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ENHANCING SHIPBOARD TECHNICAL FACILITY PERFORMANCE THROUGH THE UTILIZATION OF LOW-SULFUR MARINE FUEL GRADES

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Abstract

This study explores strategies to enhance the efficiency of marine technical equipment through the adoption of low-sulfur marine fuels. The investigation incorporates a comprehensive analysis, encompassing enthalpy change calculations and thermal efficiency estimates at various temperature differentials. These calculations shed light on the impact of the specific heat capacity of low sulfur marine fuels, a crucial factor in understanding combustion characteristics. Furthermore, provides an assessment of the efficiency of converting heat to mechanical energy, offering valuable insights for optimizing equipment performance. The outcomes of this research contribute to a broader strategy aimed at bolstering the environmental sustainability and efficiency of marine propulsion systems. By scrutinizing the utilization of low sulfur marine fuels, the study seeks to inform decision-making processes by pinpointing temperature ranges that maximize efficiency. The findings also highlight areas with potential for improvement in the performance of marine diesel engines. This holistic approach is integral to fostering advancements in both environmental responsibility and operational effectiveness within the maritime industry.

Keywords: Maritime Transport; Shipping; Marine diesel engines; Marine fuels; Exhaust gases; Combustion processes; Nitrogen oxides; Sulfur compounds; Emission characteristics; Shipboard Energy Systems.

ПІДВИЩЕННЯ ЕКСПЛУАТАЦІЙНИХ ХАРАКТЕРИСТИК СУДНОВИХ ТЕХНІЧНИХ ЗАСОБІВ ШЛЯХОМ ВИКОРИСТАННЯ НИЗЬКОСІРЧИСТИХ СОРТІВ ПАЛИВА

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Анотація

У цьому дослідженні розглядаються стратегії підвищення ефективності морського технічного обладнання за рахунок використання суднового палива з низьким вмістом сірки. Дослідження включає комплексний аналіз, що охоплює розрахунки зміни ентальпії та оцінки теплової ефективності за різних температурних перепадів. Дані розрахунки проливають світло на вплив питомої теплоємності суднового палива з низьким вмістом сірки, що є вирішальним фактором для аналізу характеристик згоряння. Дослідження також дає оцінку ефективності перетворення тепла в механічну енергію, пропонуючи практичні рішення щодо оптимізації експлуатаційних характеристик обладнання. Результати цього дослідження є частиною загальної стратегії, спрямованої на підвищення екологічної сталості та ефективності використання суднових енергетичних установок. Вивчаючи використання суднового палива з низьким вмістом сірки, дослідження має на меті надати інформацію щодо процесів прийняття рішень, визначивши температурні діапазони, які забезпечують максимальну експлуатаційну ефективність суднових технічних засобів і систем. Результати дослідження також висвітлюють сфери з потенціалом для покращення експлуатаційних характеристик суднових дизельних двигунів. Такий цілісний підхід є невід'ємною частиною розвитку як екологічної відповідальності, так і експлуатаційної ефективності транспортних засобів у морській галузі.

Ключові слова: морський транспорт; судноплавство; суднові дизельні двигуни; суднові палива; викиди відпрацьованих газів; процеси згоряння; оксиди азоту; сполуки сірки; характеристики викидів; суднові енергетичні системи.

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Introduction

The stagnation in maritime cargo transport necessitates stakeholders, including charterers, shipowners, and shipping company managers, to prioritize vessels with the most efficient power plants. This includes developing rational technological processes and other measures to minimize operational costs, with fuel costs being a significant component. Efficient operation of Shipboard Energy Systems (SES) is contingent on the judicious use of fuels and lubricants, ensuring the reliable and economical performance of all SES components while meeting environmental protection requirements. To address operational costs, stakeholders must consider specific fuel usage requirements when vessels operate in Emission Control Areas (ECAs) and adhere to relevant national and regional regulations. Notably, sulfur content in all fuels used by vessels in ports of European Union (EU) countries and Turkish ports should not exceed 0.1 % by mass. Pursuant to the requirements of Annex VI of the International MARPOL Convention, as of December 1, 2015, only fuels with sulfur content less than 0.1 % (distillate grades) must be used in ECA regions. As an alternative to distillate fuels, the MARPOL Convention recommends equipping maritime vessels with Exhaust Gas Cleaning Systems (scrubbers).

The maritime industry has been navigating complex challenges related to environmental regulations, fuel choices, and the adoption of emission reduction technologies. In exploring the factors influencing shipowners' decisions, it is evident that economic considerations play a pivotal role. Ship & Bunker News highlighted the minimal incentive for shipowners to invest in scrubbers before 2020 [1]. The financial landscape and regulatory uncertainty likely influenced their hesitancy. Regulatory frameworks, particularly the MARPOL 73/78 convention, set standards for pollution prevention from ships, emphasizing its role in shaping environmental practices in the maritime sector [2]. The pursuit of alternative fuels has become a focal point in environmental discussions. Article [3] explores the intricacies of alternative fuels, offering insights into their chemistry and potential as environmentally friendly options. MAN Diesel & Turbo provides practical guidelines for operating on fuels with less than 0.1% sulfur, underscoring the industry's adaptation to stringent sulfur content regulations [4].

Fuel-related challenges extend beyond compliance issues. Source [5] explores methods to prevent wear on piston-cylinders when using Low Sulfur Fuel Oil (LSFO) in emission control areas. Paper [6] focuses on the distribution of low sulfur shipping fuels in the Baltic Sea region, highlighting logistical challenges in bunkering boat-ship supply. Efforts to monitor and manage fuel consumption are evident in [7], examining main engine fuel oil consumption using flow meters on tugboats. Source [8] discusses management tools for enforcing sulfur oxide reduction regulations in Latvia and Lithuania, providing insights into practical implementation. The work [9] introduces a novel method using Computational Fluid Dynamics (CFD) modeling to identify fuel sulfur content violations, showcasing technological advancements, while [10] offers valuable insights into crafting international regulations to address air pollution from ships, emphasizing the need for cohesive policies.

The comprehensive economic analyses related to the maritime Sulphur 2020 regulation and models and analyzes the effects of China's potential domestic emission control area with a 0.1% sulfur limit provided in [11; 12]. Papers [13–15] assess the supervision and multi-sectoral guarantee mechanism of the global marine sulfur limit, particularly from the perspective of the Chinese shipping industry, operational concerns arising from compliance with IMO2020 sulfur limits through Very Low Sulfur Fuel Oil (VLSFO) and questions whether low-sulfur marine fuels are a panacea or a new threat. In [16] explored biofuels as a means of reducing carbon emissions in the marine industry, assess of the costs and environmental benefits of converting to low-sulfur oil for berthing vessels in the Pearl River Estuary Bay Area conducted in [17]. Sources [18; 19] analyze available solutions for commercial vessels to comply with the IMO strategy on low sulfur, estimate the costs and external benefits of reducing shipping-induced air pollution, using Xiamen Harbour, China, as a case study. In [20] examined scrubber installation and green fuel use for inland river ships with non-identical streamflow.

The works [21; 22] examine air quality and sulfur emissions in Canadian port cities after the regulation of low-sulfur marine fuel. Source [23] discusses recent developments in air pollution from ships, while [24] provides an economic assessment of IMO sulfur regulations on Canadian crude oil markets. Sources [25; 26] evaluate NOx reduction system selection and energy efficiency for ships in restricted areas and assess black carbon emissions from in-use ships in California.

Paper [27] analyzes the effects of an open-loop exhaust-gas cleaning system on the pH of Barcelona Port water, LNG as a transitional choice for marine fuels explored in [28]. In [29] conducted a life cycle comparison of marine fuels for the IMO 2020 sulfur cap. The articles [30–35] cover various legal, operational, and environmental aspects of maritime transportation, including responsibility for pollution, legal consequences of ocean change, autonomous ships, vulnerability assessment of ship equipment, environmental efficiency of ship operation, and ship information security risks.

A safety-oriented study [36] used a Markov model approach to evaluate navigation safety. This was complemented by the work of [37] on the topic of navigation safety in the aspect of environmental mitigation. The dynamics of information panic in the case of COVID-19 was modeled in [39], in [40] proposed its view on energy efficiency in the study of propulsive electric motor operation modes of an autonomous navigation vehicle. In [41] presented the concept of a decision support system for the design of combined propulsion systems. The authors in [42] engaged in predictive modeling by predicting the instability of centrifugal compressor in internal combustion engines. Their subsequent work, published in [43], presented the performance of a digital dual test rig for marine diesel engines. The papers [44; 45] made valuable contributions to the consideration of emission reduction in Danube River shipping and explored the complex relationship between transportation infrastructure and the sustainability of the Great Lakes ecosystem. Sources [46; 47] explored innovative attitudes towards natural resource property rights in remote maritime regions and analyzed and measured emissions from auxiliary port ships. The authors in [48–50] advocate the use of environmental decision support systems in modeling air pollution after chemical accidents and propose an approach to model the temperature field in the extruder hull and present a fractional analysis approach for hybrid modeling of information diffusion processes.

In [51; 52] a multi-criteria approach to determining the optimal composition of technical means, design and optimization of maritime transport infrastructure projects is presented. In [53] a comprehensive assessment of the influence of hull geometry on the maneuvering characteristics of a modernized ship is presented. The discussion on the development and assessment of an intelligent decision support system for locomotives [54], and focus on strategies to ensure environmental friendliness in drillship operations within specific ecological regions of Northern Europe presented in [55]. The paper [56] focuses on fuel selection strategies, providing insights into optimizing fuel efficiency, performance, while [57] deals with analyzing, and organizing extensive data related to the technical condition of complex transport equipment. In [58] discussed strategies and actions aimed at decreasing greenhouse gas emissions and enhancing the environmental and energy efficiency of ships.

The literature review clearly identifies the major trends and current challenges facing the industry. Notably, there is a strong tendency for current research to address ship environmental issues and develop technologies to reduce the environmental impact of ships. Based on this review, several key areas for further research can be identified. First, it is important to develop energy efficient technologies and energy management approaches in the maritime industry. Developing integrated approaches to ecosystem management and reducing the environmental impact of maritime transportation is also important. Thus, the challenges for further research include deepening the understanding of safety and energy efficiency, and analyzing environmental aspects to ensure sustainable development of the maritime industry.

Methods and materials

Presently, existing exhaust gas cleaning technologies have significant drawbacks, including high costs, increased weight and size, disruption of vessel stability, and the lack of comprehensive infrastructure in ports for storing and disposing of absorbents and wastewater. Existing disincentives for shipowners to invest in exhaust gas cleaning systems until 2025 leave issues of waste management unresolved, further complicating the adoption of these technologies. Thus, all vessels operating within Emission Control Areas (ECAs) and other regions subject to requirements for low-sulfur fuel must carry the appropriate types of fuel and lubricating oils. This entails significant capital expenditures for the modernization of fuel and lubrication systems, as well as additional costs for unused fuel and lubricating oil reserves.

It should be noted that the operation of main propulsion and auxiliary power systems of modern ships is designed for operation on heavy residual fuel and is poorly adapted for long-term use of distillate fuel. Special attention should be paid to the problems arising from the use of low-sulfur fuel, such as insufficient lubricity characterized by low viscosity values. Insufficient lubricity leads to reduced efficiency and damage to fuel system components and combustion apparatus of the main and auxiliary power systems. This, in turn, leads to disturbances in fuel injection and combustion processes, resulting in system malfunctions. Therefore, the objective of this study is to ensure safe operation and high performance of the main and auxiliary power systems, as well as their auxiliary equipment, by implementing design and operational changes that allow the use of low sulfur fuel. In addition, alternative measures that comply with the regulatory requirements for fuel utilization on marine vessels are considered.

The fourth edition of the International Standard (IS) ISO 8217:2010(E) sets unified technical requirements for marine fuels used on ships, considering the sulfur content regulations of the International Maritime Organization (IMO) outlined in the amended Annex VI of the MARPOL Convention, edition published on June 15, 2010, specifies base temperatures for viscosity limits and uses alphanumeric codes to denote petroleum fuel types and their quality parameters.

The transition to low sulfur marine fuels, as mandated by regulations such as MARPOL Annex VI, has led to a shift in the composition of marine fuels. The discussion about Fatty Acid Methyl Ester (FAME) levels in marine fuels, as governed by ISO 8217:2010 and subsequently amended in 2017, is part of the broader context of changes in fuel specifications to meet environmental requirements.

The International Maritime Organization (IMO) anticipates a substantial reintroduction of fuel blending to the market, estimated at 75 % to 80 % of the total low sulfur supply since 2020. These blending components may also come from distressed fuel cargo, off-spec fuel, and generic materials like cutter stock of unknown or partially unknown composition.

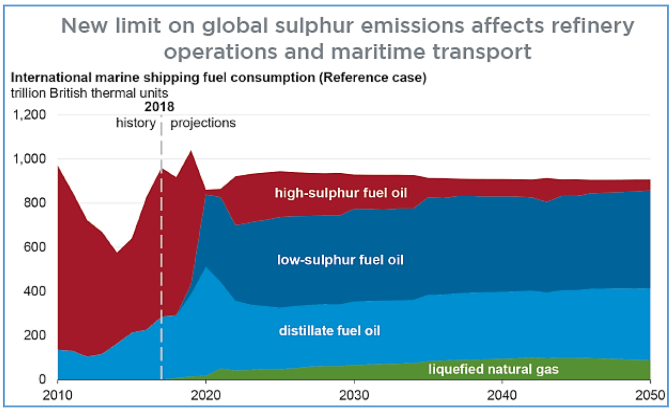

Fig. 1. Limits of global sulfur emissions [2]

In addressing Fatty Acid Methyl Ester (FAME) levels in marine fuels, ISO 8217:2010 initially required them to be free from bio-derived substances, with a de minimis FAME level of 0.10 %. By 2017, this was raised to 0.50 % to align with increased biodiesel experience. ISO 8217:2017 introduced new distillate fuel specs allowing up to 7.0 % FAME.

The broader scenario involves bunker suppliers exploring various low sulfur blend products from refinery processes. With an expected 75–80 % of the 2020 low sulfur supply involving blending, these components may come from distressed fuel cargo, off-spec fuel, and generic materials. This reflects an evolving fuel market, shaped by regulatory changes and technological advancements, emphasizing the ongoing quest for fuel quality and compliance in the maritime industry.

The base temperature for determining the viscosity limits for all residual marine fuels is –50 °C, and for distillate fuels, it is –40 °C. The numerical viscosity values measured at 50 °C determine the grade and are indicated in the designations of residual marine fuels (Table 1). In accordance with IS ISO 8217:2010(E), petroleum fuels have the following alphanumeric designations: F – distillate fuel; DM – marine distillate; RM – marine residual fuel. The subsequent letter characterizes the fuel type, and accordingly, its quality parameters. The numbers specified in the residual fuel symbol indicate the viscosity values in centistokes (cSt) at 50 °C.

The standard recommends four types of distillate fuels: DMX, DMA, DMZ, and DMB. DMX is a pure distillate fuel but due to its low flashpoint (not lower than 43 °C), should be stored and used outside the engine room. DMA is also a pure distillate fuel and should appear light and transparent. DMZ is a distillate fuel with an increased minimum viscosity of 3 cSt at 40 °C, with all other characteristics identical to DMA. This is related to the loss of density, increasing the flow of fuel pumps, their damage, and wear. DMB has characteristics similar to DMA but may contain small amounts of residual components, giving it a dark color. Distillate fuels DMA and DMZ are sometimes referred to as "Marine Gas Oil" – MGO, and fuel DMB as "Marine Diesel Oil" – MDO.

Table 1

Main properties of fuel oil defined in ISO 8217 (2010)

Grade	Sulphur Content (%)	Viscosity at 40°C (cSt)	Flash Point (°C)
MGO	max 1.00	1.40 - 5.50	min. 43
MDO	max 1.50	1.50 - 6.00	min. 60
ULSFO	max 1.50	3.00 - 6.00	min. 60
DMX	max 2.00	N/A	min. 60
DMA	max 0.10	11.00 - 40.00	min. 70

The hydrodynamic properties of fuel oil are closely related to its temperature and viscosity, as the viscosity of fuel oil has a great influence on the operation of the fuel system, which includes various devices such as pumps, filters, heaters and coolers. Maintaining the optimum temperature is crucial to ensure smooth circulation of fuel oil in the system, so taking into account the relationship between viscosity and temperature is necessary to optimize the fuel system. Adhering to recommended viscosity values, especially at critical points such as the engine intake tract, ensures reliable and efficient operation.

The plot on Fig. 2 helps to visualize how the viscosity of low-sulfur marine fuels responds to temperature changes and provides insight into how to maintain optimum operating conditions for marine engines depicts the relationship between viscosity and temperature for different initial viscosities of low sulfur distillates. The x-axis represents the temperature in degrees Celsius, while the y-axis represents the viscosity in centistokes (cSt). The plot includes three curves, each corresponding to a different initial viscosity at 40 °C (1.5 cSt, 2.0 cSt, and 3.0 cSt).

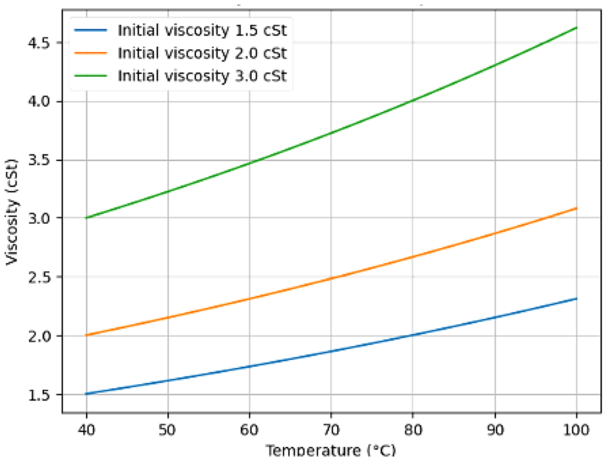

Fig. 2. Viscosity variation with temperature

As the temperature increases, the viscosity of the distillates decreases, exemplifying the expected behavior of liquids. The curves show an exponential decrease in viscosity with increasing temperature. This phenomenon is critical to understanding the effect of temperature on the operating conditions of marine fuel systems, especially in engine rooms where temperatures can reach elevated values. The legend indicates the initial viscosity at 40 °C for each curve. This information is important for evaluating how different distillate grades respond to temperature changes. The lower the initial viscosity at 40 °C, the more smoothly the viscosity decreases with increasing temperature. These principles are valuable for maintaining proper fuel pump operation and providing a stable fuel supply to the ship's equipment.

In addition, the impact of fuel characteristics on engine performance goes beyond operational efficiency. Solving the problem of atmospheric pollution, in particular emissions from industrial and transportation sources, is one of the most important modern challenges. To understand this issue, we can study the structure of ship power plant exhaust gases as shown in Table 2.

Table 2

Structure and characteristics of exhaust gas emissions from fuel combustion

Exhaust Gas Components	Percentage Content	Toxic Components in Exhaust Gas (g/(kW·h))	Specific Emission (g/(kW·h))
Nitrogen, N_2	74–78 %	-	-
Oxygen, O_2	2.0–18 %	-	-
Water Vapor, H_2O	0.5–9.0 %	15–100	-
Carbon Dioxide, CO_2	1.0–12.0 %	40–240	-
Nitrogen Oxides, NOx including:			
Nitric Oxide, NO	0.004–0.5 %	1.0–8	10–30
Nitrogen Dioxide, NO_2	0.00013–0.013 %	1.0–4.5	6–18
Carbon Monoxide, CO	0.005–0.4 %	0.25–2.5	1.5–12.0
Hydrocarbons, HC	0.009–0.3 %	0.25–2.0	1.5–8.0
Soot, C	0.01-1.1 g/m3	0.05–0.5	0.25–2.0
Sulfur Dioxide, SO_2	0.0018–0.02 %	0.1–0.5	0.4–2.5
Sulfur Trioxide, SO_3	0.00004–0.0006 %	-	-
Aldehydes, R-CHO, including:			
Formaldehyde, HCHO	0.002 %	0.0001–0.0019	1.0–10.0
Acrolein, CH_3CHO	0.0001–0.00013 %	0.001–0.04	-

The table provides information on the composition of exhaust gases (EG) from marine diesel engines. The main components include nitrogen (N_2), oxygen (O_2) and carbon dioxide (CO_2). At full load, toxic oxides of nitrogen (NOx), carbon monoxide (CO) and hydrocarbons (HC) are emitted. Sulfur dioxide (SO_2) is also present. Although the concentrations of formaldehyde and acrolein are small, their presence is also noted. It is important to note that the concentration of water vapor depends on the operating conditions. These data are important for environmental and health impact assessment.

Harmful emissions from maritime transport play a predominant role in global, regional, and local air pollution, as the operation of vessels is accompanied by the release of harmful toxic components from Exhaust Gas Cleaning Systems (EGCS) and Marine Diesel Engine Exhaust Gases (DEEG) into the atmosphere. The type of fuel and the conditions of its combustion influences the toxicity of DEEG and EGCS emissions. Approximately 80–95 % of the total mass of toxic components in the exhaust gases can be attributed to five main components: nitrogen oxide (NO_x), carbon monoxide (CO), hydrocarbons (C_XH_Y), aldehydes (RCNO), and sulfur dioxide (SO_x). All toxic components formed in DEEG and EGCS can be divided into two main groups based on the nature of their origin. The first group includes products of incomplete fuel combustion (carbon monoxide, hydrocarbons, aldehydes, soot). Toxic components of the second group are formed as a result of the complete oxidation of chemical elements present in the fuel and air—NO_x and SO_x.

Describing the main toxic components of exhaust gases from marine diesel engines and marine boiler plants, the main attention should be paid to nitrogen oxides (NOx), which account for 30–80 % by mass and 60–95 % by equivalent toxicity. N_2O is seven times more toxic than NO. Approximately 42 % of nitrogen oxide emissions are attributable to DEEG s, with 80–90 % of DEEG s being NO and 10–20 % NO_2. Other nitrogen oxide compounds (N_2O, N_2O_2, N_2O_4, N_2O_5) are present in minimal amounts. Nitrogen oxide is unstable and oxidizes to nitrogen dioxide (NO_2) in the atmosphere in 0.5–100 hours.

Carbon monoxide (CO) is present in small amounts in the atmosphere but can be significant in DEEGs, although typically not exceeding 0.4–0.5 %. CO, less stable than CO_2, exists in the atmosphere from 2 to 42 months. Hydrocarbons (C_XH_Y) include various groups such as paraffins, olefins, and aromatic hydrocarbons (including polycyclic aromatic hydrocarbons – PAHs). Light gaseous hydrocarbons such as methane, ethane, propane, ethylene, acetylene and PAHs are present, with methane comprising only 2–6 %. Other light hydrocarbons are present in smaller amounts. Oxygen-containing hydrocarbons, particularly RCHO aldehydes, result from incomplete combustion of fuel hydrocarbons. Formaldehyde (71–91 %) and acrolein (9–22 %) predominate; other aldehydes (acetaldehyde, tolualdehyde, benzaldehyde, and furfural) make up 10–15 %. The aldehyde content in DEEG and SBP (ship boiler plants) reaches 30 mg/m3. Carbon black, consisting mainly of carbon (95–98 %) and hydrogen (3–5 %) significant toxic component. The presence of soot leads to loss of transparency and black smoke clouds if its content exceeds 0.1 g/m^3. Sulfur oxides (SO_x) from gaseous emissions, especially sulfur dioxide (SO_2), are among the most hazardous components. Sulfur compounds are emitted mainly from the combustion of sulfur-rich fuels, forming SO_2. In DEEG, 97–98 % is SO_2 and 2–3 % is sulfur trioxide (SO_3). SO_2 remains in the atmosphere for several hours to several days before being oxidized to SO_3, presented in Table 3.

Table 3

Composition of exhaust gases from diesel engines and shipboard boiler plants

Component	Main Source	Content in Exhaust Gases from Marine Diesel Engines (DEEG) and Shipboard Boiler Plants (SBP)	Characteristics
NOx	DEEG and SBP	30–80 % (by mass), 60–95 % in equivalent toxicity;	Toxicity of N_2O is seven times higher than NO;
CO	DEEG	Not exceeding 0.4–0.5 %;	Less stable than CO_2, existence time 2–42 months;
Hydrocarbons	Various	Methane: 2–6 %, others in smaller quantities;	Wide range of substances, including light gases and PAHs;
Aldehydes	Incomplete combustion	Formaldehyde: 71–91 %, Acrolein: 9–22 %, others: 10–15 %	Formed in early stages of hydrocarbon oxidation;
Soot	DEEG	95–98 % C, 3–5 % H;	One of the most toxic components, visible smoke when content > 0.1 g/m^3;
SOx	Combustion of sulfur-rich fuels	SO_2: 97–98 %, SO_3: 2–3 %;	Sulfur compounds from fuel, oxidation of SO_2 to SO_3;

A study of the composition of exhaust gases from diesel engines and marine boiler plants revealed the significant presence of pollutants such as nitrogen oxides (NO_x), carbon monoxide (CO), hydrocarbons, aldehydes, particulate matter (soot) and sulphur oxides (SO_x). The negative impact of these emissions on the environment and human health has prompted a shift towards more environmentally friendly practices in the maritime industry.

One of the key strategies to reduce the environmental impact of marine operations has been the switch to low-sulfur fuels. This initiative aims to reduce emissions of sulfur dioxide (SO_2) and its derivatives, which are major sources of air pollution and acid rain. By switching to low sulfur fuel, ships not only comply with strict environmental regulations, but also contribute to the overall improvement of air quality.

Switching to low sulfur fuels has a complex effect on the overall composition of exhaust gases. Reducing sulfur minimizes SO_x emissions, which addresses respiratory and environmental health concerns. Additionally, this transition intersects with efforts to address other pollutants such as nitrogen oxides and particulate matter, thus presenting a holistic approach to exhaust cleanup.

As the marine industry embraces these changes, the synergistic effect of reducing pollutants by switching to low sulfur fuels becomes apparent. The interrelationship of exhaust components emphasizes the need to develop integrated strategies to achieve a sustainable and environmentally responsible maritime shipping industry. The transition to low-sulfur fuels involves several key steps and considerations that take into account different mechanisms, a common algorithm that can be used (Fig. 3).

Each stage of this process requires thorough research, design, and testing to ensure the safe and effective operation of the vessel when using low-sulfur fuel.

When investigating marine engine emissions and the conversion to low sulphur fuels, understanding the chemical processes underlying combustion is critical. Complex reactions involve the conversion of hydrocarbons into gases such as carbon dioxide, nitrogen oxides, and sulfur compounds. By presenting the equations governing these reactions, we gain insight into the composition of the exhaust gases, allowing a comprehensive assessment of the environmental impact and the effectiveness of switching to cleaner fuels in following sequsnce: combustion reactions - formation of nitrogen oxides (NO_x) – release of carbon dioxide (CO_2) and carbon monoxide (CO) - formation of soot - generation of sulfur dioxide (SO_2) and sulfur trioxide (SO_3);

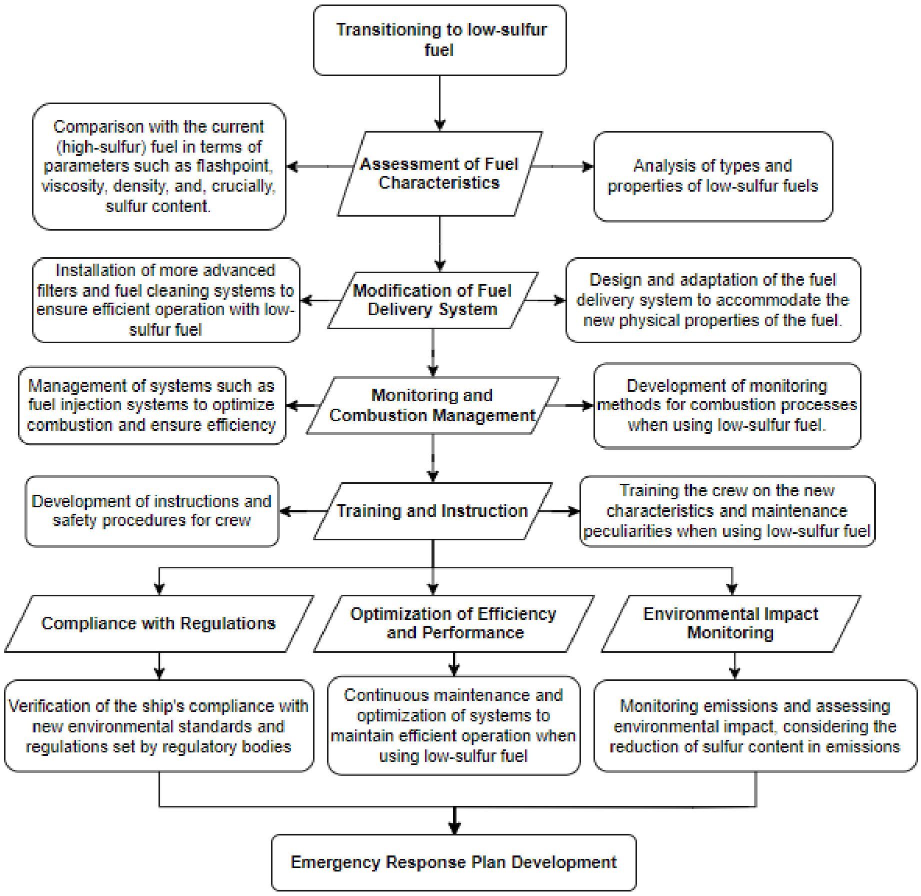

Fig. 3. Low-sulfur fuel transition algorithm

- Consider the simplified combustion reaction of methane (CH_4) in oxygen (O_2):

$$CH_4+2O_2 \rightarrow CO_2+2H_2O.$$

The combustion of methane results in the formation of carbon dioxide (CO_2) and water (H_2O). The formation of nitrogen oxides occurs due to the high temperatures of combustion, typical in internal combustion engines. The process can be represented by the following equation:

$$N_2+O_2 \rightarrow 2NO.$$

Nitric oxide (NO) can further combine with oxygen to form more toxic nitrogen dioxide (NO_2):

$$2NO+O_2 \rightarrow 2NO_2.$$

The amount of CO_2 and CO released during fuel combustion depends on the completeness of combustion, CO_2 release:

$$C_xH_Y+(x+4y)O_2 \rightarrow xCO_2+2yH_2O,$$

CO release:

$$C_xH_Y+2xO_2 \rightarrow xCO+2yH_2O.$$

The formation of soot can be a result of incomplete combustion of hydrocarbons:

$$C_xH_Y+O_2 \rightarrow CO+CO_2+H_2O + \text{particulate soot}$$

Soot particles typically consist of solid carbon.

The reactions for the formation of sulfur dioxide and sulfur trioxide depend on the sulfur content in the fuel:

$$2S+O_2 \rightarrow SO_2,$$
$$2SO_2+O_2 \rightarrow 2SO_3$$

These chemical equations provide a fundamental understanding of the complex processes that occur during combustion in marine engines. Methane combustion produces carbon dioxide (CO_2) and water (H_2O). High-temperature combustion produces nitrogen oxides (NO_x), with nitrogen oxide (NO) reacting to form the more toxic nitrogen dioxide (NO_2). Completeness of combustion affects the release of carbon dioxide (CO_2) and carbon monoxide (CO). Incomplete combustion of hydrocarbons results in the formation of soot, consisting mainly of solid carbon particles. The sulfur content of the fuel determines the formation of sulfur dioxide (SO_2) and sulfur trioxide (SO_3). Although these equations provide a simplified view, understanding the chemical reactions is critical to assessing the environmental impact of marine engine emissions and developing strategies to reduce emissions.

Results and discussion

In this study, we will evaluate and compare the thermal efficiency (η) of shipboard engines utilizing different classes of marine fuels. The focus is particularly on the comparison between high-sulfur and low-sulfur fuel grades. The transition to low-sulfur fuel is anticipated to impact combustion efficiency, subsequently influencing thermal efficiency. The analysis involves a detailed calculation considering enthalpy, heat balance, combustion efficiency, mechanical efficiency, and overall efficiency (1–5). The aim is to quantify the potential enhancements in shipboard technical facility performance achieved by adopting low-sulfur marine fuel grades.

$$H = C_p \cdot \Delta T \cdot \mathrm{TF} + P_{\mathrm{mech}} \tag{1}$$

$$\dot{Q}_{\mathrm{in}} = \dot{m} \cdot \int_{T_{\mathrm{in}}}^{T_{\mathrm{out}}} C_p(T)\,dT \tag{2}$$

$$\eta_{\mathrm{comb}} = 1 - \frac{T_{\mathrm{in}}}{T_{\mathrm{out}}} \tag{3}$$

$$\eta_{\mathrm{m}} = \frac{\dot{Q}_{\mathrm{in}}}{P_{\mathrm{mech}}} \tag{4}$$

$$\eta_{total} = \eta_{\mathrm{comb}} \cdot \eta_{\mathrm{m}} \tag{5}$$

Let's formulate the combustion efficiency and thermal efficiency model, taking into account specific parameters: C_p – specific heat capacity of the fuel; ΔH – change in enthalpy (energy), ΔT – change in temperature, $m^{\cdot}$– mass flow rate of the fuel, T_{in}, T_{out} – temperatures of the inlet and outlet, and P_{mech} – mechanical power, TF – temperature influence factor.

Let us introduce the proposed parameter values to illustrate the relationship between the temperature change (ΔT) and the combustion efficiency (η_{comb}) of marine engines fueled by different sulfur content fuels. The specific parameters used for this simulation include a heat capacity of 45 J/(mol·°C), a change in enthalpy (ΔH) of –50000 J/mol, a mass flow rate ($\dot{m}$) of 0.1 mol/s, an inlet temperature (T_{in}) of 300 °C, an outlet temperature (T_{out}) of 400 °C, and mechanical power (P_{mech}) of 10000 J/s.

The graph on Fig. 4 demonstrates the relationship between enthalpy and temperature, incorporating combustion efficiency considerations. The curve represents the variation of enthalpy concerning temperature. The color gradient provides a visual indication of temperature changes, enhancing the comprehension of the thermal dynamics. Dotted lines mark the inlet (T_{in}) and outlet (T_{out}) temperatures, with corresponding labels for easy identification and serves to visualize the thermal alterations in the system, taking into account the efficiency of combustion.

As the temperature difference increases, the combustion efficiency experiences a notable rise, indicating a more effective utilization of the fuel's energy. This trend underscores the importance of temperature management in optimizing the combustion process for marine engines. The graph provides valuable insights into how temperature adjustments can impact the overall efficiency of the combustion process in maritime applications.

The graph on Fig. 5 illustrates the relationship between temperature change (ΔT) and two key parameters: enthalpy change and thermal efficiency. The blue line represents the enthalpy change calculated as the product of the specific heat capacity of the fuel (C_p), the mass flow rate of the fuel, and the change in temperature. The red line plotted on the secondary y-axis represents the thermal efficiency. It is calculated from the inlet and outlet temperature difference and shows how efficiently the system converts heat into mechanical energy. The vertical dashed line at $\Delta T = 100$ serves as a visual reference or specific point of interest, providing additional information or highlighting a particular condition and helps visualize the effect of temperature change on the enthalpy and thermal efficiency of a given system.

This graph also shows the effect of temperature change on enthalpy and thermal efficiency when using low-sulfur marine fuel in marine technical equipment, where the enthalpy change representation shows how the specific heat capacity of low-sulfur marine fuel affects enthalpy with temperature change. Simultaneously, the thermal efficiency, showing how efficiently the system converts heat from low-sulfur marine fuel into mechanical energy as a function of temperature difference.

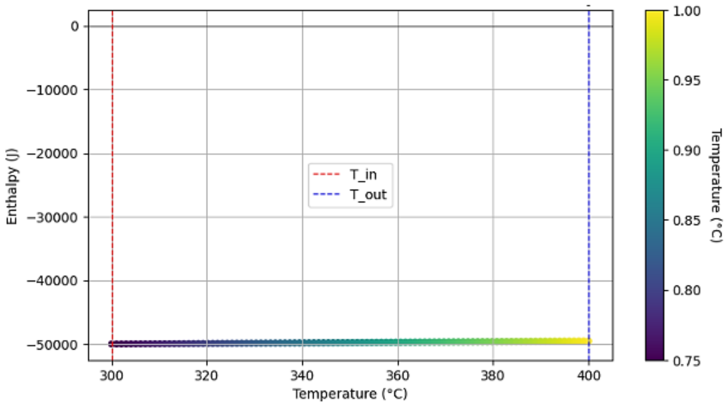

Fig. 4. Relationship between temperature change and combustion efficiency in marine engines using fuels with different sulfur content

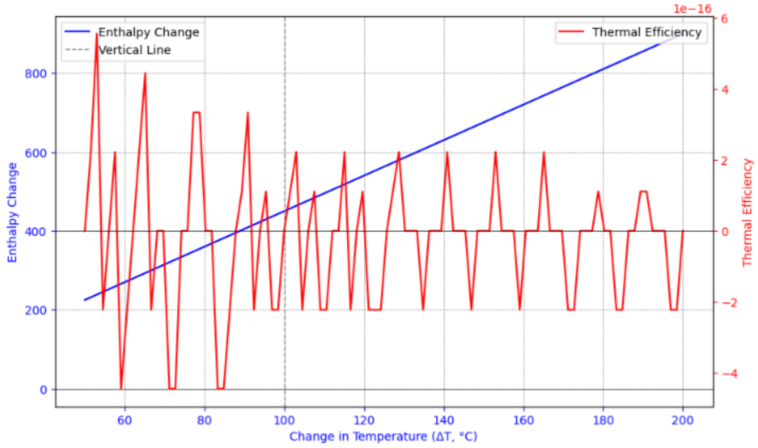

Fig. 5. Relationship between temperature, enthalpy change and thermal efficiency

Analysis of this graph helps to optimize operating conditions, define temperature ranges of efficiency, and identify potential areas for performance improvement with a critical threshold or point of particular interest for further study. Substantiation of the presented calculations carried out in the context of transition from traditional types of marine fuel to low-sulfur marine fuel and its impact on shipboard technical equipment is presented in Table 4.

Table 4

Impact of low-sulfur marine fuel on shipboard technical equipment

Parameter	Description
Change in Enthalpy	The change in enthalpy helps understand how the specific heat capacity of low-sulfur marine fuel influences the amount of heat absorbed or released during combustion. This is crucial for assessing the energy dynamics within shipboard engines.
Thermal Efficiency	Thermal efficiency provides insights into how effectively the system converts the heat from low-sulfur marine fuel into mechanical energy. It indicates the efficiency of the ship's engines in utilizing the energy content of the fuel for propulsion.
Temperature Influence	Analysis of the variable (dependence on temperature change allows to determine the temperature ranges in which the fuel demonstrates optimal performance. This helps to determine the conditions under which the ship's technical equipment operates most efficiently.
Optimization	The overall goal is to optimize the performance of shipboard machinery. By understanding how different temperatures impact the fuel properties and the efficiency of the conversion process, ship operators can adjust operating conditions to enhance fuel efficiency, reduce emissions, and improve the overall performance of marine engines.

Conclusion

This study examines strategies for improving the efficiency of marine technical equipment by switching to low-sulfur marine fuels. The analysis includes studies of enthalpy change and estimation of thermal efficiency under different temperature changes, that shed light on how the specific heat capacity of low-sulfur marine fuels affects combustion characteristics, which is important for understanding energy consumption dynamics. At the same time, the study provides estimates of heat-to-mechanical energy conversion efficiency, which provides valuable information for optimizing equipment performance, identifying temperature ranges that maximize efficiency, and thus identifying potential areas for improving the overall performance of marine diesel engines.

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