may include intermediate steps and consider factors such as temperature, catalyst efficiency, and other parameters inherent in a selective catalytic reduction (SCR) system designed to reduce NOx emissions using ammonia as the reducing agent.

$$4NO + 4NH_3 + O_2 \rightarrow 4N_2 + 6H_2O \quad (2)$$

or

$$2C_6H_{12}O_6 + 6O_2 \rightarrow 12CO_2 + 12H_2O, \quad (3)$$

where: 4NO – four molecules of nitrogen monoxide (NO) from the exhaust gas, $4NH_3$ – four molecules of ammonia (NH_3) injected into the exhaust gas, O_2 – one molecule of oxygen from the exhaust gas, $4N_2$ – four molecules of nitrogen gas (N_2) produced as a result of the reaction, $6H_2O$ – six molecules of water vapor produced as a result of the reaction and combustion of glucose ($C_6H_{12}O_6$) with oxygen (O_2) to produce carbon dioxide (CO_2) and water (H_2O). It's a representation of the process of cellular respiration in living organisms.

The above expressions represent a balanced chemical reaction occurring in the SCR system, in which oxides of nitrogen (NO_x) from the exhaust gas react with injected ammonia and oxygen to form nitrogen gas and water vapor. This reaction significantly reduces the concentration of nitrogen oxides in the exhaust gases, resulting in lower emissions.

The SCR is a highly effective means of reducing NOx emissions, often achieving NO_x reduction rates of 70% to 90 % or more. It is widely used in a variety of industries where NOx emissions need to be controlled, including:

— Automotive: SCR technology is widely used in modern diesel vehicles to meet stringent emission standards.

— Marine industry: Large marine diesel engines on ships and vessels often use SCR systems to meet emission standards set by, for example, the International Maritime Organization (IMO).

— Electric Power: Some power plants, especially those powered by natural gas, utilize SCR systems to reduce NO_x emissions and meet air quality standards.

The SCR is considered a reliable NOx reduction technology and plays an important role in reducing the environmental impact of combustion processes while ensuring compliance with emission regulations.

Exhaust gas recirculation technology. Exhaust Gas Recirculation (EGR) is an emission control method used in internal combustion engines to reduce harmful nitrogen oxide (NO_x) emissions. It works by reintroducing a portion of the exhaust gas into the engine's combustion chamber where it mixes with incoming air, lowering the combustion temperature and consequently reducing NO_x formation. EGR provides benefits such as lower emissions, improved fuel efficiency and lower combustion temperatures, making it an important tool for meeting emissions standards and improving the environmental performance of internal combustion engines.

Exhaust Gas Recirculation (EGR) technology plays a vital role in reducing NOx emissions in internal combustion engines. It involves diverting a portion of the exhaust gases into the intake manifold after turbocharging and cleaning them through an exhaust gas flushing device. This process significantly reduces NO_x emissions by about 50%–60% compared to Tier I standards. The primary mechanism for NO_x reduction in EGR is to change the combustion conditions by reducing excess air, reducing oxygen and introducing carbon dioxide (CO_2) and water vapor. CO_2 and water vapor have a higher heat capacity than air, which lowers the peak combustion temperature, preventing the formation of nitrogen oxides (NO_x). The effectiveness of EGR lies in the controlled change in the chemical composition of fuel combustion, which makes it a promising solution to environmental problems in various industries, including marine transportation.

The exhaust gas recirculation (EGR) process involves manipulation of the combustion environment to reduce NO_x emissions a simplified representation of the concept may be as follows:

$$NOx_R = NOx_I \times (1 - \eta_{EGR}) - \eta D \times NOx_I, \quad (4)$$

where: NOx_R – reduced NO_x emissions achieved through EGR, NO_{xI} – initial NO_x emissions without EGR, η_{EGR} – efficiency of the EGR system in reducing NOx emissions (ranging from 0 to 1), ηD – efficiency of dilution in reducing NOx emissions (ranging from 0 to 1).

This conceptualization accounts for the reduction in NO_x emissions achieved through both EGR and dilution processes. The term NO_{xI} × (1−η_{EGR}) calculates the NOx reduction due to EGR, while the term $\eta D \times NO_{xI}$ accounts for additional reductions achieved through dilution processes. It demonstrates a more comprehensive approach to modeling NO_x emissions reduction in internal combustion engines.

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Humidification of the air charge technology. Air charge humidification technology is an approach used in internal combustion engines to improve combustion efficiency and reduce emissions. It involves introducing moisture or water vapor into the incoming air before it enters the combustion chamber. Moisture helps to lower the combustion temperature, which in turn reduces the formation of harmful oxides of nitrogen (NO_x). By optimizing the composition of the air-fuel mixture and the combustion process, this technology improves engine efficiency and reduces environmental impact.

The process of humidifying the air charge in internal combustion engines is to introduce seawater into the hot air stream heated by the compressor of the turbocharger. These cools and moisturizes the air, and a distillation process is used to use seawater instead of fresh water. By carefully regulating the humidification process and keeping the exhaust air temperature between 60–70 degrees Celsius, the presence of water vapor in the saturated air effectively reduces the peak combustion temperature. The higher thermal conductivity of water compared to air plays a decisive role in this cooling and combustion efficiency improvement process (Fig. 3).

Notably, this approach results in a noticeable reduction of nitrogen oxide (NO_x) emissions by about 60%. By utilizing the principles of air charge humidification, the marine industry can effectively address NOx emissions and make a significant contribution to environmental sustainability.

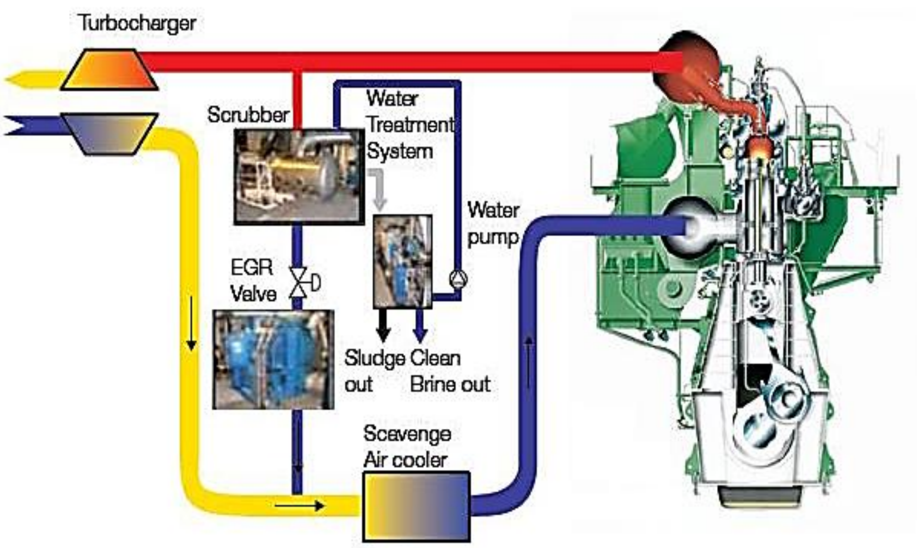

Fig. 3. Application scheme of the air charge humidification system (Source: Meiji Shipping Group)

The simplified concept of air charge humidification presented here serves as an introductory overview, recognizing that the actual effectiveness of the humidification process depends on various factors such as the degree of air cooling and saturation, engine operating conditions, and other variables not covered in this brief overview.

$$NOx_{xR} = NOx_{xI} \times (1 - \eta_H) - \Delta_{EGR} + \Delta D, \quad (5)$$

where: NOx_R – reduced NO_x emissions achieved through air charge humidification, NO_{xI} – initial NOx emissions without air charge humidification, η_H – efficiency of the air charge humidification process in reducing NO_x emissions, ΔEGR represents the change in NO_x emissions due to Exhaust Gas Recirculation (EGR), ΔD – the change in NO_x emissions due to air charge dilution or humidification techniques.

This expression considers the reduction in NO_x emissions achieved through the technology represented by η_H, as well as the contributions of EGR and air charge dilution or humidification. It provides a more comprehensive view of the factors influencing NO_x emissions reduction in internal combustion engines.

Other technologies to achieve nitrogen emission reductions. The Miller cycle, used in 4-stroke engines in conjunction with a high-efficiency turbocharger, involves closing the intake valves early before normal full throttle travel (NFT) is reached. This strategic timing results in expansion and cooling of the intake air, resulting in lower NOx emissions. Implementing the Miller cycle often requires the use of twin turbochargers (two-stage turbocharging). When combined with additional technologies such as direct water injection (DWI) and fuel-water emulsions, it achieves Tier III-compliant NO_x emission reductions. This combination of advanced technologies reflects the marine industry's ongoing efforts to improve environmental sustainability and meet emission standards.

$$NO_{xR} = NO_{xI} - \Delta NO_{xMC} - \Delta NO_{xDWI} - \Delta NO_{xE} \quad (6)$$

where: NO_{xR} – reduced NO_x emissions achieved through combined strategies (Miller's cycle, DWI, emulsions), NO_{xI} – initial NO_x emissions without the application of these strategies, ΔNO_{xMC} – reduction in NO_x emissions due to Miller's cycle and early valve closure, ΔNOx_{DWI} – reduction in NO_x emissions due to direct water injection, ΔNOx_E – reduction in NO_x emissions due to fuel-water emulsion.

The Ecospec $CSNO_x$ system is an innovative approach to emission reduction that uses fresh or seawater treated using an ultra-low frequency electrolysis system. The treated water is then fed into the exhaust gases to reduce NO_x. Remarkably, this compact unit simultaneously addresses not only NO_x, but also carbon dioxide (CO_2) and sulfur oxides (SO_x) emissions. Combined with the other NOx reduction technologies discussed above, it can help marine transportation meet Tier III emission standards. A notable advantage of the $CSNO_x$ system is its ability to provide high efficiency with low maintenance and energy consumption. The efficiency and performance of the system can be evaluated using a parameter known as reduction efficiency *(RE)*.

$$RE = (NO_{xI} - NO_{xCSNOx}) / NO_{xI} \times 100\% \quad (7)$$

where: RE – reduction Efficiency achieved by CSNOx system, NO_{xI} – initial NO_x emissions before $CSNO_x$ treatment, NO_{xCSNOx} – NO_x emissions after $CSNO_x$ treatment.

The Diesel Particulate Filters (DPF) represent another viable technology for reducing NO_x emissions in marine engines. DPFs function by capturing particulate matter (PM) present in the exhaust gases of diesel engines. These particles are subsequently combusted in a regeneration process that can occur either actively or passively. The reduction in NO_x emissions can be approximated by considering the corresponding reduction in PM emissions achieved by the DPF system. This synergistic effect of PM and NO_x emission reductions emphasizes the multifaceted environmental benefits of using DPF technology in marine applications.

$$NOx_R = NOxI - \Delta PM \quad (8)$$

Where: NO_{xR} – reduced NO_x emissions achieved through PM reduction, NO_{xI} – initial NO_x emissions without DPF, ΔPM – reduction in particulate matter (PM) emissions due to DPF.

Active regeneration in DPFs involves the use of a diesel oxidation catalyst (DOC) to raise the temperature of the exhaust gas, which promotes combustion of the collected particulate matter (PM) inside the filter. This process requires reaching a certain temperature threshold and is usually initiated and controlled by the engine control unit. Passive regeneration, on the other hand, occurs naturally during engine operation, requiring no additional catalysts. It occurs when the exhaust gas temperature naturally reaches a level sufficient to burn off the particulate matter accumulated in the filter.

While DPFs are excellent at reducing particulate emissions, their effect on reducing NOx is relatively limited. However, they can be used in combination with other NO_x reduction technologies, such as SCR or EGR systems, to achieve more comprehensive emission reductions.

$$NO_{xR} = NO_{xI} - \Sigma(\Delta NOx_{TECH}) \quad (9)$$

Where: NO_{xR} – reduced NO_x emissions achieved through a combination of multiple technologies, NO_{xI} – initial NO_x emissions without the combined technologies, ΔNO_{xTECH} – reduction in NO_x emissions achieved by each individual technology within the combination.

A combination of different technologies, including elements such as electronic variable phase number engines, the use of LPG as a fuel, direct water injection or fuel-in-water emulsion, can serve as an effective strategy for meeting Tier III emission standards. Depending on the specific combination, exhaust after treatment systems may or may not be required. The cumulative emission reductions resulting from this combination of technologies can be quantified using a cumulative approach, demonstrating the industry's commitment to meeting stringent environmental standards.

The purpose of this analysis is to provide a broad overview of the variety of technologies and methods that are now available to ship owners and ship operators to reduce NO_x emissions. We will review and compare approaches such as switching to alternative fuels, the use of SCR

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systems, innovative moisture-in-charge technologies, and the use of the Miller cycle. This analysis will help identify the most effective strategies and technologies to reduce NO_x emissions and promote a greener and more sustainable marine industry.

This horizontal bar graph presents a comparative assessment of the effectiveness of different technologies in the context of reducing NOx emissions in the offshore industry. Each bar in the graph represents a specific technology that was included in the analysis, and the height of the bar corresponds to the notional percentage of NO_x reduction achieved with the application of that technology (Fig. 4).

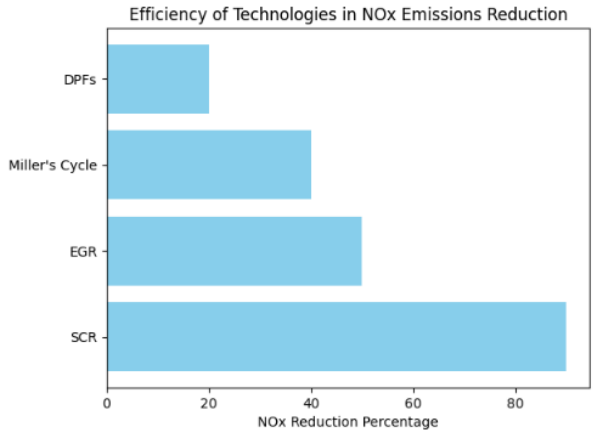

Fig. 4. Comparison charts of the efficiency of various technologies in reducing NO_x emissions (Authors)

The graph comparing the effectiveness of technologies in reducing nitrogen oxide (NO_x) emissions shows that each of the technologies considered has a different degree of effectiveness. SCR (Selective Catalytic Reduction) is the most effective, providing a 90 % reduction in NO_x due to its high ability to catalytically convert NO_x into harmless nitrogen and water. EGR (Exhaust Gas Recirculation) technology reduces NO_x by 50% by returning a portion of the exhaust gas to the intake system. The Miller cycle combined with turbocharging provides a 40% reduction in NO_x through early closure of the intake valves. On the other hand, particulate capture filters (DPFs) provide only 20% NOx reduction, but can be useful in combination with other technologies such as SCR or EGR. The choice of the most appropriate technology depends on the specific requirements and operating conditions.

This analysis emphasizes the importance of selecting the most appropriate technology depending on specific requirements and operating conditions. SCR, EGR and Miller cycle may be the most preferred to achieve significant reductions in NO_x emissions, while DPFs can be useful additional means of particle control.

Conclusions

This comprehensive review and analysis have highlighted several key strategies and technologies that are critical to addressing the identified challenges. To achieve significant NOx emission reductions, an integrated approach combining multiple strategies such as selective catalytic reduction (SCR), exhaust gas recirculation (EGR), fuel switching and alternative energy sources is required. This integrated approach not only maximizes the effectiveness of individual technologies, but also improves their practical applicability in real-world offshore operations. Successful implementation of NO_x reduction technologies requires addressing a variety of practical challenges, including economic, logistical and regulatory considerations. By understanding and mitigating these challenges, industry stakeholders will be able to implement these technologies more effectively, ensuring compliance with environmental standards and contributing to overall sustainability.

Continued research and development is needed to further develop NO_x reduction technologies where efforts should be focused on developing innovative solutions, improving the efficiency and cost-effectiveness of existing technologies, and exploring new materials and methods. Reducing NO_x emissions from marine diesel engines contributes to improved air quality, reduced formation of ground-level ozone and particulate matter, and reduced acid rain, which ultimately protects human health and preserves ecological systems. While significant progress has been made in developing and implementing strategies to reduce NO_x levels in marine diesel engines, continued efforts are needed to overcome practical challenges and stimulate further innovation through an integrated and multidisciplinary approach.

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