Renewable Energy 224 (2024) 120221

Contents lists available at ScienceDirect

Renewable Energy

journal homepage: www.elsevier.com/locate/renene

Use of biofuels in marine diesel engines for sustainable and safe maritime transport

Sergii V. Sagin [a], Sergii S. Sagin [b], Oleksij Fomin [c], Oleksandr Gaichenia [b], Yurii Zablotskyi [a], Václav Píštěk [d], Pavel Kučera [d,*]

[a] Department of Ship's Power Plants, National University Odessa Maritime Academy, Didrikhson Str., 8, 65029, Odessa, Ukraine
[b] Department of Navigation, National University Odessa Maritime Academy, Didrikhson Str., 8, 65029, Odessa, Ukraine
[c] Department of Cars and Carriage Facilities, State University of Infrastructure and Technologies, Kyrylivska Street, 9, 04071, Kyiv, Ukraine
[d] Institute of Automotive Engineering, Brno University of Technology, Technická 2896/2, 616-69, Brno, Czech Republic

ARTICLE INFO

Keywords:
Biofuels
Carbon oxide emission
Greenhouse gas emissions
Environmental friendliness of ships
Sustainability and safety of maritime transportation managing
Sulphur dioxide reduction

ABSTRACT

The article presents results of research on the use of fuel mixtures, containing with biodiesel fuel. The research was carried out on specialized sea vessels with a deadweight of 10,820 tons and 29,420 tons, which made passages in the waters of South America and the Caribbean, as well as in the Sulphur Emission Control Areas of Northern Europe. The operation of the ship's power plants (main and auxiliary engines) was provided both on marine fuel of petroleum origin and on a fuel mixture that consisted of petroleum fuel and biodiesel fuel. The experiments were carried out on marine medium-speed diesel engines 5DC-17A Daihatsu Diesel, 16V32 Wärtsilä-Sulzer and Volvo Penta TWD1645GE. Various kinds of marine fuels and as biodiesel fuel Fatty Acid Methyl Esters B99.9 FAME and B99.6 FAME were used. The concentration of biodiesel fuel in the fuel mixture was 5–20 %. The environmental friendliness of the work of sea vessels was assessed by the value of the emission of nitrogen oxides, sulphur, and carbon. As a result of the research, a variant of adjusting the sea crossing was proposed to ensure the continuous operation of the ship's power plant using biodiesel fuel.

1. Introduction

Maritime transport has dominated world trade for more than a century. Transportation of goods and passengers by sea and ocean routes is a component of the economy of all countries that have access to the sea. The volumes of maritime transport significantly exceed those for air, rail, and road transport [1,2]. Modern container ships can transport up to 24,000 TEU, oil tankers – up to 650,000 tons of liquid petroleum products, bulk carriers – up to 400,000 tons of bulk cargo, cruise ships – provide recreation and carry up to 8000 passengers. Ensuring such transportation is impossible without maintaining their stability and safety.

Sea and inland water transport consume a large amount of fuel during the transportation of goods and passengers. The most economical of the heat engines installed on sea and river vessels are diesels. In comparison with gas turbines and steam boilers, marine diesels are characterized by the lowest specific fuel consumption (for modern models, its value does not exceed 175 … 180 g/(kWh) for two-stroke diesel engines and 190 … 195 g/(kWh) for four-stroke) [3,4]. The most common type of marine fuel is liquid fuel of petroleum origin. The use of gaseous fuel, as well as its mixtures with liquid fuel, is widespread only on specialized ships of the LNG and LPG classes, on which this fuel is transported as cargo [5,6]. At the same time, as a rule, its use is possible only during the "cargo" transition. After unloading the ship and during its return to ballast, diesel engines are operated on liquid fuel [7,8].

The operation of marine diesel engines is accompanied by inevitable pollution of the environment with exhaust gases, which include toxic components – oxides of sulphur, nitrogen, and carbon [9,10]. Sulphur and nitrogen oxides later condense in the air and turn into acids that return to the surface of the world ocean, island, or mainland part of the Earth. Carbon oxides remain in the atmosphere and destroy the ozone layer, as well as reduce the energy efficiency of the ship [11,12]. This prompts us to strengthen the requirements for the environmental indicators of the operation of energy installations of sea and inland water transport vessels, namely:

* Corresponding author.
E-mail addresses: saginsergii@gmail.com (S.V. Sagin), sergeysagin20@gmail.com (S.S. Sagin), fomin_ov@gsuite.duit.edu.ua (O. Fomin), gaichenia@gmail.com (O. Gaichenia), yurzpost1966@gmail.com (Y. Zablotskyi), pistek.v@fme.vutbr.cz (V. Píštěk), kucera@fme.vutbr.cz (P. Kučera).

https://doi.org/10.1016/j.renene.2024.120221
Received 18 September 2023; Received in revised form 13 January 2024; Accepted 25 February 2024
Available online 26 February 2024
0960-1481/

- expand special zones for controlling emissions of sulphur oxides with exhaust gases – Sulphur Emission Control Areas [13,14].
- to regulate the concentration level of nitrogen oxides in exhaust gases [15,16].
- limit emissions of carbon oxides [17,18].

To the features of operation diesel of marine and inland water transport vessels, their periodic (depending on the transport task being performed) work in special ecological areas to control emissions of sulphur oxides – Sulphur Emission Control Areas (SO_x-ECAs) and nitrogen oxides – Nitrogen Emission Control Areas (NO_x-NECAs). Diesel operation in such areas is possible only on fuel with a sulphur content of no more than 0.1 % by mass (Fig. 1). Emissions of nitrogen oxides NOx in these zones must meet the requirements Annex VI MARPOL (Fig. 2). The maximum value of the emission of sulphur oxides should not exceed the ratio of sulphur dioxide SO_2 to carbon dioxide CO_2 (Table 1), while the use of fuel with a sulphur content exceeding 0.5 % is possible only in the case of the application of additional technologies for cleaning exhaust gases from sulphur impurities.

Sulphur, which is part of the liquid fuel, during burning in a diesel cylinder, not only releases the thermal energy, but also forms sulphur oxides SO_2 and SO_3. Subsequently, these oxides react with water (which is in the air) and form sulphurous H_2SO_3 and sulfuric H_2SO_4 acids. These acids return to the water and continental surface in the form of acid rain and adversely affected on the environment [19,20]. Particularly relevant are the issues of reducing the emission of sulphur oxides SO_x in the northern regions, which are characterized by high humidity. Exactly these areas are classified as special sulphur emission control areas (Fig. 1).

The problem of ensuring the environmental friendliness of marine internal combustion engines (in particular, in terms of emissions of nitrogen oxides) has become particularly acute for four-stroke diesel engines due to the use of heavy and medium-heavy motor fuels [21,22]. The shortened (compared to two-stroke diesel) cycle time of these diesels leads to nitrogen oxidation in the exhaust manifold (at low temperatures). This shifts the mechanism of formation of nitrogen oxides from rapid to thermal, which contributes to an increase in their total number in exhaust gases. This makes it necessary to constantly monitor the content of nitrogen oxides in exhaust gases, especially when ships are in special ecological zones or in coastal water areas [23,24].

Nitrogen, which is the part of liquid fuels and part of air, is converted during combustion into nitrous oxide N_2O, monoxide NO and nitrogen dioxide NO_2. Subsequently, NO and nitrogen dioxide NO_2 are converted into nitric acid HNO_3, which (like sulphurous H_2SO_3 and sulfuric H_2SO_4 acids) is returned to in the form of acid rain [25,26]. Nitrous oxide N_2O is a greenhouse gas and contributes to global warming (Fig. 3). At the same time, the global warming potential of nitrous oxide N_2O is 300 times greater than that of carbon dioxide CO_2.

Carbon dioxide CO_2 is a greenhouse gas and contributes to the intensity of global warming. To control and manage CO_2 emissions, the International Maritime Organization requires all shipping companies to develop an Energy Efficiency Management Plan for each ship, as well as to monitor and provide data on ship fuel consumption [27,28].

Considering with above, the purpose of the research was, to determine the method of managing the sustainability and safety of maritime transportation, which would ensure the reliable operation of the ship power plant and improve the environmental friendliness of its operation (in particular, would help reduce the emission of nitrogen, sulphur, and carbon oxides).

2. Literature review

Ensuring of the Sustainable and Safe Maritime Transportation is impossible without maintaining the environmental performance of marine diesel engines.

One of the methods for controlling the emission of sulphur oxides SO_x is the use of fuel with low (0.1 % by mass) and ultra-low sulphur content (at the level of 0.03–0.08 % by mass). At the same time, such fuels have a lower (compared to fuel with a sulphur content of 0.5 %) viscosity. This leads to an increase of fuel leakage, during its movement in the high-pressure fuel system [29,30]. Reduces the cyclic fuel supply and reduces the effective power of the diesel engine. An additional method for controlling sulphur oxide emissions is fuel desulfurization using ultrasonic treatment [31,32], use of fuel additives [33,34] and cleaning of exhaust gases in scrubbers [35,36].

Management of NO_x emissions is achieved by reducing the temperature peaks in the diesel cylinder. At the same time, provided conditions, under which the maximum temperature in the diesel cylinder does not exceed 1500°C (the critical temperature at which occurs the chain reaction formation of nitrogen oxide). The main control methods, that are used in this case, are the injection of water into the cylinder or air receiver of the diesel engine, the recirculation of gases, also their bypass [37,38]. In addition, it is possible to change the design of the high-pressure fuel equipment and change the fuel supply phases [39,40].

Management of carbon dioxide emissions CO_2 (which, like nitrogen oxides, increases the greenhouse effect) is only possible by using fuels that contain less carbon [41,42]. However, in this case (because carbon

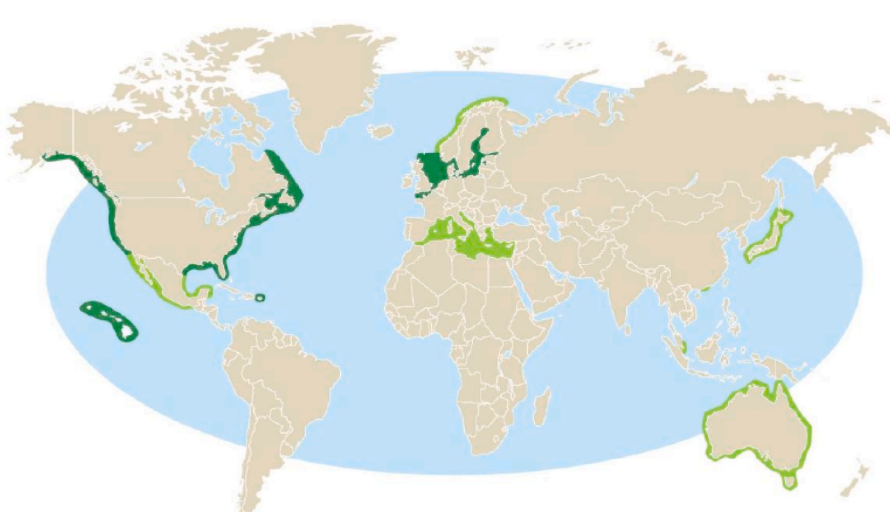

Fig. 1. Special areas for monitoring the emission of sulphur oxides SO_x.

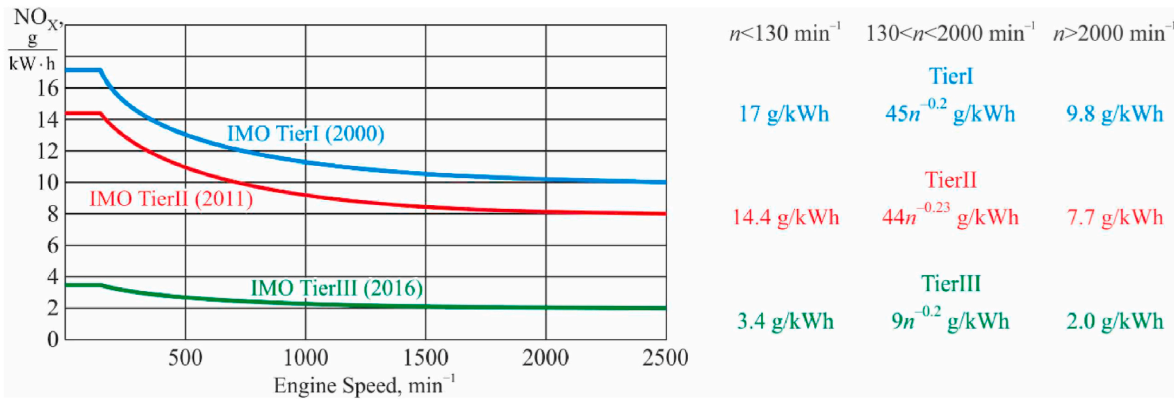

Fig. 2. Requirements of Annex VI MARPOL for emissions of nitrogen oxides NO_x.

Table 1
Classification of control systems.

Sulphur content in fuel, mass %	Emission ratio SO2/CO2, ppm/volume %
3.50	151.7
1.50	65.0
1.00	43.3
0.50	21.7
0.10	4.3

is the main energy component of liquid fuel), the calorific value of the fuel decreases [43,44].

The above is one of the reasons for the use of alternative fuels of non-petroleum origin in ship power generation, which contribute to the reduction of harmful components of exhaust gases and increase the environmental friendliness of the work of ship diesel engines [45,46]. One of the types of alternative fuel is fuel of biological origin, which is obtained from vegetable fats and oils by esterification with methanol or ethanol [47,48].

This method of managing the environmental safety of maritime transport vessels, has been actively used over the past five years [49,50]. However, systemic application on marine vessels, does not currently exist. Recommendations for its use are based on operational results and consider only certain types of biofuels.

According to the European standard EN 14214 “Fuel for internal combustion engines. Methyl esters of fatty acids", such fuels are designated as FAME – Fatty Acid Methyl Ester and are recommended for use in diesel engines installed on road and rail transport, as well as diesel engines of power plants [51,52]. The limitation of the distribution of biodiesel fuel in ship power plants is associated with a relatively short period of its storage (which makes it necessary to reduce the volumes of its bunkering and becomes the basis for the impossibility of its use during long ocean crossings) and the absence of this fuel in some seaports (which are located outside the areas of its production or storage). Another disadvantage of biodiesel fuel is its reduced (compared to petroleum fuel) calorific value, which does not exceed 37000–37500 kJ/kg. This does not allow the use of biodiesel fuel as a separate source of energy and necessitates the production of fuel mixtures, some of which (70–90 %) consists of petroleum (ship motor) fuel, the rest - biodiesel. Considering the correspondence of the specific mass of biodiesel and marine motor fuel, the use of such mixtures ensures the gradual introduction of biodiesel fuel in marine power plants during the operation of marine diesel engines. The absolute advantage of using mixtures of biodiesel and marine motor fuel is the improvement of the

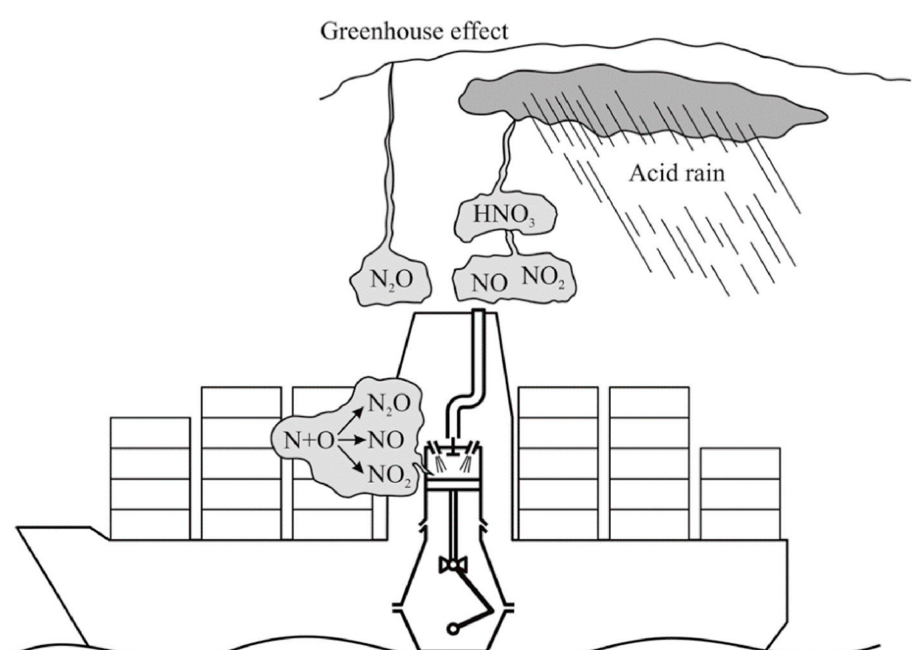

Fig. 3. Impact of nitrogen oxides on the environment.

environmental indicators of the operation of marine diesels, which is manifested in a significant decrease in the concentration of sulphur, nitrogen, and carbon oxides in the exhaust gases [53–55].

3. Materials and methods

The main source of energy for diesel there is fuel of petroleum origin. According to the data of the transnational company British Petroleum (which carried out an analysis of the annual volumes of fuel consumption and production), oil reserves in the already existing and developing deposits of the world's energy industry will be enough for the next 40 … 45 years. This, as well as modern environmental requirements to diesel road, rail and sea transport, force to develop alternative energy and develop alternative fuels [5,16,52]. One of the characteristics of alternative fuels, which favour their use in heat engines, is the minimal amount or complete absence of sulphur and nitrogen. At the same time, during their combustion, the amount of sulphur oxides SO_x and fuel nitrogen oxides NO_x in the exhaust gases decreases.

For diesel of marine and inland water transport vessels, biodiesel fuel based on methyl esters of fatty acids was most widely used as an alternative fuel (Fatty Acid Methyl Esters – FAME) and fuel based on hydrogenated vegetable oils (Hydrogenated Vegetable Oil – HVO). The specific gravity of these fuels is like the specific gravity of petroleum fuels, this allows mixing FAME and HVO in an unlimited ratio with petroleum diesel fuel without changing the density and viscosity of the fuel mixture obtained in this way [20,47,51].

One of the tasks that must be solved when using biodiesel fuel is to determine its volume during bunkering of the ship. At the same time, it is necessary to consider the shelf life of biofuel, its consumption, and the possibility of replenishing stocks. The design of the ship's fuel systems does not provide for the transportation and storage of biofuel in fuel storage tanks, settling or waste tanks. These capacities are designed and calculated for marine engine fuel (diesel or heavy). Therefore, the supply of biofuel during bunkering is carried out in a barrel with a volume of up to 200 L. Their preservation is carried out on the open decks of the ship (which is impossible for some types of ships) and directly in the engine compartment of the ship (which significantly reduces the amount of biofuel). This requires constant replenishment of biofuel reserves, while the period of obtaining biofuel (in the case of its constant use in marine diesel engines) is shorter than the period of obtaining motor fuel. An important factor when obtaining biofuels is the need to return an empty keg after its use (i.e., reducing biofuel stocks does not reduce the volume of ship space occupied by this fuel). When determining the required volume of biofuel, it is also necessary to consider its optimal concentration in the fuel mixture with petroleum fuel. Due to the limited amount of biofuel that can be obtained and stored on board the ship, the fuel mixtures that include it are used in the ship's auxiliary diesel engines, which (compared to the main ones, due to their lower power, have a lower hourly/daily or trip fuel consumption) [56–58].

The world leaders in the production of biofuel are Brazil (in South America, the USA (in North America), Germany in the EU countries, Indonesia in the Asian and Pacific basins. However, not every seaport has the possibility of receiving biofuel – with the aim of its further use in This leads to only periodic use of biofuels during the operation of diesel engines and a decrease in their environmental sustainability [59,60].

The research was carried out on various sea vessels that made passages in the waters of South America and the Caribbean Sea, as well as in the Sulphur Emission Control Areas of Northern Europe. The operation of the ship's power plants (main and auxiliary engines) was provided both on marine fuel of petroleum origin and on a fuel mixture that consisted of petroleum fuel and biodiesel fuel. The main characteristics of marine fuel and biodiesel fuel, that were used in the experiment are shown in Table 2.

The main characteristics of marine diesel engines, on which the experiments were performed, are given in Table 3.

The diesel fuel system allowed the use of fuel mixtures, which included up to 20 % of biodiesel fuel. This was also facilitated by the identical density and viscosity values of marine diesel fuel and biodiesel fuel.

Table 2
Main characteristics of marine fuel and biodiesel fuel.

Characteristic	Marine fuel				Biodiesel fuel	
	DMA10	RMB30	RMG420	RME180	B99.9 FAME	B99.6 FAME
Density at 15°C, kg/m^3	892	912	922	916	870	882
Viscosity at 40°C, cSt	6.5	30	36	34	20	23
Sulphur content, %	0.08	0.36	0.5	0.26	0.03	0.06

Table 3
Main characteristics of marine diesel engines.

Characteristic	5DC-17A Daihatsu Diesel	16V32 Wärtsilä-Sulzer	Volvo Penta TWD1645GE
Speed, n, min^{-1}	1000	750	1200
Effective power at nominal operating mode, N_{enom}, kW	490	5760	595
Specific effective fuel oil consumption in the range of operating loads (0.6–0.95) N_{enom}, kg/(kW h)	0.194–0.186	0.192–0.183	0.198–0.192
Number of diesel engines in the ship's power plant	3	2	3

During the experiments, the power and speed of diesel engines were controlled, as well as their environmental performance: emission of nitrogen oxides NO_x, emission of sulphur oxides SO_x (as a ratio of SO_2/CO_2), emission of carbon dioxide CO_2.

4. Results

The task of the comprehensive research was:

1. correction of the passage between different ports, considering the provision of bunkering of the vessel with biofuel and further ensuring the operation of marine diesel engines on a mixture of motor fuel and biofuel
2. determination of the optimal concentration of biofuel, in its mixture with diesel fuel, which ensures the maximum reduction in the emission of sulphur oxides, nitrogen and carbon.

The first research cycle was carried out on a 10,820 tons deadweight General Cargo vessel between the ports of Brazil and the Caribbean. The experiments were carried out on marine medium-speed diesel engines 5DC-17A Daihatsu Diesel, which were part of the ship's auxiliary power plant on a mixture of motor fuel and biofuel (this, in turn, will contribute to increasing the environmental friendliness of diesel operation due to a decrease in the emission of nitrogen oxides).

Schematic diagram of the expendable fuel system of marine diesel engines 5DC-17A Daihatsu Diesel, considering the possibility of producing and using a fuel mixture that includes biofuel and marine motor fuel, given in Fig. 4.

The fuel system worked as follows (see Fig. 5). The presence of different groups of tanks 1 and 4 made it possible to use different types of fuel. Diesel engines were operated on diesel (light) fuel DMA10 (with a sulphur content of 0.08 %) or medium-heavy fuel RMB30 (with a sulphur content of 0.36 %), the characteristics of which ensured the

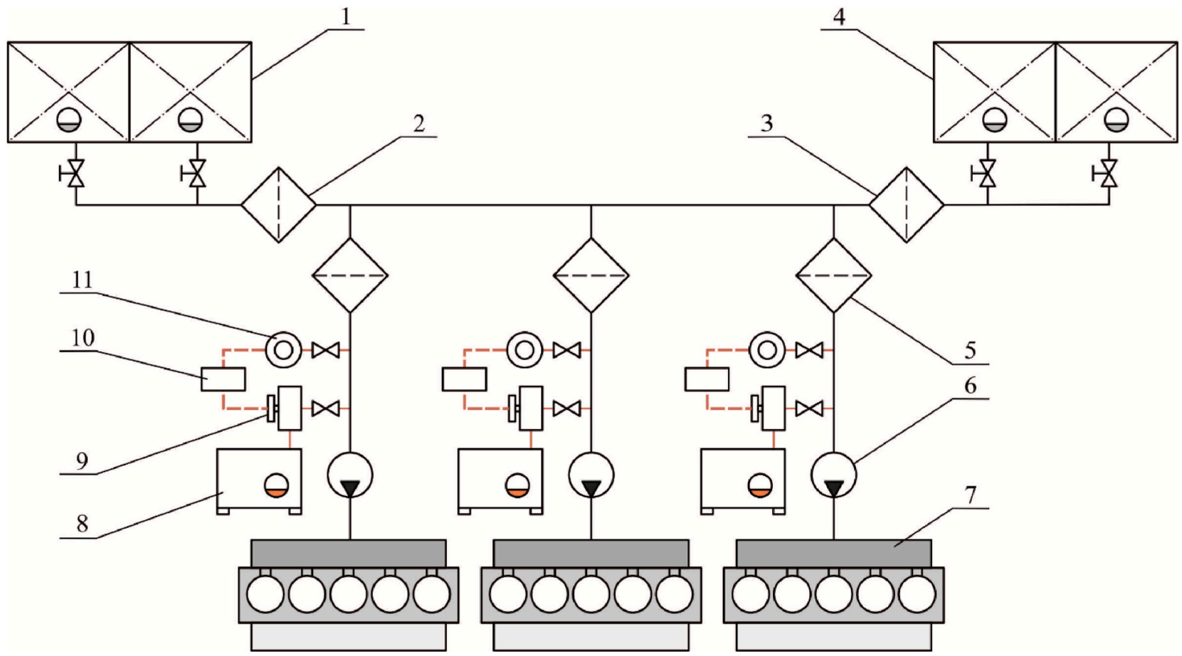

Fig. 4. Schematic diagram of the fuel system of marine diesel engines 5DC-17A Daihatsu Diesel: 1 – expendable tank of diesel (light) fuel DMA10; 2, 3 – coarse cleaning fuel filter; 4 – expendable tank of medium heavy fuel RMB30; 5 – fine cleaning fuel filter; 6 – fuel pump; 7 – diesel; 8 – biofuel tank; 9 – dispenser; 10 – microcontroller; 11 – flow meter.

Fig. 5. The navigation passage Sao Paulo – Havana – Sao Paulo.

high-quality formation of their mixtures with biofuel [61,62]. The use of these fuels met the requirements of Annex VI of MARPOL, according to which the sulphur content in marine fuel should not exceed 0.5 %. From waste tanks 1 or 3 (depending on the operating conditions of the diesel engine), DMA10 or RMB30 fuel through the coarse cleaning filter 2 or 3 entered the fuel pumps 6 and then went to the diesel engines 7. During the experiment, diesel engines operated either in parallel mode (in the case of using two or three diesel engines at the same time) or in individual mode. In the first case, the load on diesel engines was evenly distributed by the regulator. In the second, the operating time of the diesel engine at a given load was controlled, after which the remaining diesel engines exploited for the same period at the same load. Thus, the same operating time and the same load on all diesel engines were maintained. Additional fuel cleaning was provided using the fine cleaning filter 5, which was installed directly in front of the fuel pump 6. In the main line diesel engines were additionally equipped with a biofuel waste tank 8, a dispenser 9 and a flow meter 11 [63,64]. The dispenser 9 provided the supply of biofuel from the tank 8 to the suction line of the pump 6. The amount of biofuel supplied to the fuel line was regulated by the microcontroller 10 depending on the readings of the flow meter 11. B99.9 FAME fuel was used as biofuel. The necessary amount of biofuel in the fuel mixture was provided with the help of microcontroller 10.

The crossing was carried out along the route of Sao Paulo (Brazil) – Rio de Janeiro (Brazil) – Salvador (Brazil) – Fortaleza (Brazil) – Port of Spain (Trinidad and Tobago) – Puerto Cabello (Venezuela) – Kingston (Jamaica) – Havana (Cuba). The return passage from Havana to Sao Paulo was carried out in ballast.

During the transition, the total load on the Daihatsu Diesel 5DC-17A marine auxiliary diesels varied in the range of 350–750 kW, but the weighted average load was used for calculations, which was calculated as follows:

$$\overline{N_e^w} = 0,65 N_{e\mathrm{nom}} n_{\mathrm{AE}}^w, \tag{1}$$

where 0.65 is the accepted weighted average load factor during the operation of Daihatsu Diesel 5DC-17A marine diesels at the transition (which includes losses during the conversion of the calorific value of the fuel into useful energy [65,66]); n_{AE}^w – the number of auxiliary diesel engines that provided required energy needs of the ship, during the sea passage (for the running mode of operation it was accepted $n_{\mathrm{AE}}^w = 2$). Then: $\overline{N_e^w} = 0,65 \cdot 490 \cdot 2 = 637$ kW.

Biofuel consumption during the transition:

$$B_{\mathrm{BF}}^w = \overline{N_e^w} b_e^w C_{\mathrm{BF}} T_i^w, \tag{2}$$

where b_e^w – specific effective fuel consumption in running mode corresponding to the selected load, kg/(kW h); C_{BF} – concentration of biofuel in a fuel mixture with petroleum fuel; T_i^w – transit time of the vessel between ports, hours.

During the parking with cargo operations, the total load on the ship's auxiliary diesel engines 5DC-17A Daihatsu Diesel company varied in the range of 850–1200 kW, but the weighted average load was used for calculations,

$$\overline{N_e^c} = 0,75 N_{\text{enom}} n_{\text{AE}}^c, \tag{3}$$

where 0.75 – adopted weighted average load factor during operation of Daihatsu Diesel 5DC-17A marine diesels in the parking lot with cargo operations [67,68]; n_{AE}^c – the number of auxiliary diesel engines that provided the energy needs of the ship during parking with cargo operations (it was assumed $n_{\text{AE}}^c = 3$).

Then: $\overline{N_e^c} = 0,75 \cdot 490 \cdot 3 = 1103$ kW.

Biofuel consumption during parking with cargo operations:

$$B_{\text{BF}}^c = \overline{N_e^c} b_e^c C_{\text{BF}} T_i^c, \tag{4}$$

where b_e^c – specific effective fuel consumption during parking with cargo operations corresponding to the selected load, kg/(kWh); T_i^c – parking time with cargo operations, hours.

For the running mode of operation, considering the weighted average load factor, the value of specific effective fuel consumption was taken $b_e^w = 0.192\ kg/(kWh)$.

For the mode of parking with cargo operations, this indicator was accepted $b_e^c = 0.188\ kg/(kWh)$.

Determination of these indicators was carried out experimentally, by measuring fuel consumption and operating time of diesel engines in selected modes [69,70]. The error in measurements did not exceed 1.5 %. The indicated values coincide with the indicators specified in the diesel engine operating instructions.

The total consumption of biofuel, which is necessary to ensure the operation of marine auxiliary diesels 5DC-17A Daihatsu Diesel company during the transition between ports and during parking in one of the ports with cargo operations.

$$\Sigma B_{\text{BF}} = B_{\text{BF}}^w + B_{\text{BF}}^c, \tag{5}$$

The calculation of biofuel consumption values for different sea crossings and different operating conditions, according to equations (2), (4) and (5), as well as the values of the distance between ports and the time of transit between them and the time of parking in ports are given in Table 4.

Biofuel bunkering during transits (for the sailing area in question) is possible only in the following ports: Sao Paulo, Fortaleza, Puerto Cabello, Havana. Considering the structural features of the deck space, technical rooms, and engine room of the ship, they were able to accommodate 25,200-L barrels of biofuel. Thus, the volume of biofuel during bunkering did not exceed 5000 L. To ensure the operation of Daihatsu Diesel's 5DC-17A marine auxiliary diesel engines on a fuel mixture (which consists of marine motor fuel and biofuel) throughout the passage (including for the passage from Havana to Sao Paulo, which was carried out in ballast) and to maintain environmental indicators of their work, the scheme of the navigation transition was adjusted according to the Table 5.

The data given in the Table 5, testify to the possibility of providing the necessary reserves of biofuel at all sections of the navigation passage. Further production and use of fuel mixtures, which include biofuel, will contribute to increasing the environmental friendliness of the work of marine auxiliary diesel engines.

During the research, the main energy [30,71], thermal [63,72] and environmental [25,73] performance indicators of marine diesel engines 5DC-17A Daihatsu Diesel company were monitored throughout the entire navigation passage. Their value did not exceed critical values and met the requirements set forth by international classification societies and manufacturers of diesel engines and their auxiliary equipment. All performances were monitored and recorded using software for asset management on ships [67,74]. Current and final performance indicators of the vessel and its power plant were drawn up as reports and submitted to the technical management department of the company [70,75].

The second research cycle was carried out on a specialized ship with a deadweight of 29,420 tons during its operation in special ecological regions of Northern Europe. The functions of the main engine on the ship are performed by two of the same type of marine diesel engines 16V32 Wärtsilä-Sulzer.

Each of the main engines was operated on its own grade of fuel. Main engine No. 1 (ME No. 1) – on RMG420 fuel (with a sulphur content of 0.5 % by weight), main engine No. 2 (ME No. 2) – on RME180 fuel with a sulphur content of 0.26 % by weight). When the vessel was in the Sulphur Emission Control Areas, diesel engines run on a fuel mixture, that consisted of 80 % RMG420 fuel and 20 % FAME99.6 biodiesel for ME No. 1, as well as 80 % RME180 fuel and 20 % FAME99.6 biodiesel – for ME No. 2.

During the research, the vessel carried out cargo transportation on the route Klaipeda (Lithuania) – Gothenburg (Sweden) and further between ports located in SOX-ECAs: Gothenburg (Sweden) – Esbjerg (Denmark) – Bremerhaven (Germany) – Rotterdam (Holland) – Antwerp (Belgium) – Dover (Great Britain) – Honfleur (France) – Brest (France) –

Table 4
Calculation of biofuel consumption for different conditions of the navigation passage.

Sea passage	Distance between ports, nautical miles	Time of passage, h	Weighted average power of diesel engines during the transition, kW	Biofuel consumption during the passage, kg/h	Port stay, h	Weighted average power of diesel engines during port stay, kW	Biofuel consumption during port stay, kg/h	Total consumption of biofuel, kg/h
Sao Paulo – Rio de Janeiro	210	21	637	385	12	1103	373	758
Rio de Janeiro – Salvador	749	75	637	1376	16	1103	497	1873
Salvador – Fortaleza	798	80	637	1468	9	1103	280	1747
Fortaleza – Port of Spain	1663	166	637	3045	14	1103	435	3481
Port of Spain – Puerto Cabello	392	39	637	715	11	1103	342	1057
Puerto Cabello – Kingston	690	69	637	1266	8	1103	249	1515
Kingston – Havana	743	74	637	1358	18	1103	560	1917

Table 5
Adjusted scheme of the navigation passage Sao Paulo – Havana – Sao Paulo.

Sea passage	Biofuel consumption during the passage, kg/h	Biofuel consumption during port stay, kg/h	Nature of passage	Total consumption of biofuel between bunkering, kg/h
Sao Paulo – Rio de Janeiro	385	373	bunkering, sea passage, cargo operations	4379
Rio de Janeiro – Salvador	1376	497	sea passage, cargo operations	
Salvador – Fortaleza	1468	280	sea passage, cargo operations	
Fortaleza – Port of Spain	3045	–	bunkering, sea passage	4102
Port of Spain – Puerto Cabello	715	342	sea passage, cargo operations	
Puerto Cabello – Kingston	1266	249	bunkering, sea passage, cargo operations	3433
Kingston – Havana	1358	560	sea passage, cargo operations	
Havana – Kingston	1358	–	bunkering, transit	2624
Kingston – Puerto Cabello	1266	–	sea passage	
Puerto Cabello – Port of Spain	715	435	bunkering, sea passage, cargo operations	4195
Port of Spain – Fortaleza	3045	–	sea passage	
Fortaleza – Salvador	1468	–	bunkering, sea passage	3229
Salvador – Rio de Janeiro	1376	–	sea passage	
Rio de Janeiro – Sao Paulo	385	–	sea passage	

Fig. 6.

The main characteristics of sea passage are given in Table 6.

Considering the navigational circumstances (the intensity of navigation, hydrometeorological conditions, the location and depth of the fairway), the power of the main engine 16V32 Wärtsilä-Sulzer varied in the range (0.65–0.85) N_{enom}, where $N_{enom} = 5760$ kW (see Table 7). At the same time (due to a change in the cyclic fuel supply) the amount of sulphur and carbon dioxide in the exhaust gases changed and, accordingly, the ratio SO_2/CO_2. Also, due to the change in the load on the diesel, the concentration of nitrogen oxides in the exhaust gases did not remain constant, the maximum value of which (because the 16V32 Wärtsilä-Sulzer diesel belongs to the Tier II level) should not be exceeded:

$$NO_X^{max} = 44n^{-0.23} = 44 \cdot 750^{-0.23} = 9.60 \text{ g}/(\text{kW} \cdot h), \tag{6}$$

where n = 750 min^{-1} – nominal speed of the diesel engine [9,23,55].

Change in SO_2/CO_2 and NO_x parameters when a vessel navigates outside a special ecological zone is shown in Figs. 7 and 8 (section of the diagram, which corresponds to the time 0–43 h).

During the stay of the ship in special ecological areas, constant monitoring of its environmental parameters was ensured, including emissions of sulphur dioxide SO2, carbon CO2 and nitrogen NOx [76–78]. The change in these indicators when using RMG420 fuel, as well as a fuel mixture consisting of 80 % RMG420 fuel and 20 % FAME99.6 biodiesel, is shown in Figs. 7 and 8 (section of the diagram, which corresponds to the time 43–190 h).

Throughout the experiment, the emission of sulphur oxides (which was determined by the SO_2/CO_2 ratio in accordance with Table 1) did not exceed the maximum value: 21.7 ppm/%V – when operating outside the SO_x-ECAs areas and 4.3 ppm/%V – when operating in the areas SO_x-ECAs. The emission of nitrogen oxides did not exceed the maximum value of 9.6 g/kWh, which was calculated by the expression (6).

At the same time, tests were carried out on Volvo Penta TWD1645GE marine diesel engines, which were part of the ship's auxiliary power plant. The diesels each had a separate fuel supply system, which allowed two of them to use a mixture of DMA10 diesel fuel and FAME99.6 biodiesel fuel. The concentration of FAME99.6 biofuel in the mixture varied in the range of 5–20% for each of the test cycles. The third diesel was operated exclusively on DMA10 fuel. During the research, diesel engines were operated for the same amount of time at the same loads (within 0.55–0.85 N_{enom}, were N_{enom} – nominal load). This was ensured by redistributing the load between them. During the tests, the emission of nitrogen oxides NO_x and carbon dioxide CO_2 with exhaust gases was

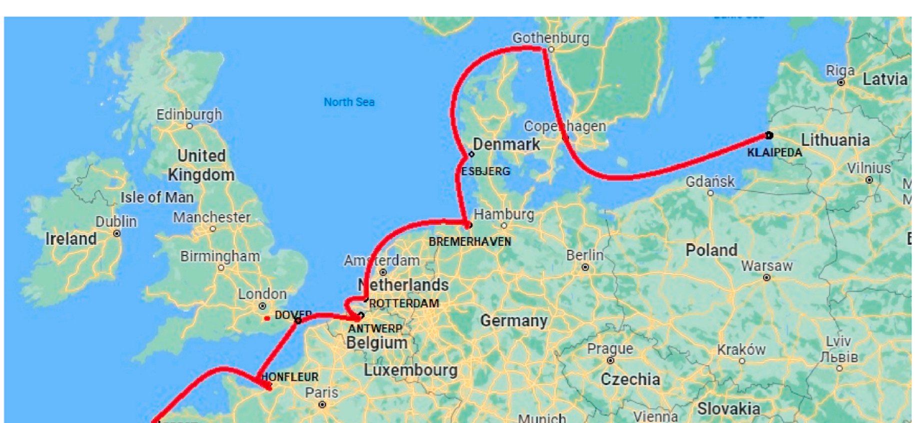

Fig. 6. The navigation passage Klaipeda – Brest.

Table 6
Main characteristics of navigation passage Klaipeda – Brest.

Sea passage	Distance, nautical miles	Time of sea passage, h	The fuel used,
Klaipeda – Gothenburg	430	43	RMG420/RME180
Gothenburg – Esbjerg	418	42	80 % RMG420/ RME180 + 20 % FAME99.6
Esbjerg – Bremerhaven	220	22	80 % RMG420/ RME180 + 20 % FAME99.6
Bremerhaven – Rotterdam	238	24	80 % RMG420/ RME180 + 20 % FAME99.6
Rotterdam – Antwerp	89	9	80 % RMG420/ RME180 + 20 % FAME99.6
Antwerp – Dover	260	26	80 % RMG420/ RME180 + 20 % FAME99.6
Dover – Honfleur	207	21	80 % RMG420/ RME180 + 20 % FAME99.6
Honfleur – Brest	237	24	80 % RMG420/ RME180 + 20 % FAME99.6

Table 7
Concentration of nitrogen oxides in exhaust gases, g/(kWh), for fuel of different composition.

Diesel load	DMA	DMA10 + 5% biofuel	DMA10 + 10% biofuel	DMA10 + 15% biofuel	DMA10 + 20% biofuel
0.55 N_{enom}	7.42	7.09	6.52	6.03	6.67
0.65 N_{enom}	7.83	7.35	6.78	6.18	6.84
0.75 N_{enom}	8.17	7.67	6.54	6.28	6.93
0.85 N_{enom}	8.35	7.82	6.36	6.32	7.08

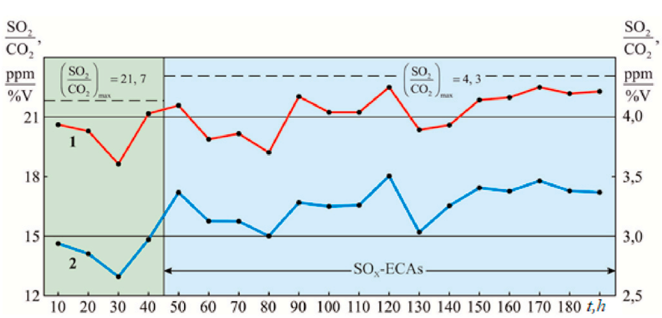

Fig. 7. Change in the SO_2/CO_2 ratio in exhaust gases during marine diesel engine operation 16V32 Wärtsilä-Sulzer: 1 – fuel RMG420 (0–43 h), mixture 80 % of RMG420 and 20 % FAME99.6 (43–190 h); 2 – fuel RME180 (0–43 h), mixture 80 % of RMG420 and 20 % FAME99.6 (43–190 h).

monitored.

Carbon dioxide CO_2 is a greenhouse gas and increases the level of global warming. Nitrogen oxides NO_x include nitrogen oxide N_2O, which is also a greenhouse gas, while the greenhouse activity of N_2O is almost 300 times higher than that of CO_2.

The maximum value of nitrogen oxide emission for diesel Volvo Penta TWD1645GE is determined by the expression (6)

$$NO_X^{max} = 44n^{-0.23} = 44\cdot 1200^{-0.23} = 8.61\ g/(kW\cdot h), \quad (7)$$

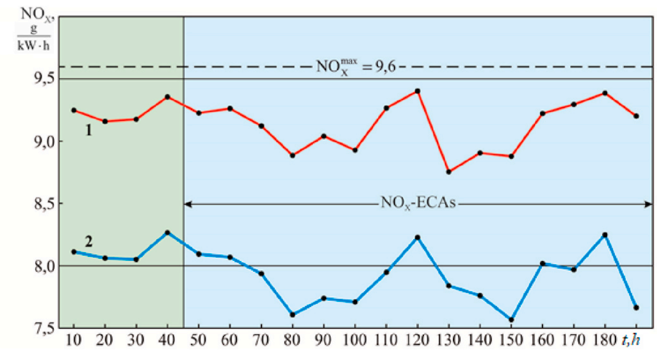

Fig. 8. Change in the concentration of NO_X in exhaust gases during the operation of a ship's diesel engine 16V32 Wärtsilä-Sulzer: 1 – fuel RMG420; 2 – mixture of RMG420 (80 %) and FAME99.6 (20 %).

where $n = 1200\ min^{-1}$ is the rated speed of the diesel engine.

The results of the study are shown in the Tables 5–6

Based on the results of the experiments, charts were constructed showing changes in NO_x emissions (Fig. 9(a)) and volume concentration of CO2 in exhaust gases (Fig. 9(b)) for different operating conditions of a marine diesel engine Volvo Penta TWD1645GE.

Relative changes in the concentration of nitrogen oxides ΔNO_X and volume content of carbon dioxide ΔCO_2 in exhaust gases were calculated according to the expressions:

$$\Delta NO_X = \frac{NO_X^{DMA} - NO_X^{bio}}{NO_X^{DMA}}\cdot 100\%, \quad (8)$$

$$\Delta CO_2 = \frac{CO_2^{DMA} - CO_2^{bio}}{CO_2^{DMA}} \bullet 100\%, \quad (9)$$

where NO_X^{DMA}, NO_X^{bio} – concentration of nitrogen oxide in exhaust gases during diesel operation on DMA fuel and a mixture of DMA and biofuel, g/(kWh); CO_2^{DMA}, CO_2^{bio} – volume content of carbon dioxide in exhaust gases during the operation of a diesel powered by DMA fuel and a mixture of DMA and biofuel, %.

The obtained values are summarized in the Tables 9–10, as well as displayed on the diagrams shown in Fig. 10 (see Table 8).

During the research, the main indicators of diesel operation were

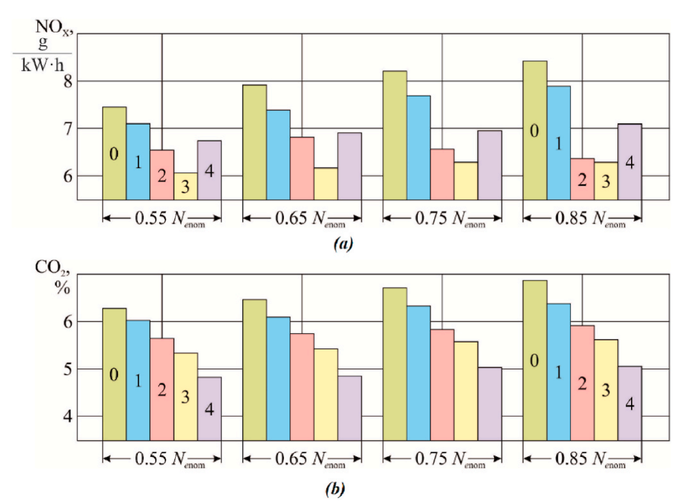

Fig. 9. Dependencies of diesel performance indicators Volvo Penta TWD1645GE from the load when using fuel of different composition: 0 – DMA; 1 – DMA+5 % biofuel; 2 – DMA+10 % biofuel; 3 – DMA+15 % biofuel; 4 – DMA+20 % biofuel; a – emission of nitrogen oxides; b – volume content of carbon dioxide in exhaust gases.

Table 8
Volume content of carbon monoxide in exhaust gases, %, for fuels of different composition.

Diesel load	DMA	DMA10 + 5% biofuel	DMA10 + 10% biofuel	DMA10 + 15% biofuel	DMA10 + 20% biofuel
0.55 N_{enom}	6.31	6.03	5.71	5.34	4.84
0.65 N_{enom}	6.44	6.09	5.76	5.44	4.91
0.75 N_{enom}	6.74	6.35	5.91	5.61	5.05
0.85 N_{enom}	6.88	6.47	5.97	5.66	5.14

Table 9
Relative decrease in the concentration of nitrogen oxides NO_x in exhaust gases, %, for fuels of different composition.

Diesel load	DMA10 + 5% biofuel	DMA10 + 10% biofuel	DMA10 + 15% biofuel	DMA10 + 20% biofuel
0.55 N_{enom}	4.45	12.13	18.73	10.11
0.65 N_{enom}	6.13	13.41	21.07	12.64
0.75 N_{enom}	6.12	19.95	23.13	15.18
0.85 N_{enom}	6.35	23.83	24.31	15.21

Table 10
Relative decrease in volume content of carbon dioxide CO_2 in exhaust gases, %, for fuels of different composition.

Diesel load	DMA10 + 5% biofuel	DMA10 + 10% biofuel	DMA10 + 15% biofuel	DMA10 + 20% biofuel
0.55 N_{enom}	4.14	9.55	15.45	23.25
0.65 N_{enom}	4.83	10.75	15.73	24.14
0.75 N_{enom}	5.95	12.5	16.96	25.3
0.85 N_{enom}	5.99	13.14	17.81	25.4

controlled: maximum combustion pressure, compression pressure, exhaust gas temperature, as well as parameters in cooling and lubrication systems. Their change did not exceed the values, recommended by the operating instructions.

5. Discussion

Ensuring the environmental efficiency of marine four-stroke diesel engines in terms of reducing the emission of nitrogen oxides with exhaust gases is possible by using fuel mixtures consisting of marine motor fuel and fuel of biological origin (biofuel). Replenishment of biofuel reserves is currently not possible in each of the ports where the ship is bunkered, also due to the structural features of the ship (deck space, technical rooms, and engine compartment), only a limited amount of biofuel can be placed on the ship during bunkering. This is the reason for only the periodic use of biofuel during the operation of diesel engines and leads to a decrease in their environmental sustainability.

In the case when the navigation passage of the ship includes ports that allow obtaining biofuel in the amount that ensures the operation of diesel engines during the further passage to other ports, it becomes expedient to adjust it, which on the one hand ensures the fulfilment of the voyage task, on the other hand - provides the opportunity to replenish stocks biofuel The latter contributes to ensuring the operation of marine diesel engines on a fuel mixture that includes biofuel and

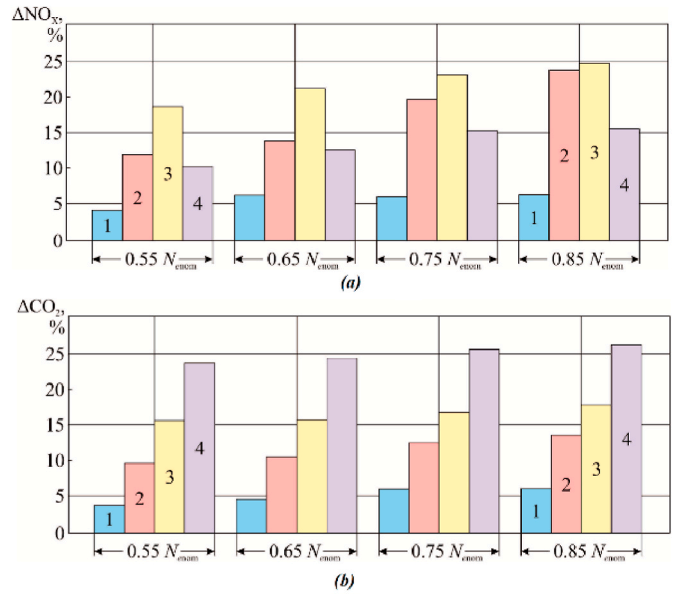

Fig. 10. The relative change in performance indicators of the Volvo Penta TWD1645GE diesel engine depending on the load when using fuel of different composition: 1 – DMA+5% biofuel; 2 – DMA+10% biofuel; 3 – DMA+15% biofuel; 4 – DMA+20% biofuel; a – reduction of the emission of nitrogen oxides; b – decrease in volume content of carbon monoxide in exhaust gases.

improves their environmental performance.

Calculations made regarding the adjustment of the navigation passage between the ports of Brazil and the Caribbean basin (some of which had the possibility of receiving biofuel) confirm the possibility of replenishing the reserves of biofuel in the amount that ensures the continuous operation of ship diesels on a fuel mixture of marine motor fuel and biofuel. It is most expedient to adjust the navigation passage by changing the sequence of measures in the ports.

It is advisable to use the proposed version of the correction of the navigation passage during the operation of sea and inland water transport vessels in special ecological areas.

The identical values of density and viscosity of motor fuel and biodiesel fuel allow the creation of fuel mixture. The main component of these mixtures is motor fuel (the content of which is 80–95 %), as a component of these mixture biodiesel fuel is used (the content of which is 20–5 %).

The use of fuel mixtures, which include biodiesel fuel, increases the stability and safety of the operation of marine vessels and their power plants during their operation in special ecological regions. This reduces the emission of sulphur oxides SO_x, nitrogen oxides NO_x and carbon dioxide CO_2. This reduces the formation of acid rain in the atmosphere and reduces the impact of ship power plants on the greenhouse effect.

Results of the research are showing the following trends in the relative decreasing of the content of nitrogen oxides NOx in the exhaust gases. The use of biofuels (as a renewable energy sources) ensures a reduction in nitrogen oxide emissions over the entire range of diesel operating loads. The greatest reduction in NOx emissions (about 20–24.5%) occurs at loads of 75–85% of rated power. At the same time, the concentration of biofuel in its mixture with petroleum fuel has an optimal value, which (for the studies carried out) is in the range of 10–15%. It is in this range that the maximum reduction in the content of nitrogen oxides in the exhaust gases is ensured.

Also the positive effect in the case of using biofuels, are achieved on CO2 emissions. A fuel mixture containing 5–20% biodiesel fuel provides a reduction in CO2 in exhaust gases by 4.1–25.4%. Moreover, the more biofuel is in the fuel mixture, then more carbon dioxide emissions are reduced. The greatest reduction in CO2 emissions are achieved at maximum biofuel concentration and on maximum diesel load.

The efficiency of using biofuels (as a renewable energy sources) increased in case of the operation of sea vessels in the special ecological areas for control of sulphur and nitrogen emissions. At the same time, one of the problems with using biofuel is the possibility of bunkering and storing it on a ship. In addition, it is necessary to re-equip ship fuel systems in order to ensure the possibility of creating fuel mixtures that include biofuel. At the same time, the use of biofuel increases the environmental sustainability of marine diesel engines. In addition, biofuel is a renewable source of energy, the reserves of which (unlike petroleum fuel) will only increase in the coming years.

6. Conclusions

The presented results allow us to draw the following conclusions.

Sustainable and safe maritime transportation is determined not only by the navigational safety of the sea or ocean passage of the vessel, but also by the environmental safety of the operation of the ship's power plant. One of the methods for controlling emissions of nitrogen oxides, sulphur, and carbon oxides (which characterize the environmental friendliness of marine vessels) is the use of biodiesel fuel.

The use of fuel mixtures containing biodiesel improves the environmental friendliness of marine vessels. At the same time, the emission of nitrogen oxides NOx, sulphur oxides SOx and carbon dioxide CO2 from exhaust gases is reduced. The values of NOx and SOx emissions are regulated by the requirements of Annex VI MARPOL, the value of CO2 emissions determines the energy efficiency of a sea vessel. Therefore, their reduction characterizes the advantages of using biofuels. This fact is especially relevant for marine medium-speed diesel engines, which are operated for a long time not only during sea voyages, but also when the vessel is in coastal waters and moored in a port. The optimal concentration of biofuel in the fuel mixture with petroleum fuel is determined experimentally and depends on the characteristics of the petroleum fuel and the diesel load.

Currently, biodiesel bunkering is not yet possible in all seaports. This leads to the need to adjust the sea passage to ensure the continuous operation of the ship's power plant using biodiesel fuel.

It has been experimentally established that the use of fuel mixtures (which include 5–20% of biodiesel fuel) in marine medium-speed diesel engines provides:

- improving the environmental friendliness of the operation of marine vessels in the main operating modes of their power plants (in the range of loads on the main and auxiliary engines (0.55–0.85) Nenom, where Nenom is the nominal power of the diesel engine)
- maintenance of the required level of sulphur oxide emissions (which is determined by the SO_2/CO_2 ratio) and does not exceed 21.7 ppm/%V when the vessel navigates outside special environmental areas and does not exceed 4.3 ppm/%V, when the vessel navigates in Sulphur Emission Control Areas
- reduction in the concentration of nitrogen oxides NO_x in the exhaust gases by 4.45–24.31 % (with the maximum reduction corresponding to 10–15 % of the concentration of biodiesel fuel in the fuel mixture)
- reduction in the concentration of carbon dioxide CO_2 in the exhaust gases by 4.14–25.4 % (with the maximum reduction corresponding to 15–20 % of the concentration of biodiesel fuel in the fuel mixture)

The use of fuel mixtures containing biodiesel fuel increases the environmental friendliness of the operation of ship power plants, therefore it can be considered a method of managing the sustainability and safety of maritime transportation.

Also, the usage of biodiesel fuel ensures the reliability of ship machines and mechanisms [78], the safety of sea passages [79], and the survivability of sea transport ships [80,81].

Increasing the production of renewable energy sources (which includes biofuel Fatty Acid Methyl Esters – FAME) and their further use in ship power plants will help improve the environmental friendliness of marine vessels.

CRediT authorship contribution statement

Sergii V. Sagin: Conceptualization, Data curation, Methodology, Supervision. **Sergii S. Sagin:** Data curation, Methodology, Writing – original draft. **Oleksij Fomin:** Conceptualization, Investigation, Methodology, Visualization. **Oleksandr Gaichenia:** Formal analysis, Methodology, Resources, Software. **Yurii Zablotskyi:** Methodology, Validation. **Václav Píštěk:** Data curation. **Pavel Kučera:** Data curation, Software, Visualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgments

The authors gratefully acknowledge funding from the Specific research on BUT FSI–S-23-8235.

References

[1] O. Fomin, A. Lovska, P. Kučera, V. Píštěk, Substantiation of improvements for the bearing structure of an open car to provide a higher security during rail/sea transportation, J. Mar. Sci. Eng. 9 (2021) 873, https://doi.org/10.3390/jmse9080873.

[2] A. Lovska, O. Fomin, V. Pistek, P. Kucera, Dynamic load modelling within combined transport trains during transportation on a railway ferry, Appl. Sci. 10 (2020) 5710, https://doi.org/10.3390/app10165710.

[3] G. Yunusov, P. Smirnov, O. Lopatin, Determination of soot formation parameters in a gasdiesel cylinder, in: AIP Conference Proceedings, 2700, 2023 050029, https://doi.org/10.1063/5.0137370.

[4] V. Likhanov, O. Lopatin, G. Mikheev, N. Belova, A. Maksimov, Mathematical problem of the stability theory of the gas diesel transport control system, Transport. Res. Procedia 61 (2022) 219–223, https://doi.org/10.1016/j.trpro.2022.01.036.

[5] M. Bogdevicius, V. Semaskaite, T. Paulauskiene, J. Uebe, A. Danilevicius, Modelling and simulation hydrodynamics processes in liquefied natural gas transportation systems, J. Mar. Sci. Eng. 10 (2022) 1960, https://doi.org/10.3390/jmse10121960.

[6] V. Semaskaite, M. Bogdevicius, T. Paulauskiene, J. Uebe, L. Filina-Dawidowicz, Improvement of regasification process efficiency for floating storage regasification unit, J. Mar. Sci. Eng. 10 (2022) 897, https://doi.org/10.3390/jmse10070897.

[7] X. Wang, J. Zhu, M. Han, Industrial development status and prospects of the marine fuel cell: a review, J. Mar. Sci. Eng. 11 (2023) 238, https://doi.org/10.3390/jmse11020238.

[8] T. Salova, P. Lekomtsev, V. Likhanov, O. Lopatin, E. Belov, Development of calculation methods and optimization of working processes of heat engines, in: AIP Conference Proceedings, 2700, 2023 050015, https://doi.org/10.1063/5.0137793.

[9] S.V. Sagin, O.A. Kuropyatnyk, The use of exhaust gas recirculation for ensuring the environmental performance of marine diesel engines, Naše more: International Journal of Maritime Science & Technology 65 (2) (2018) 78–86, https://doi.org/10.17818/NM/2018/2.3.

[10] J. Huang, H. Fan, X. Xu, Z. Liu, Life cycle greenhouse gas emission assessment for using alternative marine fuels: a very large crude carrier (VLCC) case study, J. Mar. Sci. Eng. 10 (2022) 1969, https://doi.org/10.3390/jmse10121969.

[11] A. Kytariolou, N. Themelis, Optimized route planning under the effect of hull and propeller fouling and considering ocean currents, J. Mar. Sci. Eng. 11 (2023) 828, https://doi.org/10.3390/jmse11040828.

[12] D. Borge-Diez, E. Rosales-Asensio, E. Açıkkalp, D. Alonso-Martínez, Analysis of power to gas technologies for energy intensive industries in European union, Energies 16 (2023) 538, https://doi.org/10.3390/en16010538.

[13] M.A. Ershov, V.D. Savelenko, A.E. Makhmudova, E.S. Rekhletskaya, U.A. Makhova, V.M. Kapustin, D.Y. Mukhina, T.M.M. Abdellatief, Technological potential analysis and vacant technology forecasting in properties and composition of low-sulfur marine fuel oil (VLSFO and ULSFO) bunkered in key world ports, J. Mar. Sci. Eng. 10 (2022) 1828, https://doi.org/10.3390/jmse10121828.

[14] K.I. Smyshlyaeva, V.A. Rudko, V.G. Povarov, A.A. Shaidulina, I. Efimov, R. R. Gabdulkhakov, I.N. Pyagay, J.G. Speight, Influence of asphaltenes on the low-sulphur residual marine fuels' stability, J. Mar. Sci. Eng. 9 (2021) 1235, https://doi.org/10.3390/jmse9111235.

[15] Y. Wang, Y. Wang, Y. Sun, K. Zhang, C. Zhang, J. Liu, C. Fu, J. Wang, Selective NO2 detection by black phosphorus gas sensor prepared via aqueous route for ship pollutant monitoring, J. Mar. Sci. Eng. 10 (2022) 1892, https://doi.org/10.3390/jmse10121892.

[16] M. Puškár, M. Kopas, D. Sabadka, M. Kliment, M. Šoltésová, Reduction of the gaseous emissions in the marine diesel engine using biodiesel mixtures, J. Mar. Sci. Eng. 8 (2020) 330, https://doi.org/10.3390/jmse8050330.

[17] M.A. Ershov, E.V. Grigorieva, T.M.M. Abdellatief, Hybrid low-carbon high-octane oxygenated environmental gasoline based on low-octane hydrocarbon fractions, Sci. Total Environ. 756 (2021) 142715, https://doi.org/10.1016/j.scitotenv.2020.142715.

[18] J. Zhu, D. Zhou, W. Yang, Y. Qian, Y. Mao, X. Lu, Investigation on the potential of using carbon-free ammonia in large two-stroke marine engines by dual-fuel combustion strategy, Energy 263 (2023) 125748, https://doi.org/10.1016/j.energy.2022.125748.

[19] S. Vedachalam, N. Baquerizo, A.K. Dalai, Review on impacts of low sulfur regulations on marine fuels and compliance options, Fuel 310 (2022) 122243, https://doi.org/10.1016/j.fuel.2021.122243.

[20] K.I. Smyshlyaeva, V.A. Rudko, K.A. Kuzmin, V.G. Povarov, Asphaltene genesis influence on the low-sulfur residual marine fuel sedimentation stability, Fuel 328 (2022) 125291, https://doi.org/10.1016/j.fuel.2022.125291.

[21] S. Sagin, V. Madey, A. Sagin, T. Stoliaryk, O. Fomin, P. Kučera, Ensuring reliable and safe operation of trunk diesel engines of marine transport vessels, J. Mar. Sci. Eng. 10 (2022) 1373, https://doi.org/10.3390/jmse10101373.

[22] J. Huang, H. Fan, X. Xu, Z. Liu, Life cycle greenhouse gas emission assessment for using alternative marine fuels: a very large crude carrier (VLCC) case study, J. Mar. Sci. Eng. 10 (2022) 1969, https://doi.org/10.3390/jmse10121969.

[23] O.A. Kuropyatnyk, S.V. Sagin, Exhaust gas recirculation as a major technique designed to reduce NOx emissions from marine diesel engines, Naše more : International Journal of Maritime Science & Technology 66 (1) (2019) 1–9, https://doi.org/10.17818/NM/2019/1.1.

[24] O. Fomin, A. Lovska, P. Kučera, V. Píštěk, Substantiation of improvements for the bearing structure of an open car to provide a higher security during rail/sea transportation, J. Mar. Sci. Eng. 9 (2021) 873, https://doi.org/10.3390/jmse9080873.

[25] S.V. Sagin, O.A. Kuropyatnyk, YuV. Zablotskyi, O.V. Gaichenia, Supplying of marine diesel engine ecological parameters, Naše more: International Journal of Maritime Science & Technology 69 (1) (2022) 53–61, https://doi.org/10.17818/NM/2022/1.7.

[26] N.K. Kondrasheva, V.A. Rudko, D.O. Kondrashev, V.S. Shakleina, K.I. Smyshlyaeva, R.R. Konoplin, A.A. Shaidulina, A.S. Ivkin, I.O. Derkunskii, O.A. Dubovikov, Application of a ternary phase diagram to describe the stability of residual marine fuel, Energy Fuels 33 (2019) 4671–4675, https://doi.org/10.1021/acs.energyfuels.9b00487.

[27] S. Gorb, M. Levinskyi, M. Budurov, Sensitivity optimisation of a main marine diesel engine electronic speed governor, Scientific Horizons 24 (11) (2021) 9–19, https://doi.org/10.48077/scihor.24(11).2021.9-19.

[28] M. Gallo, M. Marinelli, The use of hydrogen for traction in freight transport: estimating the reduction in fuel consumption and emissions in a regional context, Energies 16 (2023) 508, https://doi.org/10.3390/en16010508.

[29] S.V. Sagin, O.V. Semenov, Motor oil viscosity stratification in friction units of marine diesel motors, Am. J. Appl. Sci. 13 (2) (2016) 200–208, https://doi.org/10.3844/ajassp.2016.200.208.

[30] S.V. Sagin, O.V. Semenov, Marine slow-speed diesel engine diagnosis with view to cylinder oil specification, Am. J. Appl. Sci. 13 (5) (2016) 618–627, https://doi.org/10.3844/ajassp.2016.618.627.

[31] S.V. Sagin, V.G. Solodovnikov, Cavitation treatment of high-viscosity marine fuels for medium-speed diesel engines, Mod. Appl. Sci. 9 (5) (2015) 269–278, https://doi.org/10.5539/mas.v9n5p269.

[32] H. Ju, S. Jeon, Analysis of characteristic changes of blended very low sulfur fuel oil on ultrasonic frequency for marine fuel, J. Mar. Sci. Eng. 10 (2022) 1254, https://doi.org/10.3390/jmse10091254.

[33] YuV. Zablotsky, S.V. Sagin, Maintaining boundary and hydrodynamic lubrication modes in operating high-pressure fuel injection pumps of marine diesel engines, Indian J. Sci. Technol. 9 (20) (2016) 208–216, https://doi.org/10.17485/ijst/2016/v9i20/94490.

[34] YuV. Zablotsky, S.V. Sagin, Enhancing fuel efficiency and environmental specifications of a marine diesel when using fuel additives, Indian J. Sci. Technol. 9 (46) (2016) 353–362, https://doi.org/10.17485/ijst/2016/v9i46/107516.

[35] H. Winnes, E. Fridell, J. Moldanová, Effects of marine exhaust gas scrubbers on gas and particle emissions, J. Mar. Sci. Eng. 8 (2020) 299, https://doi.org/10.3390/jmse8040299.

[36] H. Ju, S. Jeon, Effect of ultrasound irradiation on the properties and sulfur contents of blended very low-sulfur fuel oil (VLSFO), J. Mar. Sci. Eng. 10 (2022) 980, https://doi.org/10.3390/jmse10070980.

[37] M.I. Lamas Galdo, Marine engines performance and emissions II, J. Mar. Sci. Eng. 10 (2022) 1987, https://doi.org/10.3390/jmse10121987.

[38] E. Öztürk, Ö. Can, Effects of EGR, injection retardation and ethanol addition on combustion, performance and emissions of a DI diesel engine fueled with canola biodiesel/diesel fuel blend, Energy 244 (2020) 123129, https://doi.org/10.1016/j.energy.2022.123129.

[39] O. Melnyk, S. Onyshchenko, O. Onishchenko, Development measures to enhance the ecological safety of ships and reduce operational pollution to the environment, Scientific Journal of Silesian University of Technology. Series Transport 118 (2023) 195–206, https://doi.org/10.20858/sjsutst.2023.118.13.

[40] O. Melnyk, S. Onyshchenko, O. Onishchenko, O. Lohinov, V. Ocheretna, Integral approach to vulnerability assessment of ship's critical equipment and systems, Trans. Marit. Sci. 12 (1) (2023), https://doi.org/10.7225/toms.v12.n01.002.

[41] M.A. Ershov, E.V. Grigorieva, T.M.M. Abdellatief, E.A. Chernysheva, D.Y. Makhin, V.M. Kapustin, A new approach for producing mid-ethanol fuels E30 based on low-octane hydrocarbon surrogate blends, Fuel Process. Technol. 213 (2021) 106688, https://doi.org/10.1016/j.fuproc.2020.106688.

[42] V.A. Likhanov, O.P. Lopatin, Dynamics of soot formation and burnout in a gas diesel cylinder, IOP Conf. Ser. Mater. Sci. Eng. 862 (2020) 062033, https://doi.org/10.1088/1757-899X/862/6/062033.

[43] M. Inci, Future vision of hydrogen fuel cells: a statistical review and research on applications, socio-economic impacts and forecasting prospects, Sustain. Energy Technol. Assessments 53 (2022) 102739, https://doi.org/10.1016/j.seta.2022.102739.

[44] J.D. Ampah, X. Liu, X. Sun, X. Pan, L. Xu, C. Jin, T. Sun, Z. Geng, S. Afrane, H. Liu, Study on characteristics of marine heavy fuel oil and low carbon alcohol blended fuels at different temperatures, Fuel 310 (2022) 122307, https://doi.org/10.1016/j.jclepro.2021.128871.

[45] C.G. Rodríguez, M.I. Lamas, J.d.D. Rodríguez, A. Abbas, Possibilities of ammonia as both fuel and NOx reductant in marine engines: a numerical study, J. Mar. Sci. Eng. 10 (2022) 43, https://doi.org/10.3390/jmse10010043.

[46] S. Ovchukova, T. Sharonova, V. Likhanov, O. Lopatin, The use of alcohols in transport, in: AIP Conference Proceedings, 2700, 2023 050027, https://doi.org/10.1063/5.0137346.

[47] T. Paulauskiene, M. Bucas, A. Laukinaite, Alternative fuels for marine applications: biomethanol-biodiesel-diesel blends, Fuel 248 (2019) 161–167, https://doi.org/10.1016/j.fuel.2019.03.082.

[48] C. Kyriklidis, M.E. Kyriklidis, E. Loizou, A. Stimoniaris, C.G. Tsanaktsidis, Optimal bio marine fuel production evolutionary computation: genetic algorithm approach for raw materials mixtures, Fuel 323 (2022) 124232, https://doi.org/10.1016/j.fuel.2022.12423.

[49] R. Manimaran, T. Mohanraj, S. Prabakaran, Biodegradable waste-derived biodiesel as a potential green fuel: optimization of production process and its application in diesel engine, Ind. Crop. Prod. 192 (2023) 116078, https://doi.org/10.1016/j.indcrop.2022.116078.

[50] V. Madey, Assessment of the efficiency of biofuel use in the operation of marine diesel engines, Technol. Audit Prod. Reserves 2 (1.64) (2022) 34–41, https://doi.org/10.15587/2706-5448.2022.255959.

[51] S. Sagin, S. Karianskyi, V. Madey, A. Sagin, T. Stoliaryk, I. Tkachenko, Impact of biofuel on the environmental and economic performance of marine diesel engines, J. Mar. Sci. Eng. 11 (2023) 120, https://doi.org/10.3390/jmse11010120.

[52] S.M. Turpak, I.O. Taran, O.V. Fomin, O. Tretiak, Logistic technology to deliver raw material for metallurgical production, Sci. Bull. Natl. Min. University. 1 (2018) 162–169, https://doi.org/10.29202/nvngu/2018-1/3.

[53] D. Zhou, H. Wei, Z. Tan, S. Xue, Y. Qiu, S. Wu, Biodiesel as dispersant to improve the stability of asphaltene in marine very-low-sulfur fuel oil, J. Mar. Sci. Eng. 11 (2023) 315, https://doi.org/10.3390/jmse11020315.

[54] O.A. Kuropyatnyk, Reducing the emission of nitrogen oxides from marine diesel engines, in: International Conference "Scientific Research of the SCO Countries: Synergy and Integration, 2020, pp. 154–160, https://doi.org/10.34660/INF.2020.24.53689.

[55] S. Sagin, O. Kuropyatnyk, A. Sagin, I. Tkachenko, O. Fomin, V. Píštěk, P. Kučera, Ensuring the environmental friendliness of drillships during their operation in special ecological regions of northern europe, J. Mar. Sci. Eng. 10 (2022) 1331, https://doi.org/10.3390/jmse10091331.

[56] M. Puškár, P. Tarbajovský, M. Lavčák, M. Šoltésová, Marine ancillary diesel engine emissions reduction using advanced fuels, J. Mar. Sci. Eng. 10 (2022) 1895, https://doi.org/10.3390/jmse10121895.

[57] A. Ruiz Zardoya, I. Oregui Bengoetxea, A. Lopez Martinez, I. Loroño Lucena, J. A. Orosa, Methodological design optimization of a marine LNG internal combustion gas engine to burn alternative fuels, J. Mar. Sci. Eng. 11 (2023) 1194, https://doi.org/10.3390/jmse11061194.

[58] R. Iuzmukhametova, R. Boldushevskii, O. Shmelkova, Y. Khamzin, A. Minaev, P. Nikulshin, Adsorptive treatment of residues on macroporous adsorbent for marine fuel production scheme on refinery, J. Mar. Sci. Eng. 11 (2023) 525, https://doi.org/10.3390/jmse11030525.

[59] Z. Shu, H. Gan, Z. Ji, B. Liu, Modeling and optimization of fuel-mode switching and control systems for marine dual-fuel engine, J. Mar. Sci. Eng. 10 (2022) 2004, https://doi.org/10.3390/jmse10122004.

[60] C.G. Rodríguez, M.I. Lamas, J.d.D. Rodríguez, A. Abbas, Multi-criteria analysis to determine the most appropriate fuel composition in an ammonia/diesel oil dual fuel engine, J. Mar. Sci. Eng. 11 (2023) 689, https://doi.org/10.3390/jmse11040689.

[61] G. Labeckas, S. Slavinskas, T. Mickevicius, Experimental investigation of biodiesel-n-butanol fuels blends on performance and emissions in a diesel engine, Combustion Engines 188 (1) (2022) 90–95, https://doi.org/10.19206/CE-142030.

[62] T. Lee, J. Cho, J. Lee, Mixing properties of emulsified fuel oil from mixing marine bunker-C fuel oil and water, J. Mar. Sci. Eng. 10 (2022) 1610, https://doi.org/10.3390/jmse10111610.

[63] S.V. Sagin, V.G. Solodovnikov, Estimation of operational properties of lubricant coolant liquids by optical methods, Int. J. Appl. Eng. Res. 12 (19) (2017) 8380–8391.

[64] V.V. Madey, Usage of biodiesel in marine diesel engines, Austrian Journal of Technical and Natural Sciences. Scientific journal. 7–8 (2021) 18–21, https://doi.org/10.29013/AJT-21-7.8-18-21.

[65] S.V. Sagin, Decrease in mechanical losses in high-pressure fuel equipment of marine diesel engines, in: Materials of the International Conference «Scientific Research of the SCO Countries: Synergy and Integration», 2019, pp. 139–145, https://doi.org/10.34660/INF.2019.15.36258.

[66] S. Sagin, V. Madey, T. Stoliaryk, Analysis of mechanical energy losses in marine diesels, Technol. Audit Prod. Reserves 5 (2.61) (2021) 26–32, https://doi.org/10.15587/2706-5448.2021.239698.

[67] S. Gorb, M. Budurov, Increasing the accuracy of a marine diesel engine operation limit by thermal factor, Int. J. Theor. Appl. Mech. 6 (2021) 18–26, https://doi.org/10.15866/ireme.v15i3.20865.

[68] I. Burmaka, I. Vorokhobin, M. Vorokhobin, I. Zhuravska, Forming the area of unacceptable of the parameters of vessels' movement for vessels' divergence at remote control process, Acta Innovations 44 (2022) 5–17, https://doi.org/10.32933/ActaInnovations.44.1.

[69] O. Melnyk, O. Onishchenko, S. Onyshchenko, O. Shumylo, S. Volyanskyy, A. Bondar, N. Cheredarchuk, Application of fuzzy controllers in automatic ship motion control systems, Int. J. Electr. Comput. Eng. 13 (4) (2023) 3948–3957, https://doi.org/10.11591/ijece.v13i4.pp3948-3957.

[70] R. Varbanets, O. Fomin, V. Píštěk, V. Klymenko, D. Minchev, A. Khrulev, V. Zalozh, P. Kučera, Acoustic method for estimation of marine low-speed engine turbocharger parameters, J. Mar. Sci. Engineering. 9 (2021) 321, https://doi.org/10.3390/jmse9030321. https://www.mdpi.com/2077-1312/9/3/321/htm.

[71] G. Vatulia, J. Gerlici, A. Lovska, O. Fomin, A. Okorokov, M. Pavliuchenkov, D. Petrenko, O. Kravchenko, Experimental studies on the strength of a flatcar during shunting impacts, Appl. Sci. 13 (2023) 4901, https://doi.org/10.3390/app13084901.

[72] T. Rymar, H. Tatarchenko, O. Fomin, V. Píštěk, P. Kučera, M. Beran, O. Burlutskyy, The study of manufacturing thermal insulation materials based on inorganic polymers under microwave exposure, Polymers 14 (2022) 3202, https://doi.org/10.3390/polym14153202.

[73] H. Ju, S. Jeon, Analysis of characteristic changes of blended very low sulfur fuel oil on ultrasonic frequency for marine fuel, J. Mar. Sci. Eng. 10 (2022) 1254, https://doi.org/10.3390/jmse10091254.

[74] P. Rapalis, G. Šilas, J. Žaglinskis, Ship air pollution estimation by AIS data: case port of Klaipeda, J. Mar. Sci. Eng. 10 (2022) 1950, https://doi.org/10.3390/jmse10121950.

[75] I. Jovanović, M. Perčić, M. Koričan, N. Vladimir, A. Fan, Investigation of the viability of unmanned autonomous container ships under different carbon pricing scenarios, J. Mar. Sci. Eng. 10 (2022) 1991, https://doi.org/10.3390/jmse10121991.v.

[76] R. Sultanbekov, K. Denisov, A. Zhurkevich, S. Islamov, Reduction of sulphur in marine residual fuels by deasphalting to produce VLSFO, J. Mar. Sci. Eng. 10 (2022) 1765, https://doi.org/10.3390/jmse10111765.

[77] L. Toneatti, C. Deluca, A. Fraleoni Morgera, M. Piller, D. Pozzetto, Waste to energy onboard cruise ships: a new paradigm for sustainable cruising, J. Mar. Sci. Eng. 10 (2022) 480, https://doi.org/10.3390/jmse10040480.

[78] YuM. Popovskii, S.V. Sagin, S.A. Khanmamedov, M.N. Grebenyuk, V.V. Teregerya, Designing, calculation, testing and reliability of machines: influence of anisotropic fluids on the operation of frictional components, Russ. Eng. Res. 16 (9) (1996) 1–7.

[79] A. Sulym, P. Khozia, E. Tretiak, V. Píštěk, O. Fomin, P. Kučera, Aspects of strength testing of tank containers in compliance with the requirements of the UN navigation rules and regulations, J. Mar. Sci. Eng. 9 (2021) 349, https://doi.org/10.3390/jmse9030349.

[80] I. Vorokhobin, I. Burmaka, I. Fusar, O. Burmaka, Simulation modeling for evaluation of efficiency of observed ship coordinates, TransNav: The International Journal on Marine Navigation and Safety of Sea Transportation 16 (1) (2022) 137–141, https://doi.org/10.12716/1001.16.01.15.

[81] T.D. Chountalas, M. Founti, D.T. Hountalas, Review of biofuel effect on emissions of various types of marine propulsion and auxiliary engines, Energies 16 (2023) 4647, https://doi.org/10.3390/en16124647.