

Article

Improving Green Shipping by Using Alternative Fuels in Ship Diesel Engines

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Abstract: This paper aims to consider the issue of increasing the environmental friendliness of shipping by using alternative fuels in marine diesel engines. It has been determined that marine diesel engines are not only the main heat engines used on ships of sea and inland waterway transport, but are also sources of emissions of toxic components with exhaust gases. The main compounds whose emissions are controlled and regulated by international organizations are sulfur oxides (SO_x) and nitrogen oxides (NO_x), as well as carbon dioxide (CO_2). Reducing NO_x and CO_2 emissions while simultaneously increasing the environmental friendliness of shipping is possible by using fuel mixtures in marine diesel engines that include biodiesel fuel. During the research carried out on Wartsila 6L32 marine diesel engines (Shanghai Wartsila Qiyao Diesel Co. Ltd., Shanghai, China), RMG500 and DMA10 petroleum fuels were used, as well as their mixtures with biodiesel fuel FAME. It was found that when using mixtures containing 10–30% of FAME biodiesel, NO_x emissions are reduced by 11.20–27.10%; under the same conditions, CO_2 emissions are reduced by 5.31–19.47%. The use of alternative fuels in marine diesel engines (one of which is biodiesel and fuel mixtures containing it) is one of the ways to increase the level of environmental sustainability of seagoing vessels and promote ecological shipping. This is of particular relevance when operating vessels in special ecological areas of the World Ocean. The relatively low energy intensity of the method of creating and using such fuel mixtures contributes to the spread of its use on many means of maritime transport.



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Keywords: green shipping; emission reduction; alternative fuels; marine petroleum fuels; FAME biodiesel; fuel blend; marine diesel; environmental performance; maritime transport

1. Introduction

Sea and inland waterway transport ensures the transportation of cargo between countries and continents, which are connected by rivers or connected by seas and oceans. In this case, sea transport vessels are the only means of transport that ensure the transoceanic transportation of cargo. The most common type of heat engines used on sea and inland waterway vessels are internal combustion engines, which include gas and dual-fuel engines, as well as engines that operate on self-ignition fuel. The latter type is most often called “diesel” [1,2]. Modern trends in the use of solar energy [3,4], flexible and rigid sails [5,6], as well as batteries [7,8] can only partially compensate for the vessel's energy needs. In addition, such technologies are still in the development and improvement stages [9,10]. Therefore, today, there are isolated examples of the use of such power plants and, accordingly, such vessels.

The most common type of heat engines used on sea and inland waterway vessels are internal combustion engines (diesels) [11,12]. Diesels have the highest efficiency, and

diesels are characterized by the lowest fuel consumption (specific, hourly, and per mile of sailing). In addition, the design of marine diesels allows for an increase in their aggregate power by increasing the number of cylinders, a method that is impossible for steam turbine or gas turbine units. These factors are a major reason why diesels are installed on all vessels and act as main or auxiliary engines [13,14]. In the first case, they transmit their power to the propeller and ensure the movement of the vessel [15,16]; in the second, they are drivers of electric generators that supply energy to ship machines, mechanisms, and equipment [17,18].

Liquid fuels of petroleum origin are the main source of obtaining effective power in marine diesel engines [19,20]. At the same time, modern ships are equipped with engines of the ME-GI and X-DF class, which can operate on gas fuel. Also, engines that operate using methanol and ammonia are being implemented on some ships; perhaps these engines are the future of marine energy. However, at the moment, their number is not able to compete with the number of engines operating on liquid fuels of petroleum origin. Currently, there are only a few examples of diesel engines whose operation is ensured by using gas fuel [21,22]. Fuel combustion in the cylinder of a marine diesel engine is accompanied not only by the release of heat and its transformation into torque, but also by the formation and emission of exhaust gases into the atmosphere [23,24]. Exhaust gases are a multicomponent gas mixture which includes toxic components (primarily nitrogen oxides (NO_x), sulfur oxides (SO_x), and carbon monoxide (CO)) [25,26], as well as chemical compounds that contribute to global warming (such as nitrous oxide (N_2O) and carbon dioxide (CO_2)) [27,28]. Thus, the main negative factor associated with the use of petroleum-based fuels is its harmful impact on the environment. All this is associated with the emission of carbon oxides (CO and CO_2), sulfur oxides (SO_x), as well as nitrogen oxides (NO_x) [29,30]. In connection with this, the environmental performance of marine diesel engines is regulated and controlled by international organizations and classification societies.

The task of protecting the environment during the operation of sea and inland waterway vessels arose in the late 1950s and was reflected in the 1954 International Convention for the Prevention of Pollution from Ships (OILPOL), which entered into force in 1958. Over time, new challenges arose, which led to the development and adoption of the International Convention for the Prevention of Pollution from Ships in 1973 and its Protocol in 1978 (MARPOL 73/78) [31]. In this convention, the requirements for preventing the pollution of the sea from ships are reflected in six Annexes, which set out the rules regarding the pollution of the sea by specific substances, such as oil; harmful chemicals carried in bulk; substances carried in packaged forms; sewage; garbage; and air pollution from ships.

Emissions of nitrogen oxides (NO_x), as well as the sulfur content (S) in marine fuel (which is the source of sulfur oxides (SO_x)) are regulated by the requirements of Annex VI MARPOL [32,33].

Annex VI MARPOL establishes three levels of nitrogen oxide emissions—Tier I, Tier II, and Tier III—which depend on the year of construction of the vessel and the rotation speed of the diesel engine (Figure 1).

Tier I and Tier II requirements can be met by additional fuel preparation (e.g., homogenization, ultrasonic treatment, and production of water–fuel emulsions) and by improving the operating cycle (e.g., control of air supply, exhaust gas, and fuel injection phases) [34–36]. Tier III requirements can only be met by using additional technical systems and devices. The most common of these are an exhaust gas purification system—Selective Catalytic Reduction (SCR) [37,38]; recirculation system—Exhaust Gas Recirculation (EGR) [39]; and bypass system—Exhaust Gas Wastegate [40].

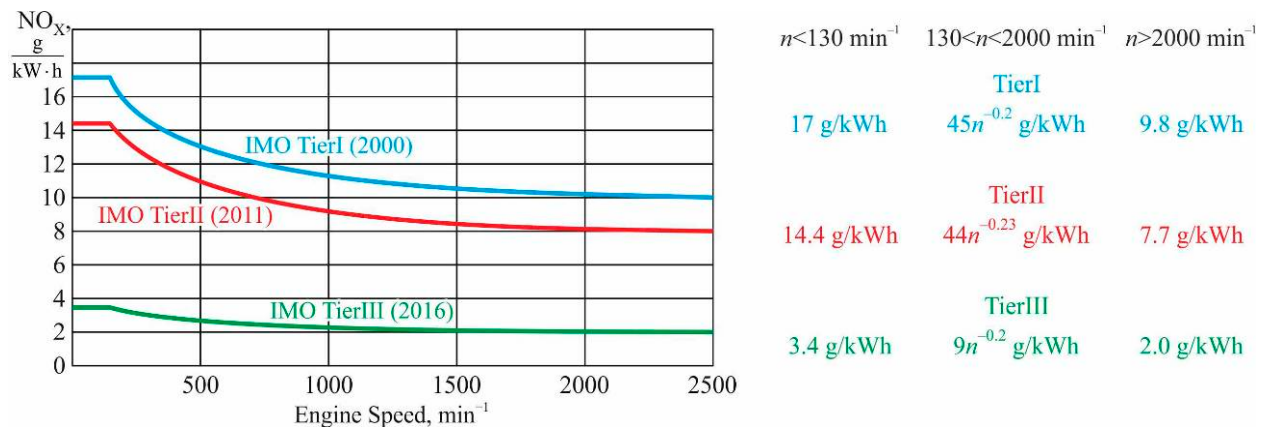


Figure 1. Nitrogen oxide (NO_x) emission levels in accordance with the requirements of Annex VI of MARPOL [10,31].

From 01.01.2020, Annex VI of MARPOL limits the sulfur content in fuel to the following values:

- No more than 0.1% when the vessel is in special environmental areas (Sulfur Emission Control Areas—SECAs);
- No more than 0.5% when the vessel is outside SECAs.

Annex VI MARPOL permits the use of marine fuels with a sulfur content of more than 0.5% only in the case of the additional cleaning of exhaust gases in special installations (usually in SO_x scrubbers); in this case, all exhaust gases of all heat engines that use marine fuel with a sulfur content of more than 0.5%. In the case of using a system for cleaning exhaust gases from sulfur oxides, their concentration is determined by the ratio SO₂ (ppm)/CO₂ (volume %). The value of this quantity, as well as the restrictions on the amount of sulfur in fuel in accordance with the requirements of Annex VI of MARPOL are given in Table 1.

Table 1. Annex VI MARPOL requirements for the sulfur content of marine fuels and sulfur oxide emissions from exhaust gases [11,31].

Vessel Operating Area	Operation Without Additional Exhaust Gas Cleaning System for Sulfur Oxides	Use of an Additional Exhaust Gas Cleaning System for Sulfur Oxides
	Fuel Oil Sulfur Content, %	Ratio Emission SO ₂ (ppm)/CO ₂ (v %)
Outside SECAs	0.5	21.7
Inside SECAs	0.1	4.3

Emissions of carbon monoxide (CO) and carbon dioxide (CO₂) are not currently regulated by the requirements of international maritime conventions. At the same time, the CO₂ value is decisive when calculating the coefficients of the Energy Efficiency Design Index (EEDI) and the Energy Efficiency Existing Ship Index (EEXI). According to the requirements of the Marine Environment Protection Committee of the International Maritime Organization (IMO), the EEDI and EEXI values for existing and newly built ships must have the lowest possible values [41,42].

Reducing the emission of nitrogen oxides and sulfur oxides with exhaust gases is possible using design and technological methods. In the first case, scrubbers are installed in the exhaust gas line of the diesel engine to clean it of SO_x, as well as SCR systems or EGR systems to clean them of NO_x [43,44]. In the second case, water is injected into the purge receiver, the diesel cylinder, or the exhaust gas manifold or a water–fuel emulsion is used (which is a homogeneous mixture of water and marine fuel) [45,46].

One of the ways to ensure green shipping, reduce the negative environmental impact, emission reductions, and improve energy efficiency is to use alternative fuels [47–49].

Alternative fuels are used in both stationary and marine power engineering. However, there is no systematic approach to their use. Recommendations for their use do not indicate their optimal concentrations, nor the most effective modes of their use. This is an incentive to conduct research to determine the impact of alternative fuels on green shipping and the energy efficiency of sea vessels, as well as the selection of optimal operating modes for marine diesel engines using alternative fuels.

2. Literature Review

The main source of air pollution is exhaust gases from the thermal engines of ship power plants, primarily diesel engines—the most widespread and installed engines on all modern ships without exception. A large number of scientific works and technical solutions are devoted to reducing the negative impact of ship diesel engines (in particular, regarding harmful emissions with exhaust gases). The largest number of these studies are devoted to the problem of ensuring the required level of sulfur oxide (SO_x) and nitrogen oxide (NO_x) emissions from the exhaust gases of marine diesel engines. The main solutions to this problem are proposed to be fuel desulfurization [50,51], exhaust gas scrubbing [52,53], the humidification and cooling of the air by adding fresh water to the purge receiver and diesel cylinder [54,55], the use of water–fuel emulsions [56,57], the use of an EGR, and the installation of a SCR system [58,59].

Reducing the concentration of carbon dioxide (CO_2), sulfur oxides (SO_x), and nitrogen oxides (NO_x) in the volume of exhaust gases is possible in various ways. Some of them provide the direct cleaning of exhaust gases; others affect the working process in the diesel cylinder. These include the use of alternative fuels—natural and petroleum gas, hydrogen, green ammonia, methyl and ethyl alcohols, vegetable fats and oils, as well as fuels of biological origin (biodiesel) [60–65]. At the same time, due to the lower amount or absence of sulfur in the composition of biodiesel, the requirements regarding the sulfur content in the fuel are met, and due to the lower combustion temperature of biodiesel, the requirements regarding emissions of nitrogen oxides are met [66–69].

The main advantages and disadvantages of alternative fuels are as follows:

Natural gas is currently in active usage as a fuel for power plants of sea and river vessels. The initial use of natural gas as a fuel only on ships of the Liquefied Natural Gas Tanker class has been expanded to ships of other classes—container ships, Ro-Ro, and Cruise Ships.

At the same time, the use of natural gas is associated with the solutions of a number of additional problems related to its physical and chemical characteristics. The main component of natural gas (which makes up to 95% of its volume) is methane. The Lower Heating Value is about 50,000 kJ/kg, which is 1.2–1.25 times higher than the calorific value of diesel fuel. The density at 20 °C and 0.1 MPa is 0.715–0.720 kg/m³, which is 1100–1200 times less than the density of liquid fuels of petroleum origin. This leads to the emergence of the main problem—the rational placement on board the vessel of the amount of natural gas required for a sea passage. The storage and transportation of natural gas on board a vessel in a compressed state reduces the autonomy of navigation (due to the limited space of the ship's premises intended for storing cylinders with compressed gas). The storage of natural gas on board a vessel in a liquefied state requires the presence of cryogenic equipment. In addition, when using natural gas as a fuel, it is necessary to additionally ensure explosion safety regulations. Despite these limitations, it is important to note the growing role of natural gas in shipping [70,71].

Liquefied petroleum gases have been used in the automotive industry for many years, and the advent of marine gas diesel of the ME-GI type has made it possible to use them also as marine fuel. Switching to petroleum gas causes a significant reduction in CO₂, NO_x, and SO_x emissions. Liquefied petroleum gas as a fuel for two-stroke ME-GI engines has the same effect in terms of reducing harmful emissions as liquefied natural gas; in both cases, the emission values are sharply reduced compared to marine diesel MDO. This creates a strong incentive for the widespread use of gas fuel in coastal waters and inland waterways. The GI system is also used on diesel engines designed for small tankers, general purpose vessels, container ships, and Ro-Ro vessels. As a rule, petroleum gas is a mixture consisting of propane C₃H₈ (60%) and butane C₄H₁₀ (40%). The lower calorific value of petroleum gas is within 47,500–48,500 kJ/kg, and the density of the gas phase at 20 °C is 1.8–2.5 kg/m³. Similarly, using liquefied natural gas requires a change in the design of fuel systems using liquefied petroleum gas, particularly regarding the use of special nozzles [72,73].

The most optimal option for using natural and petroleum gas as an alternative fuel is the power plants of LNG Tanker and LPG Tanker class vessels. These vessels transport natural or petroleum gas as cargo, therefore eliminating the need for the additional installation of cryogenic equipment [74,75]. However, diesel engines can only operate on gas in the case of a “cargo” passage. After unloading, during the ballast passage, marine diesel engines operate on liquid petroleum fuel. In addition, it is necessary to calculate and strictly control the amount of gas that will be used as fuel. Exceeding this volume (which may be associated with an unplanned increase in the navigational passage) may violate charter obligations and lead to penalties or even the arrest of the vessel.

Currently, such concerns as MAN Diesel, Wärtsilä, and WinGD produce engines capable of operating on two types of fuel—liquid (petroleum origin) and gaseous—in most cases, on LNG): MAN B&W ME-GI, Wärtsilä-SG, Wärtsilä-DF, WinGD X-DF. The ignition of gas in the cylinders of these diesel engines can occur either due to a small volume of liquid pilot fuel or due to a spark plug. In addition, engines that can use methanol, MAN B&W ME-LGIM, as well as ammonia, MAN B&W ME-LGIA and WinGD X-DF-A are manufactured. The use of such engines significantly improves their environmental performance in terms of CO₂ and SO_x emissions, and also meets the requirements of the Tier III Annex VI of MARPOL regarding NO_x emissions. However, the number of these engines installed on seagoing vessels does not yet allow them to compete with diesel engines, which run only on liquid fuel.

Hydrogen energy is one of the popular energy supply trends. The main advantage of hydrogen is its environmental friendliness (no harmful components are released when hydrogen burns) and its high calorific value, which reaches 120,000–140,000 kJ/kg. However, the release of such an amount of energy in a closed space (which is the cylinder of a marine diesel engine) leads to increased mechanical loads [76,77]. In addition (given the specific sequence of cylinder operation in a multi-cylinder diesel engine), a sharp increase in pressure from the gases on the piston increases the dynamic loads and dynamic imbalance of the diesel engine. In addition, hydrogen (like any gas) has a lower density compared to liquid fuel. This necessitates its storage under high pressure in special thermal cylinders. Special equipment is used to pump hydrogen to the diesel engine and inject it into the cylinder.

Alternative fuels also include mixtures of ethyl and methyl alcohol with diesel fuel. These substances are currently produced from plant materials, which transfers them to the category of green energy. One of the advantages of methanol and ethanol is their density, which is 780–790 kg/m³ and is practically no different from the density of diesel fuel. This simplifies the task of creating their mixtures and also makes it possible to use the same fuel equipment for feeding to a diesel engine and for injection into its cylinder. The disadvantage of methanol and ethanol is their low calorific value (22,700 kJ/kg and

30,000 kJ/kg, respectively). This forces us to increase the cyclic feed and increase the feed advance angle compared to the operation of a diesel engine on petroleum-based fuel. As a result, dynamic loads on the parts of the diesel cylinder group increase. In addition, these types of alternative fuel are characterized by a relatively low ignition temperature: 13 °C for methanol and 18 °C for ethanol. This puts forward additional requirements for ensuring their fire safety [78–80].

The most commonly used vegetable oils in marine diesel engines are palm, soybean, and rapeseed oils. These oils have a density (873–882 kg/m³), a viscosity (4.26–4.61 cSt @ 40 °C), and flash points (159–169 °C) similar to diesel fuel. This gives them an opportunity to be used in two ways: as a stand-alone fuel and as part of a mixture with liquid petroleum fuel. The sulfur content in vegetable oils is within 0.02–0.04% by weight, which facilitates their use as the main fuel for the operation of ships in SECA environmental control areas. The disadvantage of vegetable oils is their lower calorific value compared to diesel fuel. For soybean oil, this is 37,000 kJ/kg; for palm oil—37,200 kJ/kg; and for rapeseed oil—37,800 kJ/kg. It is for this reason that rapeseed oil has become the most widely used vegetable oil [81–83].

Over the past decade, fuels of biological origin have been actively introduced into the global fuel market (for stationary energy, automobile, rail, and maritime transport)—namely biodiesel fuel or biodiesel. The general designation of these fuels is FAME—Fatty Acid Methyl Ester. During their production, vegetable oils are used—palm, namely soybean, rapeseed, and sunflower. The coincidence of the density of these oils with the density of liquid fuels of petroleum origin contributes to the formation of stable fuel mixtures that do not undergo stratification for a long time. This allows not only the use of mixtures of biodiesel and petroleum fuel directly during their supply to the diesel engine and injection into its cylinder, but also to store them in a prepared state in the fuel system tanks. This contributes to increasing the reliability of the fuel preparation system [84,85]. In recent years, developments have been carried out in the field of creating biodiesel fuel from algae (a “third-generation” biofuel) [86,87]. The performance characteristics and properties of biodiesel fuel (like any other fuel used for the operation of vehicles) must meet the requirements specified by a special standard [88,89].

Biodiesel fuel is not used as a separate energy source. First of all, this is due to its higher (compared to diesel fuel) density and viscosity. This negatively affects the parameters of the fuel supply, injection, and atomization process, which worsens the quality of these processes. Reducing the viscosity of biodiesel fuel by additional heating leads to increased paraffin formation and the subsequent coking of high-pressure fuel equipment. Another reason that limits the use of biodiesel fuel as a separate energy source is its lower calorific value compared to petroleum fuels. As a rule, this value does not exceed 37,500–38,000 kJ/kg, which is almost 10% less than the calorific value of heavy fuel class RM and almost 15% less than the calorific value of diesel class DM. In this regard, biodiesel fuel is mixed in various proportions with motor (diesel/light or heavy) fuel. Adding biofuel to traditional types of motor fuel improves the environmental performance of marine diesel engines. It is also necessary to determine that biofuel production allows countries with small reserves of their own energy resources to reduce economic and political dependence on imported supplies of fuels of oil origin [90,91].

The use of biodiesel fuel in recent years has found applications in railway and road transport (including on tractor diesel engines), as well as in industrial power plants (in which diesel engines are used to drive electric generators). At the same time, biodiesel fuel is part of a mixture with diesel (light) fuels, the density of which does not exceed 830–850 kg/m³. The use of biodiesel fuel in power plants of sea and inland waterway

transport vessels is currently not widespread [92,93]. There are only a few studies on determining the efficiency of using biodiesel fuel in diesel engines of ship power plants [94,95].

There is also no generally defined concentration of biodiesel in its mixture with motor fuel (diesel or heavy). For example, the multinational oil and gas company British Petroleum supplies marine vessels with the Marine B30 fuel mixture, which consists of 30% biodiesel and 70% heavy fuel with an extremely low sulfur content (Very Low Sulfur Fuel Oil—VLSFO); the oil corporation Exxon Mobil supplies a similar mixture containing 25% biodiesel [96,97].

The cost of biodiesel production in most countries of the world is higher than the cost of traditional marine fuels of RM or DM classes. It should also be noted that the profitability of the biodiesel production business is inferior to the profitability of oil refining. At the same time, the use of biodiesel contributes to the development of green shipping and increasing the stability of maritime transportation. First of all, this is reflected in the reduction in emissions of toxic components with exhaust gases from ship diesel engines. This becomes an important advantage of using biodiesel fuel when ships are in sea and river ports, coastal areas, and special ecological areas.

Food raw materials (vegetable oils and animal fats) are used to produce biofuels [98,99]. During the esterification process using alcohol mixtures (methanol or ethanol) and the addition of alkaline catalysts (in the form of NaOH, KOH oxides, or NaOCH₃ and KOCH₃ methoxides), these substances are converted into monoalkyl esters of fatty acids, which have the simplified name of biodiesel [100,101]. Then, the biodiesel phase is subjected to additional purification by distillation and membrane filtration. These operations are the final phase of obtaining biodiesel fuel.

The above circumstances are the basis for the use of alternative fuels in ship internal combustion engines, one of which is biodiesel fuel [102,103]. Currently, Brazil, China, EU countries, Indonesia, and the USA are actively developing the production of alternative fuels (in particular, biofuels).

The data presented emphasize the multifaceted nature of the problem of ensuring that shipping is green, the solution of which is associated with both positive and negative factors.

The analysis of the cited literature sources indicates only a partial solution to the problem of ensuring green shipping by using alternative fuel. Almost all researchers have found that alternative fuels (one of which is biodiesel) contribute to improving the environmental performance of the heat engines. This is illustrated by a decrease in the emissions of nitrogen and sulfur oxides, carbon oxide and dioxide, solid particles, as well as some other harmful and toxic substances. At the same time, there is no unambiguous assessment of the effect of alternative fuels (in particular, biodiesel fuel) on the efficiency of marine internal combustion engines, as well as on the temperature tension of their main parts.

The purpose of this research was to conduct a comprehensive analysis of fuel mixtures effect, which include biodiesel fuel, on the environmental performance of marine diesel engines, as well as their efficiency and temperature tension during their operation at various loads. The solution to the problem will allow us to assess the possibility of using biodiesel fuel to ensure green shipping.

The studies were performed on marine internal combustion engines that run exclusively on liquid fuel. Currently, engines of this type occupy an overwhelming position on sea vessels. At the same time (taking into account the warranty period of diesel engines), this trend will continue for at least 10–12 years. Currently, dual-fuel engines that can run on both liquid fuel and gas are installed on modern sea and inland waterway transport vessels. However, the conversion of diesel engines running on liquid fuel to dual-fuel technologies requires additional analytical calculations, as well as additional technical

work. This requires installing new high-pressure fuel equipment (which will ensure the supply of both liquid and gaseous fuel to the cylinder); installing special tanks for storing gaseous fuel; installing equipment for re-condensing gaseous fuel from a liquid to a gaseous state; as well as coordinating the re-equipment technology with classification societies and the register.

3. Materials and Methods

The motivation for the research was the task of increasing the information field on the possibility and prospects of using biofuel in marine diesel engines. In addition, the task was to confirm the possibility of implementing previously developed technologies for creating fuel mixtures (which include biofuel) on the next group of diesel engines. The peculiarity of the marine power plant on which the research was conducted made it possible to conduct them simultaneously on several fuel mixtures of different diesel engines in a wide range of operating loads.

The research was carried out on a sea vessel constructed to transport 8600 TEU. The auxiliary power plant of the vessel included four Wartsila 6L32 engines (Shanghai Wartsila Qiyao Diesel Co., Ltd., Shanghai, China). The general characteristics of the diesel engines are as follows:

- Type—four-stroke, trunk;
- Diameter of cylinder unit—0.32 m;
- Stroke—0.40 m;
- Rotation speed—750 min^{−1};
- Number of cylinders—6;
- Power—3480 kW.

A general view of the Wartsila 6L32 diesel engines is shown in Figure 2.

The engines were tested and operated on two types of fuel—DMA10 (in case passage in SECAs areas) and RMG500 (in case passage outside SECAs areas). In addition, the diesel engines could operate on a fuel blend, which included RMG500 or DMA10 as the priority fuel and FAME biodiesel fuel as the secondary. The main characteristics of DMA10, RMG500, and FAME fuels are described in Table 2. The fundamental schematic of the fuel system for Wartsila 6L32 diesel engines is presented in Figure 3.



Figure 2. Cont.

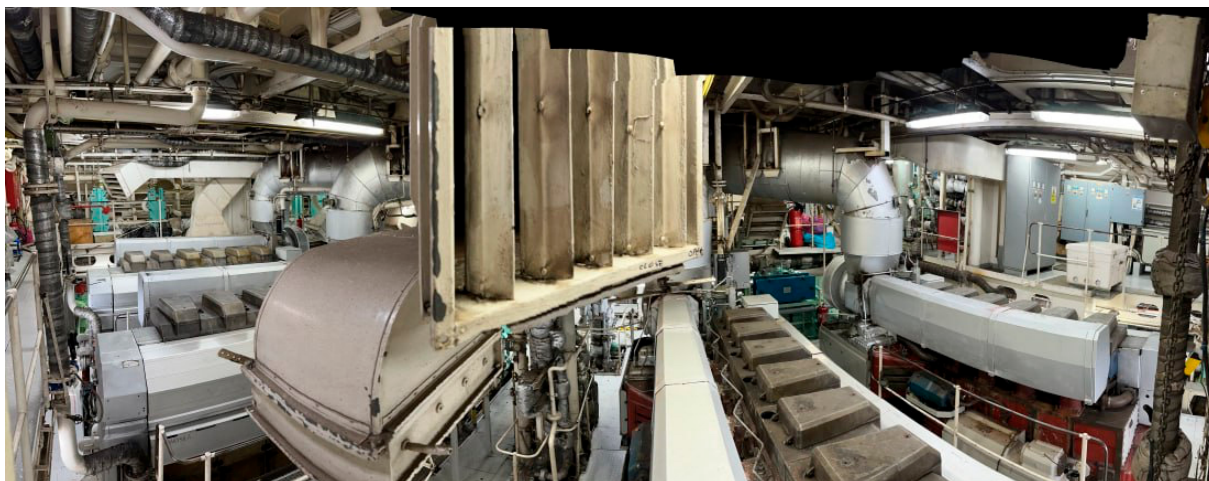


Figure 2. A general view of the Wartsila 6L32 diesel engines. Photo by the authors.

Table 2. Characteristics of engine fuels. Authors.

Characteristic	Fuel Type		
	DMA10	RMG500	FAME
Density at 20 °C, kg/m ³	884	962	926
Viscosity 40 °C, sSt	9.4	496	314
Sulfur content, %	0.057	0.48	0.022
Lower calorific, kJ/kg	43,280	39,070	37,720

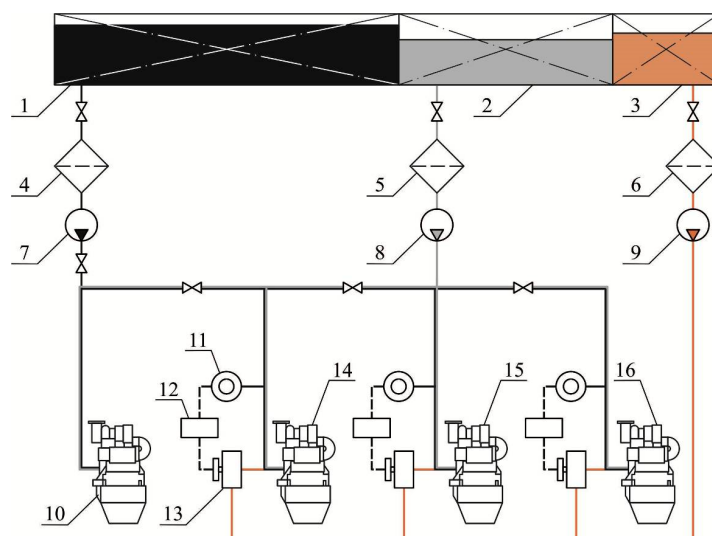


Figure 3. The fundamental schematic for Wartsila 6L32 engine fuel system: 1—RMG500 fuel; 2—DMA10 fuel; 3—FAME fuel; 4, 5, 6—fuel filters for RMG500, DMA10, and FAME fuels, respectively; 7, 8, 9—fuel pumps for RMG500, DMA10, and FAME fuels, respectively; 10, 14, 15, 16—diesel engines; 11—flow meter; 12—microcontroller; 13—dispenser. Authors.

The main advantage when creating fuel mixtures from petroleum-based fuels and bio-based fuels is the coincidence or correspondence in their density and viscosity values [104,105]. This allows creating fuel mixtures directly in the fuel line, to which these fuels are directed along separate fuel lines from the corresponding consumable tanks [106,107].

The diesel engines operated as follows: While the vessel was outside the ecological areas, the diesel engines were operated in the following manner using RMG500 fuel, which was in consumable tank 1. The condition of the RMG500 fuel (primarily its density, viscosity, and temperature) allowed its supply to the fuel equipment of diesel engines 10, 14, 15, and 16. This was ensured by fuel pump 7 after additional fuel purification in fuel filter 4. The number of simultaneously operating diesel engines was determined based on the overall load of the vessel energy system, which, in any case, did not exceed three.

While the vessel was in special ecological areas, the Wartsila 6L32 diesel engines were operated on DMA10 fuel, which was located in consumable tank 2. The sulfur gap in the fuel was no more than 0.1%, which met the requirements of Annex VI MARPOL. The DMA10 fuel was supplied to the diesel engines by pump 8, following additional cleaning through fuel filter 5.

In addition to the above options, it was also possible to operate diesel engines using a fuel blend containing FAME biodiesel. The FAME fuel was pumped to engines by supply pump 9 after additional fuel purification in fuel filter 6. The FAME fuel content in the blend was between 10 and 30% by weight. The fuel mixture, consisting of RMG500 or DMA10 fuel and FAME biodiesel, was formed by dosing FAME fuel into the general flow of RMG500 or DMA10 fuel. The dosing of FAME biodiesel was provided by dispenser 13, which was maintained on the main line to each of the engines. The amount of FAME biodiesel in the mixture depended on the consumption of RMG500 or DMA10 fuel, which was controlled by flow meter 11. The operation of FAME biodiesel dispenser 13 was controlled by microcontroller 12. A blend using RMG500 or DMA10 and FAME biodiesel was possible for diesel engines 14, 15, and 16. In this case, in diesel engine 14, a fuel mixture was used, consisting of 90% petroleum-based fuel (RMG500 or DMA10) and 10% FAME biodiesel; in diesel engine 15, a fuel mixture of 80% RMG500 or DMA10 and 20% FAME; and in diesel engine 16, a fuel mixture of 70% RMG500 or DMA10 and 30% FAME. It was on these diesel engines that experimental studies were conducted to evaluate the effectiveness of using FAME biodiesel. Diesel engine 10 was run on RMG500- or DMA10-grade fuel without the use of a fuel mixture containing FAME biodiesel.

The main figures of the operated system were automatically monitored and regulated. The Wartsila 6L32 auxiliary engines maintained a stable rotation speed and load through automatic control [108,109]. The parallel operation of auxiliary engines (two or three) was managed with automatic load distribution. The ProPower diagnostic system allowed for the monitoring of crucial diesel performance data: combustion pressure (p_z), effective power (N_e), specific effective fuel consumption (b_e), and exhaust gas temperature (t_g).

The ProPower system also monitored and analyzed diesel exhaust gases, including determining the concentration of nitrogen oxides (NO_x) and carbon dioxide (CO_2) [110,111]. In this case, the emission of nitrogen oxides is automatically converted to $\text{g}/(\text{kW}\cdot\text{h})$, and the emission of carbon dioxide is determined in volume percentages—% v. The ProPower system provides a wider range of exhaust gas composition control and allows us to determine the concentration of carbon monoxide (CO), oxygen (O_2), nitrogen (N_2), methane (CH_4), unburned hydrocarbons (HC), sulfur dioxide (SO_2), and hydrogen sulfide (H_2S), as well as the amount, temperature, humidity, and velocity of exhaust gases. The ProPower system belongs to modern systems for diagnosing the working process of marine diesel engines and is used on a large number of seagoing vessels [112,113].

The energy consumers of the Wartsila 6L32 marine diesel engines were the machines and mechanisms of the both the ship's systems and the refrigerated containers, which were transported by ship together with the usual containers (it was precisely because of the presence of the refrigerated containers that the ship's auxiliary power plant was characterized by high power). Their number for each of the sea crossings was different but

did not change during transportation. This provided different but almost constant loads on the main power control panel during one sea crossing (and, accordingly, on the Wartsila 6L32 engines, which performed the functions of auxiliary ones). During this period, the operating modes of the plant were provided by 50%, 60%, 70%, and 80% loads on the vessel engines, on which the research was carried out. An example of the operating modes in which the research was carried out and the power distribution between the Wartsila 6L32 marine diesel engines in these modes are given in Table 3.

Table 3. Load distribution between the Wartsila 6L32 diesel engines during the research *. Authors.

General Load, kW	Load on Individual Diesel Engines, kW (%)			
	Auxiliary Engine No. 1	Auxiliary Engine No. 2	Auxiliary Engine No. 3	Auxiliary Engine No. 4
5630	1750 (50)	1750 (50)	1750 (50)	380
4220	1750 (50)	—	720	1750 (50)
6720	2100 (60)	2100 (60)	420	2100 (60)
5050	2100 (60)	2100 (60)	—	850
7880	2450 (70)	530	2450 (70)	2450 (70)
5510	2450 (70)	610	—	2450 (70)
8880	2800 (80)	2800 (80)	2800 (80)	480
6310	2800 (80)	710	2800 (80)	—

* selected diesel engines and their loads, on which the research was carried out.

Alternative fuels (including fuels of biological origin, which include FAME) differ from fuels of petroleum origin in their structural composition, calorific value, and stoichiometric ratio. This leads to certain differences during its combustion and expansion processes [114,115]. Taken together, this is the reason for the differences in the economic, environmental, and temperature efficiency of marine diesel engines when using fuels of biological origin or fuel mixtures in which they are included. The following indicators were taken as such during the research: the amount of nitrogen oxides present in exhaust gases— NO_x , g/(kW·h); the amount of carbon dioxide present in exhaust gases— CO_2 , %; the rate of fuel consumption relative to the power output— b_e , g/(kW·h); and the cylinder exhaust temperature— t_g , °C.

The choice of these indicators was based on the following:

Nitrogen oxide emissions are a complex indicator. As a rule, during this measurement, emissions such as nitrous oxide (N_2O), nitrogen monoxide (NO), and nitrogen dioxide (NO_2) are summed up. The level of nitrogen oxide emissions is influenced by a number of factors: the maximum temperature of gases in the diesel cylinder (due to which thermal nitrogen oxides are formed); the nitrogen content in liquid fuel (which leads to the formation of fuel nitrogen oxides); the oxygen content in the air (which contributes to the formation of fast nitrogen oxides); and general stoichiometric conditions. The change in these indicators, as well as their impact on the total amount of nitrogen oxide emissions, is not always possible to describe with the help of analytical equations. Therefore, to assess the environmental friendliness of marine diesel engines, the NO_x emission value is taken, which is measured in the exhaust gas main using gas analyzers.

The amount of nitrogen oxides (NO_x) is limited by the requirements; therefore, it is subject to constant monitoring during diesel engine operation in marine and inland vessels. For Wartsila 6L32 marine diesel engines, the upper bound of this value is defined by the outcome of the expression

$$\text{NO}_x^{\max} = 44n^{-0.23}, \quad (1)$$

where n is the crankshaft speed of the diesel engine, min^{-1} .

Based on the characteristics of the Wartsila 6L32 marine diesel engine,

$$\text{NO}_x^{\max} = 44 \cdot 750^{-0.23} = 9.60 \text{ g}/(\text{kW} \cdot \text{h}).$$

This value must be monitored during the normal operation of Wartsila 6L32 diesel engines.

The nitrogen dioxide level in CO₂ exhaust gases is not limited and is not mandated by the provisions of international conventions, but international organizations and classification societies constantly make recommendations to cut carbon oxide emissions (CO and CO₂) in the environment. Reducing CO₂ emissions reduces the greenhouse effect and increases the energy efficiency of the vessel. Therefore, any innovative solutions that contribute to reducing CO₂ emissions are effectively implemented in the power plants of sea and inland waterway transport vessels [116,117].

Specific fuel consumption (b_e) indicates internal combustion engine efficiency. Simultaneously, fuel procurement is the largest single expenditure related to the technical operation of maritime vessels. Meanwhile, fuel consumption is related not only to the financial component, but also to the total amount of fuel on board the vessel. Due to the limited volume of ship fuel tanks, an increase in fuel consumption (specific, hourly, and per nautical mile) together with an unplanned increase in the duration of a sea crossing (for example, due to the deterioration of navigation conditions) can lead to a critical reduction in fuel reserves on board the ship [118,119]. The most favorable consequence of this is a reduction in the time between the bunkering of the ship. The worst is the stoppage of the ship during a navigation crossing.

The temperature of the exhaust at the outlet of the unit t_g is one of the main indicators characterizing the quality throughout the working cycle of a marine engine. By its value, it is possible to diagnose the course of not only the combustion, expansion, and exhaust processes, but also to determine the operational state of the high-pressure fuel equipment and the quality of the fuel injection process. In addition, the temperature at the outlet of the unit is the main indicator characterizing the amount of heat-induced strain on the diesel engine's cylinder group and exhaust system (including the turbocharger).

The values of the concentration of nitrogen oxides (NO_x) and the concentration of carbon dioxide in exhaust gases (CO₂) were determined using a gas analyzer installed in the exhaust gas line of the diesel engine and were automatically recorded by the system for diagnosing and monitoring the operation parameters of diesel engines.

The value of the specific fuel consumption b_e , g/(kW·h), was determined by the expression

$$b_e = 1000B_h / N_{ed}; \quad (2)$$

where B_h —hourly fuel consumption, kg/h;

N_{ed} —effective diesel power, kW.

In this case, the value of B_h was calculated as

$$B_h = \frac{V_1 - V_2}{\rho}; \quad (3)$$

where V_1 , V_2 —hourly volumes of fuel (or fuel mixture), which were determined using the flow meters fitted to the fuel supply line that feeds the diesel engine and the fuel residue return line, m³/h;

ρ —density of fuel (or fuel mixture) supplied to the diesel engines, kg/m³.

For a diesel engine operated without using a fuel mixture (position 10 in Figure 3), the value of fuel density ρ corresponded to the characteristics of RMG500 or DMA10 fuel.

For a diesel engine operated using a fuel mixture of 90% petroleum fuel (RMG500 or DMA10) and 10% FAME biodiesel fuel (position 14 in Figure 3), the value of fuel mixture density ρ was determined as

$$\rho = 0.9\rho_{\text{RMG}} + 0.1\rho_{\text{FAME}}, \text{ or } \rho = 0.9\rho_{\text{DMA}} + 0.1\rho_{\text{FAME}}; \quad (4)$$

where ρ_{RMG} , ρ_{DMA} , ρ_{FAME} —the fuel density of RMG500, DMA10, and FAME, kg/m^3 , respectively.

For a diesel engine operated using a fuel blend of 80% petroleum fuel (RMG500 or DMA10) and 20% FAME biodiesel (position 15 in Figure 3), the fuel density value ρ was determined as

$$\rho = 0.8\rho_{\text{RMG}} + 0.2\rho_{\text{FAME}}, \text{ or } \rho = 0.8\rho_{\text{DMA}} + 0.2\rho_{\text{FAME}}. \quad (5)$$

For a diesel engine operated using a fuel mixture of 70% petroleum-based fuel (RMG500 or DMA10) and 30% FAME biodiesel fuel (position 16 in Figure 3), the fuel density value ρ was determined as

$$\rho = 0.7\rho_{\text{RMG}} + 0.3\rho_{\text{FAME}}, \text{ or } \rho = 0.7\rho_{\text{DMA}} + 0.3\rho_{\text{FAME}}. \quad (6)$$

The effective power of the diesel engine (included in expression (2)) was defined as

$$N_{ed} = N_{eg} / \eta_{eg}; \quad (7)$$

where N_{eg} —the power of the electric generator, kW;

η_{eg} —the efficiency of the electric generator.

The value of N_{eg} was determined by the wattmeter readings installed in the central control station.

The values of η_{eg} (according to the operating instructions for Wartsila 6L32 marine diesel engines) were taken as follows: 0.87—for a load of 50%; 0.878—for a load of 60%; 0.883—for a load of 70%; and 0.886—for a load of 80%.

4. Results

The experimental studies were carried out exclusively on stable operating modes of marine diesel engines. At the same time, by redistributing energy consumers (the number of refrigerated containers and ship auxiliary equipment), the same load was maintained on the diesel engines involved in the experiments. The duration of the tests in each of the experimental modes was at least two hours. This ensured the correctness of the experiment and the reliability of the results obtained.

The test results are given in Tables 4–11.

Table 4. Specific fuel consumption b_e , $\text{g}/(\text{kW}\cdot\text{h})$ under various operating conditions of Wartsila 6L32 marine diesel engines. Authors.

Load, %	Type of Fuel			
	RMG500 (100%)	RMG500 (90%) + FAME (10%)	RMG500 (80%) + FAME (20%)	RMG500 (70%) + FAME (30%)
50	203	208	215	218
60	198	202	205	209
70	195	197	199	202
80	192	195	197	200

Table 5. Emission of nitrogen oxides, NO_x, g/(kW·h), during various operating conditions of Wartsila 6L32 marine diesel engines. Authors.

Load, %	Type of Fuel			
	RMG500 (100%)	RMG500 (90%) + FAME (10%)	RMG500 (80%) + FAME (20%)	RMG500 (70%) + FAME (30%)
50	6.82	5.81	5.63	5.43
60	7.12	5.93	5.75	5.53
70	7.62	6.12	5.93	5.73
80	7.97	6.18	6.01	5.81

Table 6. Carbon dioxide emissions, CO₂, %, during various operating conditions of Wartsila 6L32 marine diesel engines. Authors.

Load, %	Type of Fuel			
	RMG500 (100%)	RMG500 (90%) + FAME (10%)	RMG500 (80%) + FAME (20%)	RMG500 (70%) + FAME (30%)
50	6.22	5.88	5.62	5.31
60	6.43	6.03	5.72	5.40
70	6.78	6.25	5.80	5.46
80	7.22	6.42	5.86	5.52

Table 7. Average temperature of gases at the cylinder outlet, t_g , °C, during various operating conditions of Wartsila 6L32 marine diesel engines. Authors.

Load, %	Type of Fuel			
	RMG500 (100%)	RMG500 (90%) + FAME (10%)	RMG500 (80%) + FAME (20%)	RMG500 (70%) + FAME (30%)
50	343	348	356	368
60	352	358	367	379
70	359	368	378	392
80	363	376	388	403

Table 8. Specific fuel consumption, b_e , g/(kW·h), during various operating conditions of Wartsila 6L32 marine diesel engines. Authors.

Load, %	Type of Fuel			
	DMA10 (100%)	DMA10 (90%) + FAME (10%)	DMA10 (80%) + FAME (20%)	DMA10 (70%) + FAME (30%)
50	197	201	205	210
60	190	193	195	198
70	188	189	191	194
80	186	187	188	191

For better visualization, the results given in Tables 4–11 are presented in the form of Figures 4–7.

Table 9. Emission of nitrogen oxides, NO_x , g/(kW·h), during different operating conditions of marine diesel engines Wartsila 6L32. Authors.

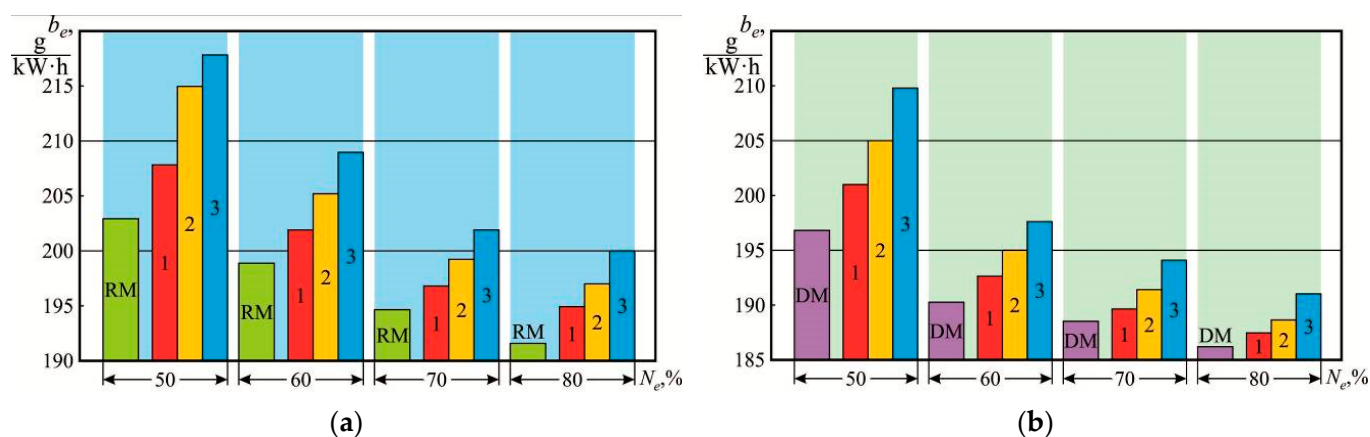
Load, %	Type of Fuel			
	DMA10 (100%)	DMA10 (90%) + FAME (10%)	DMA10 (80%) + FAME (20%)	DMA10 (70%) + FAME (30%)
50	7.68	6.82	6.55	6.32
60	7.96	7.01	6.72	6.49
70	8.53	7.22	7.02	6.78
80	8.77	7.33	6.96	6.84

Table 10. Emission of carbon dioxide, CO_2 , %, during different operating conditions of marine diesel engines Wartsila 6L32. Authors.

Load, %	Type of Fuel			
	DMA10 (100%)	DMA10 (90%) + FAME (10%)	DMA10 (80%) + FAME (20%)	DMA10 (70%) + FAME (30%)
50	6.78	6.42	6.18	5.88
60	7.03	6.61	6.27	6.03
70	7.47	6.97	6.5	6.27
80	7.82	7.18	6.68	6.35

Table 11. Average temperature of gases at the outlet of the cylinders, t_g , °C, during different operating conditions of marine diesel engines Wartsila 6L32. Authors.

Load, %	Type of Fuel			
	DMA10 (100%)	DMA10 (90%) + FAME (10%)	DMA10 (80%) + FAME (20%)	DMA10 (70%) + FAME (30%)
50	351	356	362	373
60	361	367	371	382
70	367	376	385	399
80	371	383	392	407

**Figure 4.** Specific fuel consumption under different operating conditions of Wartsila 6L32 marine diesel engines: (a) when using RMG500 fuel and its mixture with FAME biodiesel fuel; (b) when using DMA10 fuel and its mixture with FAME biodiesel fuel; RM—RMG500 fuel; DM—DMA10 fuel; 1, 2, 3—mixture of RMG500 fuel (or DMA10) and 10%, 20%, and 30% FAME fuel, respectively. Authors.

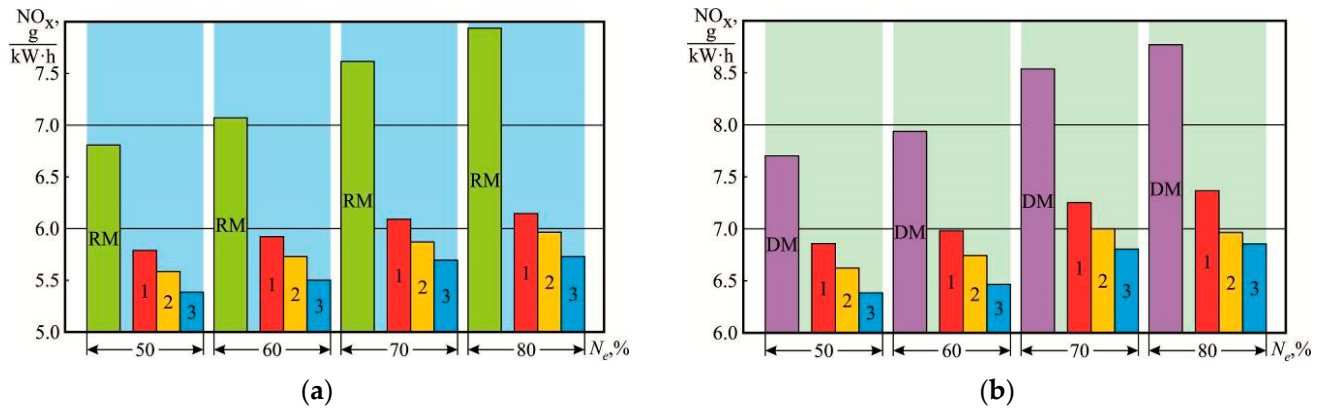


Figure 5. Emission of nitrogen oxides during different operating conditions of marine diesel engines Wartsila 6L32: (a) when using RMG500 fuel and its mixture with FAME biodiesel fuel; (b) when using DMA10 fuel and its mixture with FAME biodiesel fuel; RM—RMG500 fuel; DM—DMA10 fuel; 1, 2, 3—mixture of RMG500 fuel (or DMA10) and 10%, 20%, and 30% FAME fuel, respectively. Authors.

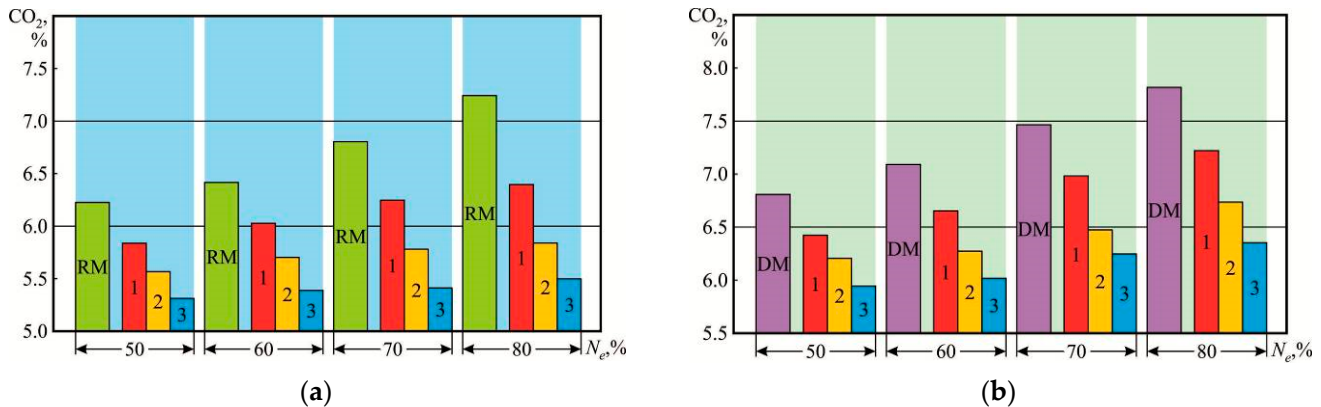


Figure 6. Carbon dioxide emissions under different operating conditions of Wartsila 6L32 marine diesel engines: (a) when using RMG500 fuel and its mixture with FAME biodiesel fuel; (b) when using DMA10 fuel and its mixture with FAME biodiesel fuel; RM—RMG500 fuel; DM—DMA10 fuel; 1, 2, 3—mixture of RMG500 fuel (or DMA10) and 10%, 20%, and 30% FAME fuel, respectively. Authors.

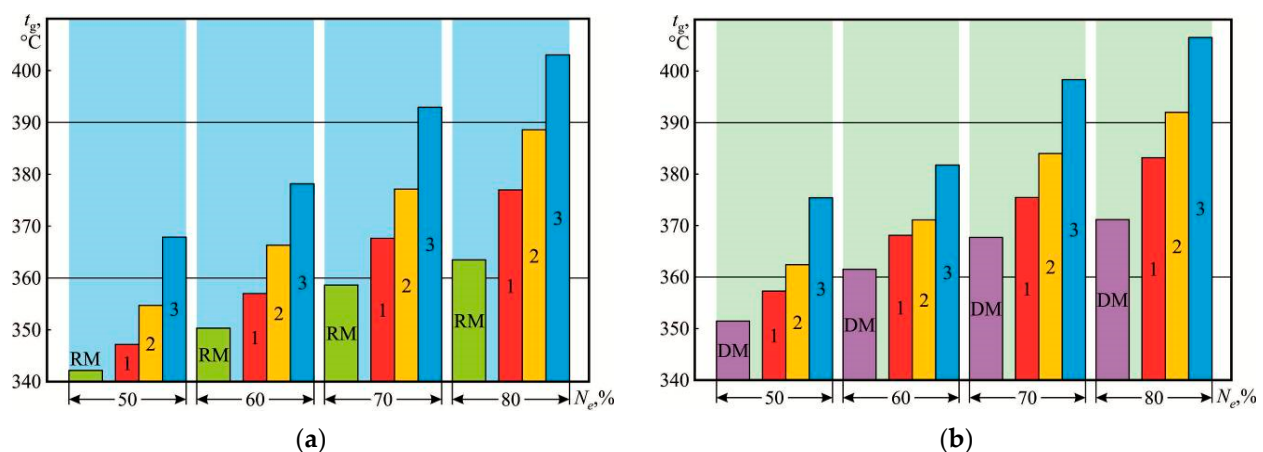


Figure 7. Average temperature of gases at the outlet of the cylinders during different operating conditions of marine diesel engines Wartsila 6L32: (a) when using RMG500 fuel and its mixture with FAME biodiesel fuel; (b) when using DMA10 fuel and its mixture with FAME biodiesel fuel; RM—RMG500 fuel; DM—DMA10 fuel; 1, 2, 3—mixture of RMG500 fuel (or DMA10) and 10%, 20%, and 30% FAME fuel, respectively. Authors.

The use of fuel mixtures containing petroleum-based fuel RMG500 or DMA10 and FAME biodiesel fuel leads to an increase in specific fuel consumption. This increase can be estimated by the relative value Δb_e :

$$\Delta b_e = \frac{b_e^{\text{FAME}} - b_e^{\text{RMG}}}{b_e^{\text{RMG}}} \cdot 100\%, \text{ and } \Delta b_e = \frac{b_e^{\text{FAME}} - b_e^{\text{DMA}}}{b_e^{\text{DMA}}} \cdot 100\%; \quad (8)$$

where b_e^{RMG} , b_e^{DMA} , b_e^{FAME} —the specific fuel consumption when using RMG500 or DMA10 petroleum fuel, as well as their mixtures with FAME biodiesel fuel with the appropriate concentration, g/(kW·h).

The environmental efficiency of using biodiesel fuel in comparison with petroleum fuel should be determined by its relative value:

$$\Delta \text{NO}_x = \frac{\text{NO}_x^{\text{RMG}} - \text{NO}_x^{\text{FAME}}}{\text{NO}_x^{\text{RMG}}} \cdot 100\%, \text{ and } \Delta \text{NO}_x = \frac{\text{NO}_x^{\text{DMA}} - \text{NO}_x^{\text{FAME}}}{\text{NO}_x^{\text{DMA}}} \cdot 100\%; \quad (9)$$

$$\Delta \text{CO}_2 = \frac{\text{CO}_2^{\text{RMG}} - \text{CO}_2^{\text{FAME}}}{\text{CO}_2^{\text{RMG}}} \cdot 100\%, \text{ and } \Delta \text{CO}_2 = \frac{\text{CO}_2^{\text{DMA}} - \text{CO}_2^{\text{FAME}}}{\text{CO}_2^{\text{DMA}}} \cdot 100\%; \quad (10)$$

where NO_x^{RMG} , NO_x^{DMA} , $\text{NO}_x^{\text{FAME}}$ —emission of nitrogen oxides when using fuels of petroleum origin RMG500 or DMA10, as well as their mixtures with FAME biodiesel fuel with the corresponding concentration, g/(kW·h);

CO_2^{RMG} , CO_2^{DMA} , $\text{CO}_2^{\text{FAME}}$ —emission of carbon dioxide when using fuels of petroleum origin RMG500 or DMA10, as well as their mixtures with FAME biodiesel fuel with the corresponding concentration, %.

The increase in the average temperature of gases at the outlet of the cylinders can be estimated by absolute

$$\Delta t_g = t_g^{\text{FAME}} - t_g^{\text{RMG}}, \text{ and } \Delta t_g = t_g^{\text{FAME}} - t_g^{\text{DMA}}, \quad (11)$$

or relative deviation

$$\Delta t_g = \frac{t_g^{\text{FAME}} - t_g^{\text{RMG}}}{t_g^{\text{RMG}}} \cdot 100\%, \text{ and } \Delta t_g = \frac{t_g^{\text{FAME}} - t_g^{\text{DMA}}}{t_g^{\text{DMA}}} \cdot 100\%, \quad (12)$$

The values obtained from expressions (8)–(12) are summarized in the form of Tables 12–19.

Table 12. Relative increase in specific fuel consumption, Δb_e , %, during different operating conditions of Wartsila 6L32 marine diesel engines (for fuels RMG500 and FAME). Authors.

Load, %	Type of Fuel		
	RMG500 (90%) + FAME (10%)	RMG500 (80%) + FAME (20%)	RMG500 (70%) + FAME (30%)
50	2.46	5.91	7.39
60	2.02	3.54	5.56
70	1.03	2.05	3.59
80	1.56	2.60	4.17

For better visualization, the results given in Tables 12–19 are presented in the form of Figures 8–11.

At the same time, for the Wartsila 6L32 diesel engine, the emission reductions in nitrogen oxides NO_x are as follows:

- For a 50% load from a value of 6.82 g/(kW·h), which corresponds to operations on fuel of oil origin RMG500 to values of 5.43 g/(kW·h), 5.63 g/(kW·h), and 5.81 g/(kW·h), which correspond to fuel mixtures containing 10%, 20%, and 30% FAME biodiesel, respectively; in relative values, this is 14.81%, 17.45%, and 20.38%;
- For a 60% load from a value of 7.12 g/(kW·h), which corresponds to operations on oil-based fuel RMG500 to values of 5.93 g/(kW·h), 5.75 g/(kW·h), and 5.53 g/(kW·h), which correspond to fuel mixtures containing 10%, 20%, and 30% FAME biodiesel, respectively; in relative values, this is 16.71%, 19.24%, and 22.33%;
- For a 70% load from a value of 7.62 g/(kW·h), which corresponds to operations on RMG500 petroleum fuel to values of 6.12 g/(kW·h), 5.93 g/(kW·h), and 5.73 g/(kW·h), which correspond to fuel mixtures containing 10%, 20% and 30% FAME biodiesel, respectively; in relative values, this is 19.69%, 22.18% and 24.80%;
- For an 80% load from the value of 7.97 g/(kW·h), which corresponds to operations on oil-based fuel RMG500 to the values of 6.18 g/(kW·h), 6.01 g/(kW·h), and 5.81 g/(kW·h), which correspond to fuel mixtures containing 10%, 20%, and 30% FAME biodiesel, respectively; in relative values, this is 22.46%, 24.59% and 27.10%.

Table 13. Relative reduction in nitrogen oxide emissions, ΔNO_x , %, during different operating conditions of Wartsila 6L32 marine diesel engines (for fuels RMG500 and FAME). Authors.

Load, %	Type of Fuel		
	RMG500 (90%) + FAME (10%)	RMG500 (80%) + FAME (20%)	RMG500 (70%) + FAME (30%)
50	14.81	17.45	20.38
60	16.71	19.24	22.33
70	19.69	22.18	24.80
80	22.46	24.59	27.10

Table 14. Relative reduction in carbon dioxide emissions, ΔCO_2 , %, during different operating conditions of Wartsila 6L32 marine diesel engines (for fuels RMG500 and FAME). Authors.

Load, %	Type of Fuel		
	RMG500 (90%) + FAME (10%)	RMG500 (80%) + FAME (20%)	RMG500 (70%) + FAME (30%)
50	5.47	9.65	14.63
60	6.22	11.04	16.02
70	7.82	14.45	19.47
80	11.08	18.84	23.55

Table 15. Relative increase in average temperature of gases at the outlet of cylinders, Δt_g , °C/%, during different operating conditions of Wartsila 6L32 marine diesel engines (for fuels RMG500 and FAME). Authors.

Load, %	Type of Fuel		
	RMG500 (90%) + FAME (10%)	RMG500 (80%) + FAME (20%)	RMG500 (70%) + FAME (30%)
50	5/1.46	13/3.79	25/7.29
60	6/1.70	15/4.26	27/7.67
70	7/2.51	19/5.29	33/9.19
80	13/3.58	25/6.89	40/11.00

Table 16. Relative increase in specific fuel consumption, Δb_e , %, during different operating conditions of Wartsila 6L32 marine diesel engines (for fuels DMA10 and FAME). Authors.

Load, %	Type of Fuel		
	DMA10 (90%) + FAME (10%)	DMA10 (80%) + FAME (20%)	DMA10 (70%) + FAME (30%)
50	2.03	4.06	6.60
60	1.58	2.63	4.21
70	0.53	1.60	3.19
80	0.54	1.08	2.69

Table 17. Relative reduction in nitrogen oxide emissions, ΔNO_x , %, during different operating conditions of Wartsila 6L32 marine diesel engines (for fuels DMA10 and FAME). Authors.

Load, %	Type of Fuel		
	DMA10 (90%) + FAME (10%)	DMA10 (80%) + FAME (20%)	DMA10 (70%) + FAME (30%)
50	11.20	14.71	17.71
60	11.93	15.58	18.47
70	15.36	17.70	20.52
80	16.42	20.64	22.01

Table 18. Relative reduction in carbon dioxide emissions, ΔCO_2 , %, during different operating conditions of Wartsila 6L32 marine diesel engines (for fuels DMA10 and FAME). Authors.

Load, %	Type of Fuel		
	DMA10 (90%) + FAME (10%)	DMA10 (80%) + FAME (20%)	DMA10 (70%) + FAME (30%)
50	5.31	8.85	13.27
60	5.97	10.81	14.22
70	6.69	12.99	16.06
80	8.18	14.58	18.80

Table 19. Relative increase in the average temperature of gases at the cylinder outlet, Δt_g , °C/%, during various operating conditions of Wartsila 6L32 marine diesel engines (for fuels DMA10 and FAME). Authors.

Load, %	Type of Fuel		
	DMA10 (90%) + FAME (10%)	DMA10 (80%) + FAME (20%)	DMA10 (70%) + FAME (30%)
50	4/1.42	11/3.13	22/6.27
60	6/1.66	10/2.77	21/5.82
70	9/2.45	18/4.90	23/8.72
80	12/3.23	21/5.66	36/9.70

When vessels are in ecological areas, the operation of marine diesel engines is possible only when using low-sulfur fuel, an example of which is distillate fuel DMA10. In comparison with DMA10 fuel, the relative emission reductions in nitrogen oxides (NO_x) when using fuel mixtures containing FAME biodiesel are as follows:

- For a 50% load—11.20%, 14.71%, and 17.71%, which correspond to 10%, 20%, and 30% of the FAME biodiesel content in the fuel mixture;

- For a 60% load—11.93%, 15.58%, and 18.47%, which correspond to 10%, 20%, and 30% of the FAME biodiesel content in the fuel mixture;
- For a 70% load—15.36%, 17.70%, and 20.52%, which correspond to 10%, 20%, and 30% of the FAME biodiesel content in the fuel mixture;
- For an 80% load—16.42%, 20.64%, and 22.01%, which correspond to 10%, 20%, and 30% of the FAME biodiesel content in the fuel mixture.
- The use of biodiesel also leads to CO₂ emission reductions, namely
- For a 50% load from a value of 6.22%, which corresponds to operations on RMG500 petroleum-based fuel to values of 5.88%, 5.62%, and 5.40%, which correspond to fuel mixtures containing 10%, 20%, and 30% FAME biodiesel, respectively; in relative values, this is 5.47%, 9.65%, and 14.63%;
- For a 60% load from a value of 6.43%, which corresponds to operations on RMG500 petroleum-based fuel to values of 6.03%, 5.72%, and 5.31%, which correspond to fuel mixtures containing 10%, 20%, and 30% FAME biodiesel, respectively; in relative values, this is 6.22%, 11.04% and 16.02%;
- For a 70% load from 6.78%, which corresponds to operations on RMG500 petroleum fuel to 6.25%, 5.80%, and 5.46%, which correspond to fuel blends containing 10%, 20%, and 30% FAME biodiesel, respectively; in relative values, this is 7.82%, 14.45% and 19.47%;
- For an 80% load from 7.22%, which corresponds to operations on RMG500 petroleum fuel to 6.42%, 5.86%, and 5.52%, which correspond to fuel blends containing 10%, 20%, and 30% FAME biodiesel, respectively; in relative values, this is 11.08%, 18.84%, and 23.55%.

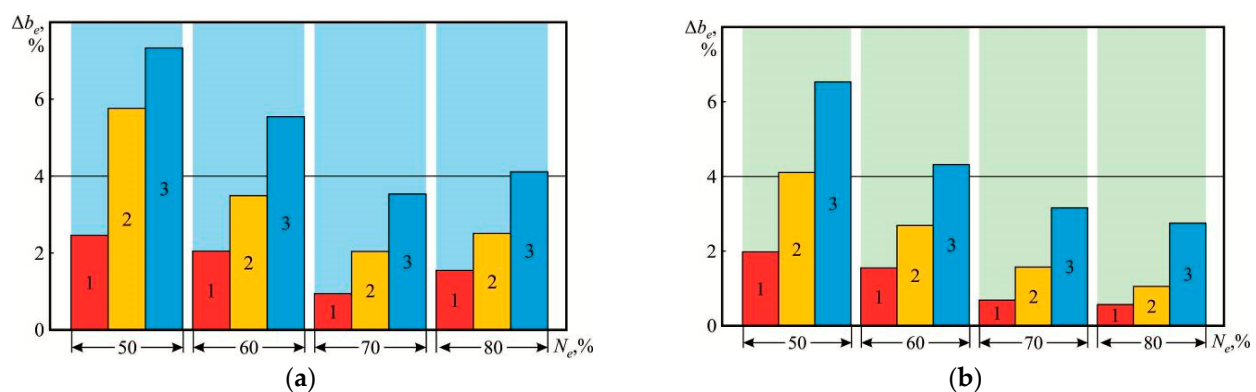


Figure 8. Relative increase in specific fuel consumption under different operating conditions of Wartsila 6L32 marine diesel engines: (a) when using a mixture of RMG500 fuel and FAME biodiesel; (b) when using a mixture of DMA10 fuel and FAME biodiesel; 1, 2, 3—mixture of RMG500 fuel (or DMA10) and 10%, 20%, and 30% FAME fuel, respectively. Authors.

When using fuel mixtures containing distillate fuel DMA10 and FAME biodiesel fuel, the relative emission reductions in carbon dioxide (CO₂) are as follows:

- For a 50% load—5.31%, 8.85%, and 13.27%, which corresponds to 10%, 20%, and 30% of the content of FAME biodiesel fuel in the fuel mixture;
- For a 60% load—5.97%, 10.81%, and 14.22%, which corresponds to 10%, 20%, and 30% of the content of FAME biodiesel fuel in the fuel mixture;
- For a 70% load—6.69%, 12.99%, and 16.06%, which corresponds to 10%, 20%, and 30% of the content of FAME biodiesel in the fuel mixture;
- For an 80% load—8.18%, 14.58%, and 18.80%, which corresponds to 10%, 20%, and 30% of the content of FAME biodiesel in the fuel mixture.

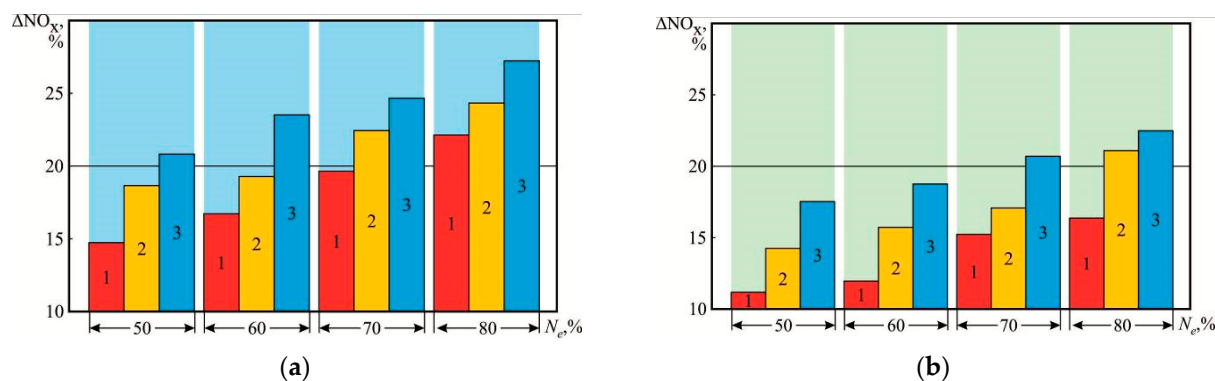


Figure 9. Relative reduction in nitrogen oxide emissions under different operating conditions of Wartsila 6L32 marine diesel engines: (a) when using a mixture of RMG500 fuel and FAME biodiesel; (b) when using a mixture of DMA10 fuel and FAME biodiesel; 1, 2, 3—mixture of RMG500 fuel (or DMA10) and 10%, 20%, and 30% FAME fuel, respectively. Authors.

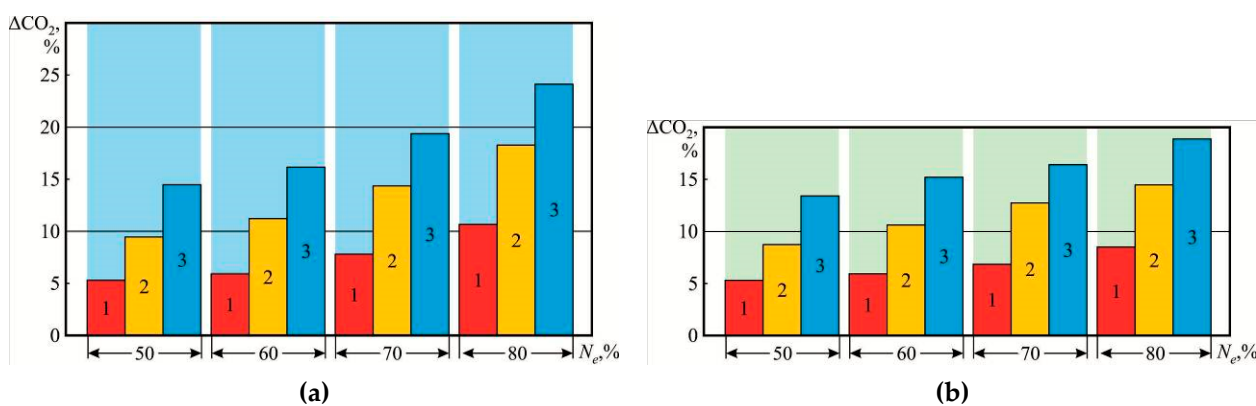


Figure 10. Relative reduction in carbon dioxide emissions under different operating conditions of Wartsila 6L32 marine diesel engines: (a) when using a mixture of RMG500 fuel and FAME biodiesel; (b) when using a mixture of DMA10 fuel and FAME biodiesel; 1, 2, 3—mixture of RMG500 fuel (or DMA10) and 10%, 20%, and 30% FAME fuel, respectively. Authors.

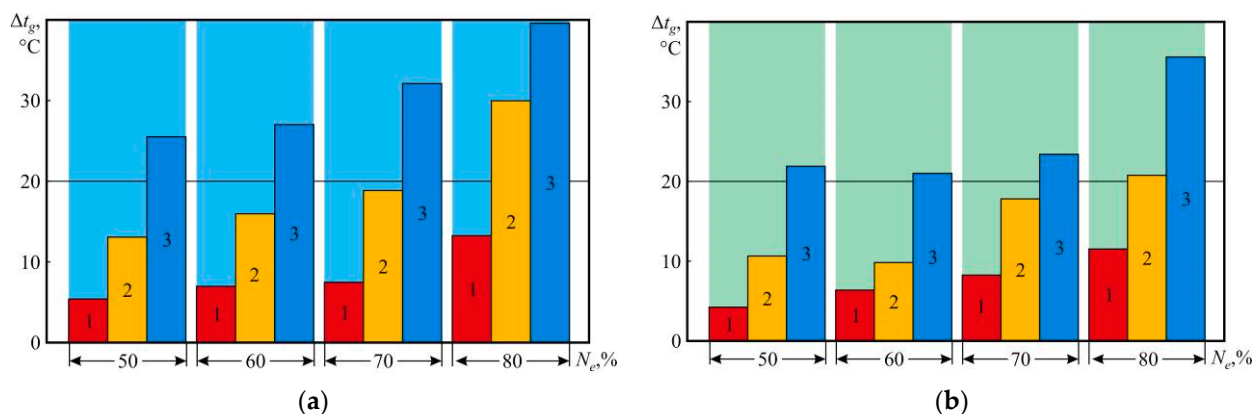


Figure 11. Relative increase in the average temperature of gases at the cylinder outlet during different operating conditions of Wartsila 6L32 marine diesel engines: (a) when using a mixture of RMG500 fuel and FAME biodiesel; (b) when using a mixture of DMA10 fuel and FAME biodiesel; 1, 2, 3—mixture of RMG500 fuel (or DMA10) and 10%, 20%, and 30% FAME fuel, respectively. Authors.

For a fuel blend consisting of RMG500 and FAME, there is an increase in specific fuel consumption:

- For a 50% load—2.46%, 5.91%, and 7.39%, corresponding to 10%, 20%, and 30% FAME biodiesel content in the fuel blend;

- For a 60% load—2.02%, 3.54%, and 5.56%, corresponding to 10%, 20%, and 30% FAME biodiesel content in the fuel blend;
- For a 70% load—1.03%, 2.05%, and 3.59%, corresponding to 10%, 20%, and 30% FAME biodiesel content in the fuel blend;
- For an 80% load—1.56%, 2.60%, and 4.17%, which corresponds to 10%, 20%, and 30% of the FAME biodiesel content in the fuel mixture.

For a fuel blend consisting of DMA10 and FAME fuels, there is an increase in specific fuel consumption:

- For a 50% load—2.03%, 4.06%, and 6.60%, corresponding to 10%, 20%, and 30% FAME biodiesel content in the fuel mixture;
- For a 60% load—1.58%, 2.63%, and 4.21%, corresponding to 10%, 20%, and 30% FAME biodiesel content in the fuel mixture;
- For a 70% load—0.53%, 1.60%, and 3.19%, corresponding to 10%, 20%, and 30% FAME biodiesel content in the fuel mixture;
- For an 80% load—0.546%, 1.08%, and 2.69%, which corresponds to 10%, 20%, and 30% of the FAME biodiesel content in the fuel mixture.

The research entailed the systematic monitoring and control of critical operational parameters of the Wartsila 6L32 auxiliary diesel engines and associated systems. The monitored parameters included cylinder pressures at compression and combustion, exhaust gas temperature, average indicator pressure and deviations, crankshaft speed, gas distribution phases, cooling water and lubricating oil pressures and temperatures, fuel temperature and viscosity, and the technical condition of the high-pressure fuel equipment.

5. Discussion

Ensuring green shipping requires reducing the environmental impact of ship power plants. First, this is manifested in emission reductions in toxic substances—carbon oxides (CO), and the release of SO_x, NO_x, and CO₂, each contributing to a decrease in energy efficiency. This can be achieved by using alternative fuels, one of which is a fuel of biological origin, FAME. Similar performance indicators for fuels of petroleum origin and fuels of biological origin (primarily viscosity and density) allow creating mixtures of these fuels directly in the fuel line, when they are directed to high-pressure fuel equipment.

During the research, a comprehensive assessment of biodiesel fuel impact on the environmental and economic performance of Wartsila 6L32 marine diesel engines was performed, with a simultaneous assessment of changes in their thermal loads. The use of fuel mixtures that include biodiesel fuel has a multifaceted effect on the performance of marine internal combustion engines. A clear advantage of using biodiesel fuel is its positive impact on the environmental friendliness of marine vessels and ensuring green shipping. At the same time, the use of biodiesel fuel reduces the efficiency of marine diesel engines and increases their temperature intense.

The most rational range of diesel concentration in its mixture with fuels of petroleum origin is 10–30%; it is at these concentration values that there is no significant decrease in the fuel mixture's energy content, as well as no alterations in its physical properties, specifically density and viscosity. Exceeding this range reduces its impact and the fuel mixture's calorific value and widens the density and viscosity differences between this and petroleum fuel.

The implementation of fuel blends, containing biologically derived fuels, in marine diesel engines, changes (in comparison with the baseline of petroleum diesel operation) the oxidation and combustion processes, causing a modification to the thermodynamic behavior during combustion. This becomes the basis for changing the environmental, economic, and temperature engine performance indicators. The change in environmental

indicators is demonstrated by a decline in the release of nitrogen oxides and carbon dioxide within the exhaust stream. This is due to the different (in comparison with petroleum fuel) structural and fractional composition of biodiesel fuel. At the same time, the CO₂ emission reduction is due to the lower carbon content in biodiesel fuel, while the NO_x emission reduction is due to the lower or complete absence of nitrogen in biodiesel fuel (which significantly reduces the formation of fuel nitrogen oxides during its combustion).

Improving the environmental performance of marine diesel engines is the main advantage of using bio-fuel. Specifically, these performance indicators contribute to green shipping. Unfortunately, when using biofuels in some operating modes of diesel engines, thermal loads increase. In this regard, one of the tasks that arises when using bio-fuel is to determine its rational concentration in a mixture with petroleum-based fuel. This task can be solved by conducting experimental studies for mixtures of different compositions at different diesel engine loads. This will ensure the operation of marine diesel engines with the best possible environmental performance and, at the same time, will stop temperature overload.

At the same time, the need to conduct experimental studies to determine the rational concentration of biofuel in the fuel mixture for each vessel and, accordingly, for each diesel engine complicates the possibility of using biofuel. At the same time, the possibility of implementing previous results on other diesel engines with similar designs and characteristics, as well as the possibility of improving these results and further developing the technology will contribute to the spread of biological origin fuel usage in order to ensure green shipping.

As biodiesel contains less energy per unit mass, the specific consumption of the fuel mixture of which it is a part increases. The outcome is a heightened level of temperature-related stress on the diesel engine, a phenomenon that is demonstrably seen in the increased temperatures of the gases exiting the cylinders.

Currently, the cost of biodiesel fuel is 7–10% higher than the cost of DM class petroleum-based fuel and 10–15% higher than the cost of RM class fuel. This certainly increases the cost of purchasing fuel, as well as the overall operating costs of the vessel [120]. Taking into consideration the constant changes in the price of fuel (both biodiesel and petroleum-based), as well as the different costs of fuel in different ports, it is not possible to calculate accurately the increase in costs in the case of using biodiesel fuel. In addition, when performing such a calculation, it is necessary to take into account that the maximum content of biodiesel fuel in its mixture with petroleum-based fuel does not exceed 30%. This helps to reduce costs in the case of using biodiesel fuel. The above-mentioned information allows us to state that the increase in costs in the case of using biodiesel fuel does not exceed 5–7%. It should be noted that the use of biodiesel fuel is one of the cheapest options for reducing nitrogen oxide emissions (for example, in comparison with Selective Catalytic Reduction and Exhaust Gas Recirculation systems). In addition, the use of biodiesel fuel reduces nitrogen dioxide emissions. This helps increase the energy efficiency of the vessel. It is also necessary to take into account that the constant increase in the production of biodiesel fuel will help reduce its cost.

The use of biodiesel fuel (as one of the types of alternative fuel) is possible in any diesel engine of any power—main or auxiliary, two-stroke or four-stroke. Similar studies were conducted on marine diesel engines, namely 5S60ME-C8 MAN-B&W Diesel Group and 6DL-16 Daihatsu [11]; 5DC-17A Daihatsu Diesel, 16V32 Wartsila-Sulzer, and Volvo Penta TWD1645GE [19]; 6N165LW Yanmar [91]; and 6H17/28 Hyundai Heavy Industries [97]. In this case, the results obtained were unidirectional and identical. There are also no restrictions on the class and characteristics of the vessel on which the use of biodiesel and petroleum fuel mixtures is possible.

The purpose of the study was to determine the impact of biodiesel on the environmental friendliness of shipping. In our opinion, we have achieved the goal. We conducted research to determine the impact of different concentrations of FAME biofuel on the emission of nitrogen oxides (NO_x) and carbon dioxide (CO_2) with exhaust gases. In addition, we took into account the possible deterioration in the efficiency of diesel engines (due to an increase in specific fuel consumption), as well as an increase in temperature stress (due to the increase in the temperature of the exhaust gases).

The conducted studies allowed us to determine the most rational composition of fuel mixtures of biological and petroleum origin. This also allows us to recommend operating modes of Wartsila 6L32 marine diesel engines that correspond to the greatest improvement in their environmental performance, while simultaneously minimizing the increase in specific fuel consumption and temperature load on diesel engine parts.

6. Conclusions

The use of petroleum fuels (diesel or distillate) while ship power plants are in service contributes to environmental pollution by harmful impurities that are part of exhaust gases and necessitates the search for ways to improve green shipping. Both this and the depletion of natural reserves of liquid hydrocarbons, which are the main primary materials in the manufacturing of petroleum-based fuels, contribute to the increasing operational use of biofuels in maritime shipping.

Studies carried out on medium-speed Wartsila 6L32 marine diesel engines have established the following:

1. Marine fuels of petroleum origin RMG500 and DMA10 form stable mixtures with FAME biodiesel; the supply fuel into the diesel cylinder is accomplished by high-pressure fuel equipment, a component of the overall diesel fuel system.
2. The development of fuel blends comprising petroleum-based and biologically derived fuels, with diverse concentrations of the biological component, facilitates progress towards ecological shipping.

For the load range of 50–80% on Wartsila 6L32 marine diesel engines and 10–30% concentrations of FAME biodiesel in its mixture with RMG500 fuel, the reduction in NO_x emissions is 14.81–27.10%. Under the same conditions, when using a mixture of FAME fuel and DMA10 fuel, the reduction in NO_x emissions is 11.20–22.01%.

The use of mixtures of biodiesel fuel and petroleum-based fuels also reduces CO_2 emissions. At the same time, for a mixture of FAME fuel and RMG500 fuel, this reduction is in the range of 5.40–23.55%; for a mixture of FAME fuel and RMG500 fuel, CO_2 emissions are reduced by 5.31–18.80%.

Additionally, it is important to mention the improvement of the environmental efficiency of the FAME heating system during the vessels operation in the ecological areas of SECAs. The intensification of maritime cargo transportation between European countries, as well as cargo operations in the sea and river ports of these countries, promotes the relevance of reducing cash flows. In this case, nitrogen oxides (NO_x) and carbon dioxide (CO_2) are bound to be the main indicators that characterize green shipping and sustainable maritime transportation.

3. The use of fuel mixtures that include FAME biodiesel in comparison with the operation of diesel engines on petroleum-based fuels RMG500 or DMA10 leads to an increase in specific fuel consumption.

When changing the load on Wartsila 6L32 marine diesel engines in the range of 50–80% and 10–30% FAME fuel content in the mixture with RMG500 fuel, the specific fuel consumption increases by 1.03–7.39%. In case of using the FAME–DMA10 mixture under the same conditions, the specific fuel consumption increases by 0.53–6.60%.

The above refers to the negative consequences of using biodiesel fuel in marine diesel engines.

The largest increase in fuel consumption is for burning sums, which contain 30% of biodiesel burning fuel. This should lead to a proportional increase in operating costs for the addition of biodiesel fuel. Therefore, from the perspective of the consumption of fuel and fuel mixtures, instead of biodiesel fuel, in which the amount is 10–20%, this is a rational approach.

4. Another negative factor in using fuel mixtures containing biodiesel is the increase in the temperature load on the cylinder group and the exhaust system of diesel engines. This is reflected in the increase in the temperature of the gases at the outlet of the cylinders, which in some operating modes (namely when using fuel mixtures with the maximum possible biodiesel content) can reach 22–36 °C.

5. The use of alternative fuels in marine diesel engines (one of which is biodiesel and fuel blends containing it) is one of the ways to increase the level of environmental sustainability of seagoing vessels and promote green shipping. This becomes particularly relevant during the operation of vessels in special ecological areas of the World Ocean. The relatively low energy intensity of the method of creating and using such fuel blends contributes to the adoption of its use in many means of maritime transport.

During the study, unambiguous results were obtained, which, on the one hand, coincide with similar studies by other authors and, on the other hand, are distinguished by their novelty. This opens up prospects for further development and allows us to recommend the obtained results for ensuring green shipping.

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