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# IMPROVEMENT OF THE PROCESS OF CLEANING EXHAUST GASES OF MARINE DIESELS FROM SULFUR OXIDES

*The object research is the process of cleaning exhaust gases of marine diesel engines from sulfur oxides, which is associated with the need to fulfill the requirements of Annex VI MARPOL. The research results on reducing emissions of sulfur oxides with exhaust gases of marine diesel engines by additional fuel treatment are presented. It is determined that during the operation of marine diesel engines, it is mandatory to ensure their environmental performance in terms of emissions of harmful substances, including sulfur oxides. Scrubber cleaning is considered as a method that ensures the cleaning of exhaust gases from sulfur-containing components. At the same time, additional fuel treatment using its ultrasonic irradiation is proposed. The results of research carried out on a Bulk Carrier class vessel with deadweight of 82,000 tons are presented. The ship's power plant included the main engine STX-MAN B&W 6S60ME-C and three auxiliary diesel generators Yanmar 6EY18ALW2, the exhaust gases of which were subjected to scrubber cleaning. At the same time, ultrasonic fuel treatment was additionally used in the diesel fuel preparation system. For various operating modes of the ship's power plant, it was found that the relative reduction in emissions of harmful substances when using additional ultrasonic fuel treatment is: for sulfur dioxide $SO_2$ emissions 12.24–24.12%; for the ratio of sulfur dioxide emissions to carbon dioxide emissions $SO_2/CO_2$ 10.56–22.54%. It is noted that the use of additional ultrasonic treatment is more effective when ships are inside special ecological areas, i. e. in coastal waters. Ultrasonic fuel treatment is possible for any types of liquid marine fuel, regardless of its viscosity, density and component composition.*

***Keywords:*** *environmental indicators, maritime transport, fuel treatment, exhaust gas cleaning, marine diesel.*

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## 1. Introduction

Transportation provided by sea vessels occupies a dominant position among transportation by other types of vehicles – road, rail and air [1, 2]. Modern Bulk Carrier class vessels provide transportation of up to 180–200 thousand tons of bulk cargo. The displacement of modern Crude Oil/Chemical Oil Tanker class vessels reaches 280–300 thousand tons. The cargo capacity of LNG/LPG Tanker class vessels in some cases exceeds 250 thousand $m^3$. This allows transporting a similar amount of oil cargo and liquefied natural or petroleum gas from production cities to consumer countries. Ro-Ro class car carriers perform a one-time transportation of up to 7,000 units of wheeled vehicles of various types (freight, passenger, passenger cars). Container Ship class vessels transport up to 24,000 TEU. Modern cruise ships provide recreation for 6000–6500 passengers with 2000–2200 crew members on board at the same time. At the same time, there are ships of other classes that transport general and refrigerated cargo, provide supplies to offshore oil and gas platforms, lay offshore cables and set anchors [3, 4]. This confirms the continuous development and improvement of maritime transport and marine means of transport.

The main source of mechanical energy on marine transport vessels are internal combustion engines/diesel engines, which are the most common type of thermal engines used in ship power plants [5–7].

Currently, diesel engines are installed on all seagoing vessels without exception and perform the functions of main or auxiliary engines. In the first case, they transmit their power to the engine (a fixed-pitch propeller or a propeller with adjustable pitch) and thus ensure the movement of the vessel. In the second, their mechanical energy is converted into electrical energy and this ensures the power supply and further functioning of ship auxiliary mechanisms, deck and navigation equipment, as well as ship lighting. In the first case, diesel engines are characterized as main engines, in the second – as auxiliary engines. Only a very small part of seagoing vessels uses gas or steam turbines as a source of mechanical energy. On an even smaller part of vessels, these heat engines perform the functions of main engines [8–10].

The main source of energy for all heat engines used in ship power plants (diesels, boilers, gas turbines) is liquid fuel of petroleum origin [11–13]. Variants of using gas fuel in ship diesel engines are currently only isolated, while there are almost no variants of using gas fuel in boilers and gas turbines [14–16].

The classification of fuels used in marine diesel engines is carried out in accordance with the international standard ISO8217 "Fuel Standard for marine distillate fuels". This document establishes the following types of marine fuels:

– Marine Gas Oil (MGO) – which consists exclusively of petroleum distillates, which during fractional distillation evaporate from gas fractions and condense into liquid substances;
– Heavy Fuel Oil (HFO) – which consists exclusively of liquid residual fractions that, as a result of fractional distillation, did not undergo evaporation;
– Marine Diesel Oil (MDO) – which is a mixture with different percentages of Marine Gas Oil and Heavy Fuel Oil [17–19].

The combustion of fuel 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 into the atmosphere of exhaust gases [20–22]. Exhaust gases are a multicomponent gas mixture, which includes toxic components (primarily nitrogen oxides $NO_X$, sulfur oxides $SO_X$, carbon monoxide CO) [23–25]. Thus, the main negative factor associated with the use of petroleum-based fuel is its harmful impact on the environment. First of all, this is associated with the emission of carbon oxides CO and $CO_2$, sulfur oxides $SO_X$, and nitrogen oxides $NO_X$ [26, 27]. In this regard, it is these environmental performance indicators of marine diesel engines that are regulated and monitored by international organizations and classification societies.

The main international document limiting the emission of nitrogen oxides NOX and sulfur oxides $SO_X$ with exhaust gases is the International Convention for the Prevention of Pollution from Ships – MARPOL 73/78. According to Annex VI of MARPOL, the concentration of nitrogen oxides in exhaust gases should not exceed values determined depending on the year of construction of the vessel and the speed of the diesel engine. Also, according to Annex VI of MARPOL, the sulfur content in marine fuel should not exceed 0.1% during the operation of vessels in special environmental areas – Sulphur Emission Control Areas (SECAs) and be no more than 0.5% during the operation of vessels outside SECAs. In the case when the exhaust gases of ship diesel engines are additionally cleaned in special devices (the most common of which are scrubbers), the use of fuel with a sulfur content of up to 3.5% is allowed.

The functioning of marine diesel engines is impossible without the use of mechanical systems, through which fuel and air enter their cylinders, exhaust gases are removed from the cylinder, and its lubrication and cooling are ensured.

The most extensive and saturated of all ship mechanical systems is the fuel system, which, moreover, is divided into several subsystems: pumping, storage, separation, and supply to the diesel engine. During the "life cycle", during which fuel from the receiving tanks enters the high-pressure fuel equipment and is injected into the diesel engine cylinder, it is subjected to constant changes in operational characteristics [28, 29]. First of all, these include temperature, density, viscosity, as well as the content of water and mechanical impurities, and in some cases, the content of sulfur. The main technologies that affect the viscosity-temperature characteristics of fuel are settling and fuel heating [30, 31]. To remove water and mechanical impurities from fuel, its filtration and separation are used [32, 33]. The reduction of sulfur content in fuel (fuel desulfurization) is facilitated by methods of fine filtration, hydrodynamic cleaning, as well as cavitation and ultrasonic treatment [34–36]. The disadvantage of fine filtration, as a method of direct removal of sulfur from fuel, is the smaller size of sulfur-containing components compared to other impurities (primarily all metal components, as well as organic compounds). At the same time, due to their large size, "non-sulfur" impurities gradually accumulate in the filter cells. In this regard, the use of fine filtration (as a method of fuel desulfurization) contributes to an increase in hydraulic resistance in the fuel system. This leads to the need to increase the pressure in the fuel line, and also reduces the time between cleaning the filter elements from contaminants. This results in increased energy losses in the fuel preparation process and an increase in its duration [37–39].

In the case of hydrotreating, distilled water is pre-added to the fuel. The mixture of fuels and water obtained in this way is first subjected to hydrodynamic treatment, after which it is either settled or separated. In both cases, part of the sulfur associated with water is precipitated and drained. The negative characteristics of this method include the need to collect and further dispose of the precipitate of the sulfur-containing mixture of fuel and water. In addition, as in the case of using any separation plants, the energy consumption of these units of the cleaning system increases significantly [40–42].

During fine filtration and hydrodynamic cleaning, maximum removal of sulfur from the fuel is ensured. However, at the same time (due to the fact that sulfur releases heat during combustion), the calorific value of the fuel decreases. This leads to an increase in the specific fuel consumption, forcing it to increase its cyclic supply and injection duration. The consequence of this is an increase in the thermal stress of the diesel engine. As a way to prevent these negative phenomena, cavitation treatment of fuel is used, with the help of which intermolecular bonds between sulfur S and carbon C, as well as sulfur S and hydrogen H, are destroyed. This contributes to the activation of the specified structural components of the fuel and leads to an improvement in the combustion process [43, 44].

During cavitation treatment using ultrasound, the fuel is subjected to high alternating pressures. In the case of using ultrasound treatment, sound waves of a specially defined frequency and amplitude act on the fuel.

The most relevant research and technologies that ensure the reduction of sulfur in marine fuel were when the sulfur content in the fuel was not limited to 0.5% and in marine areas that are not included in the SECAs zones, it was allowed to use fuels with a sulfur content of up to 3.5%. At present, fuel desulfurization is gaining relevance in terms of reducing sulfur oxide emissions with exhaust gases. In this regard, technologies that ensure the removal of sulfur from fuel should be considered in conjunction with the issue of ensuring the environmental performance of marine diesel engines [45, 46].

In this regard, *the aim of research* is to determine the impact of ultrasonic treatment of fuel (as an additional method of the fuel preparation process) on the environmental performance of marine diesel engines, in particular the emission of sulfur oxides with exhaust gases.

To achieve the specified aim, it is necessary to solve the following objectives:

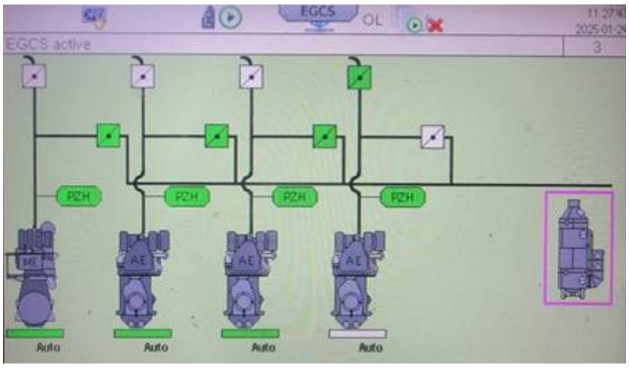
- determine the cell of the ship's fuel preparation system that is most appropriate for performing additional ultrasonic treatment of fuel for the purpose of its desulfurization;
- determine the effect of additional ultrasonic treatment on the emission of sulfur oxides with exhaust gases.

## 2. Materials and Methods

*The object of research* is the process of cleaning exhaust gases of marine diesel engines from sulfur oxides. As a scientific hypothesis, the thesis was adopted that the reduction of sulfur oxide emissions with exhaust gases is achieved by additional ultrasonic treatment of fuel.

The research was carried out on a Bulk Carrier class vessel with deadweight of 82,000 tons. The ship's power plant included the main engine STX-MAN B&W 6S60ME-C (New Diesel Machinary Co., Ltd., China) with an effective power of 9932 kW and three auxiliary diesel generators Yanmar 6EY18ALW2 (Yanmar Amagasaki Plant, Japan) with a power of 800 kW each. The exhaust gases of all diesel engines (main and auxiliary) were directed to a common scrubber $SO_X$ – Exhaust Gas Cleaning System (Shanghai Bluesoul Environmental Technology, China), where they were cleaned from sulfur compounds. Scrubber cleaning of exhaust gases allowed the use of fuels with a sulfur content of up to 3.5% during the operation of diesel engines.

Exhaust Gas Cleaning System provided cleaning of exhaust gases from sulfur impurities at various operating modes of the ship's power plant. At the same time, the minimum mode was taken to be the mode corresponding to 25% load on one of the auxiliary diesel generators Yanmar 6EY18ALW2. The maximum mode was the mode in which the main engine STX-MAN B&W 6S60ME-C was operated with a load of 85%, three simultaneously operating diesel generators Yanmar 6EY18ALW2 with a load of 75%. Some cases of operation of the Exhaust Gas Cleaning System are shown in Fig. 1.

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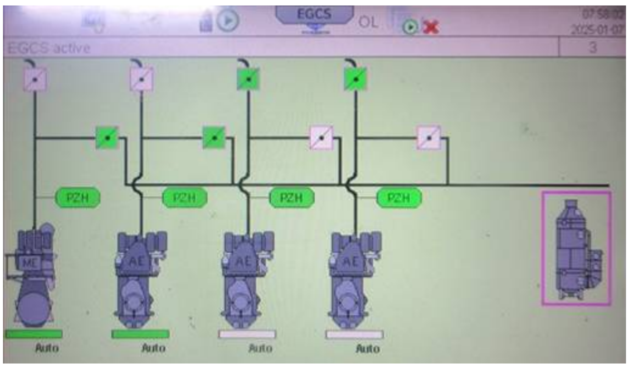



*b*

**Fig. 1.** Exhaust Gas Cleaning System operating modes: *a* – exhaust gas cleaning of the main engine STX-MAN B&W 6S60ME-C and two auxiliary diesel generators Yanmar 6EY18ALW2; *b* – exhaust gas cleaning of the main engine STX-MAN B&W 6S60ME-C and one auxiliary diesel generator Yanmar 6EY18ALW2

The Exhaust Gas Cleaning System allowed to determine the following main indicators:

– pressure – in mbar, and temperature – in °C, of exhaust gases before entering the scrubber;

– carbon dioxide content $CO_2$ – in volume percent, and sulfur dioxide content $SO_2$ – in ppm after scrubber cleaning;

– temperature – in °C, acidity – in pH, turbidity – in mg/l, flow rate – in $m^3$/h, and pressure – in bar, of seawater supplied to the scrubber;

– temperature – in °C, acidity – in pH, turbidity – in mg/l, of seawater leaving the scrubber after exhaust gas treatment;

– some other indicators.

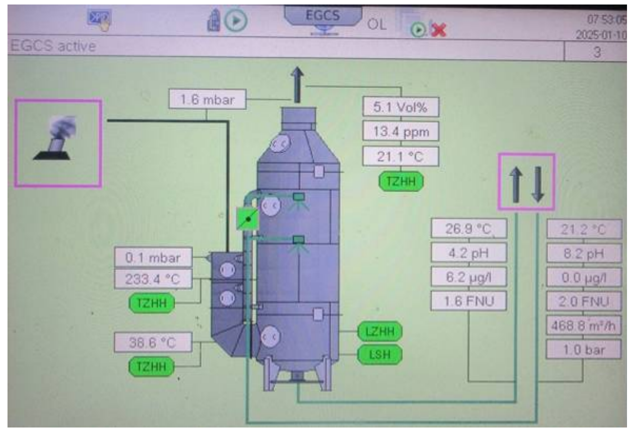
Some examples of determining these indicators are given in Fig. 2.

The main indicator determined in the case of using fuel with a sulfur content exceeding 0.5% and by which the efficiency of exhaust gas cleaning from sulfur compounds is assessed is the ratio of sulfur dioxide $SO_2$ to carbon dioxide $CO_2$. The values that the scrubber cleaning system must provide for the corresponding sulfur content in the fuel are given in Table 1.

During the operation of the ship's power plant and, accordingly, during the research, the ship's diesel engines used fuel, the main characteristics of which are given in Table 2.

During the research, the ship's power plant was operated in various modes, which are listed in Table 3.

In all operating modes, marine diesel engines (as the main STX-MAN B&W 6S60ME-C, as well as auxiliary Yanmar 6EY18ALW2) were used on RMG380 fuel (the characteristics of which are given in Table 2). At the same time, while the vessel was inside the SECAs, the scrubber cleaning system ensured a $SO_2/CO_2$ ratio of less than 4.3. While the vessel was outside the SECAs, the $SO_2/CO_2$ ratio did not exceed 21.7. This ensured the requirements of Annex VI MARPOL regarding the sulfur content in marine fuel. In some seaports and territorial waters of countries which national requirements did not allow the use of scrubber cleaning of exhaust gases from sulfur oxides, the operation of diesel engines was carried out on DMA fuel (with characteristics corresponding to those given in Table 2). Ultrasonic treatment of fuel (as an additional method of fuel preparation) can be used at various points of the fuel system. The schematic diagram of such a system is shown in Fig. 3.

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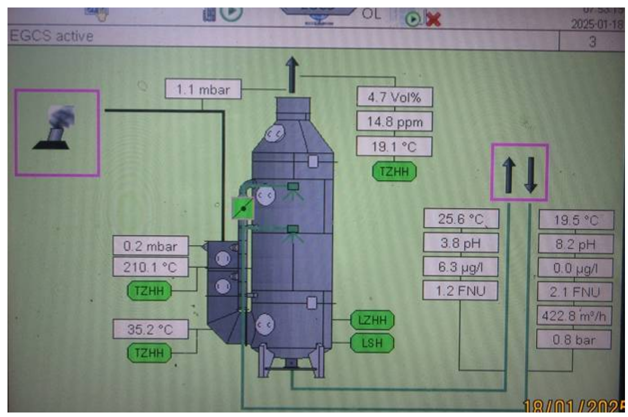


*b*

**Fig. 2.** Determination of the performance indicators of the Exhaust Gas Cleaning System: *a* – cleaning of exhaust gases of the main engine STX-MAN B&W 6S60ME-C and two auxiliary diesel generators Yanmar 6EY18ALW2; *b* – cleaning of exhaust gases of the main engine STX-MAN B&W 6S60ME-C and one auxiliary diesel generator Yanmar 6EY18ALW2

**Table 1**

$SO_2/CO_2$ ratio depending on the sulfur content in the fuel

| Sulfur content in fuel, S, % | $SO_2/CO_2$ ratio, ppm/%V |
|---|---|
| 0.5 | 21.7 |
| 0.1 | 4.3 |

**Table 2**

Main characteristics of fuels

| Characteristic | RMG380 | DMA |
|---|---|---|
| Density @ 15°C, kg/m$^3$ | 987.3 | 874.8 |
| Viscosity @ 50.0°C, cSt | 255.2 | 5.43 |
| Sulphur, % | 3.11 | 0.081 |
| Flash Point, °C | 120 | 81 |
| Net Specific Energy, MJ/kg | 40.20 | 42.43 |

**Table 3**

Operating modes of the ship's power plant

| Mode | Variant of operation of the ship's power plant |
|---|---|
| 1 | 60% load of the main engine STX-MAN B&W 6S60ME-C + 65% load of the auxiliary engine Yanmar 6EY18ALW2 |
| 2 | 75% load of the main engine STX-MAN B&W 6S60ME-C + 70% load of the auxiliary engine Yanmar 6EY18ALW2 |
| 3 | 70% load of the main engine STX-MAN B&W 6S60ME-C + 55% load of two auxiliary engines Yanmar 6EY18ALW2 |
| 4 | 75% load of the main engine STX-MAN B&W 6S60ME-C + 65% load of two auxiliary engines Yanmar 6EY18ALW2 |

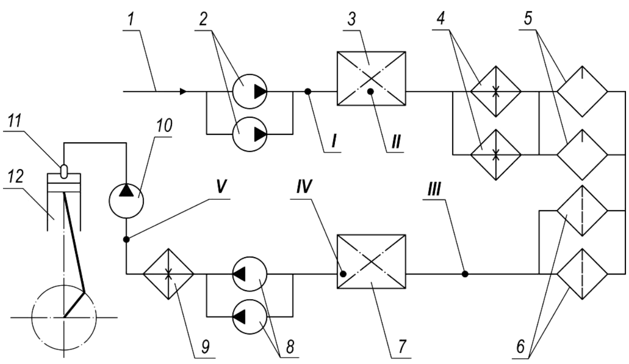


**Fig. 3.** Possible locations for ultrasonic fuel treatment in the fuel system of a marine diesel engine: 1 – fuel supply line during bunkering; 2 – fuel pumps; 3 – settling tank; 4 – heater; 5 – separator; 6 – filter; 7 – supply tank; 8 – booster pumps; 9 – heater; 10 – high-pressure fuel pump; 11 – injector; 12 – diesel; I, II, III, IV, V – possible locations for ultrasonic treatment

Fuel enters the engine room of the vessel through the main line 1. At the same time, the pumps 2 that pump fuel direct the fuel to the settling tank 3. The first cell of the fuel system where its ultrasonic treatment can be carried out is the fuel main line (position I) and the settling tank 3 (position II). In this case, ultrasonic treatment helps to remove heavy sulfur compounds from the fuel, but in return, constant cleaning of the fuel main line and the bottom of the settling tank from their sediment is necessary. The fuel is then heated, separated and filtered in the corresponding modules 3, 4, 5 of the fuel system and enters the supply tank. The section of the fuel main line connecting the separation module 6 and the supply tank 7, as well as the supply tank 7 itself, is the second cell of the fuel system in which it is recommended to perform additional ultrasonic desulfurization of the fuel. These positions are designated as III and IV. At the same time, during fuel desulfurization in the fuel line, it is necessary to monitor its technical condition, which deteriorates due to sedimentation. In the case of desulfurization in a supply tank, the reduction of sulfur content in the fuel is ensured by removing fuel vapors from the open surface of the fuel in the tank [17, 22, 23].

After the supply tank 7, the fuel is sent by the booster pump 8 to the heater 9 and then to the high-pressure fuel pump 10. Using the pump 10, the fuel is supplied under high pressure to the injector 11, which injects it into the diesel cylinder 12.

Another cell of the fuel system recommended for ultrasonic fuel treatment is the section of the fuel line directly in front of the high-pressure fuel pump 10. In this section (cell V in Fig. 1), the fuel is characterized by the highest temperature and the lowest viscosity. This additionally contributes to the removal of sulfur impurities from the fuel.

Experimental results have shown that the desulfurization process is most effective when ultrasonic fuel treatment is carried out in the supply tank (cell IV in Fig. 1) and directly in the fuel line in front of the high-pressure fuel pump (cell V in Fig. 1). In this case, cell IV can be considered as the first stage of ultrasonic fuel treatment, cell V as the second stage.

## 3. Results and Discussion

All studies were performed using licensed measuring equipment, which was equipped with the Exhaust Gas Cleaning System, as well as STX-MAN B&W 6S60ME-C and Yanmar 6EY18ALW2 marine diesel engines. The studies were performed exclusively on stable operating modes of marine diesel engines and, accordingly, the Exhaust Gas Cleaning System. Before registering the performance indicators of the Exhaust Gas Cleaning System, the diesel engines were operated for 0.5–1 hour in the selected operating mode. This ensured the stability of the measured indicators. The duration of the studies in each mode was 2–3 hours. The main indicators used to assess the efficiency of the Exhaust Gas Cleaning System were the volumetric concentration of carbon dioxide $CO_2$, the relative concentration of sulfur dioxide $SO_2$ and their ratio $SO_2/CO_2$. These values were recorded by the Exhaust Gas Cleaning System automatic registration unit and stored in the corresponding archive files and simultaneously visualized on the control monitor screen (similar to those shown in Fig. 2).

The operating modes in which the studies were performed corresponded to the modes given in Table 3. Measurement of all operational indicators of diesel engines was performed using the Doctor ship registration, control and diagnostic system.

Additional ultrasonic treatment of fuel was performed in the fuel tank (according to the scheme given in Fig. 2) by direct irradiation of fuel using an ultrasonic generator. The range of optimal frequency of ultrasonic waves was determined in previous laboratory studies for different sulfur contents in fuel [47].

The results of the studies are given in Table 4.

For better visualization, the results given in Table 4 are presented in the form of Fig. 4–7.

**Table 4**

Determination of indicators of the exhaust gas scrubber system

| Operating mode* | Exhaust gas scrubbing | | | Exhaust gas scrubbing and additional ultrasonic fuel treatment | | |
|---|---|---|---|---|---|---|
| | $CO_2$, % | $SO_2$, ppm | $SO_2/CO_2$, ppm/% | $CO_2$, % | $SO_2$, ppm | $SO_2/CO_2$, ppm/% |
| While inside SECAs | | | | | | |
| 1 | 4.5 | 17.2 | 3.82 | 4.4 | 14.0 | 3.18 |
| 2 | 4.5 | 16.1 | 3.58 | 4.5 | 13.4 | 2.98 |
| 3 | 4.9 | 19.9 | 4.06 | 4.8 | 15.1 | 3.15 |
| 4 | 5.1 | 20.5 | 4.02 | 5.0 | 16.3 | 3.26 |
| While outside SECAs | | | | | | |
| 1 | 5.3 | 97.2 | 18.34 | 5.2 | 85.3 | 16.40 |
| 2 | 5.2 | 102.6 | 19.73 | 5.0 | 84.8 | 16.96 |
| 3 | 5.4 | 106.3 | 19.69 | 5.3 | 92.3 | 17.42 |
| 4 | 5.2 | 103.8 | 19.96 | 5.1 | 89.3 | 17.51 |

**Note:** Modes 1, 2, 3, 4 correspond to those given in Table 3

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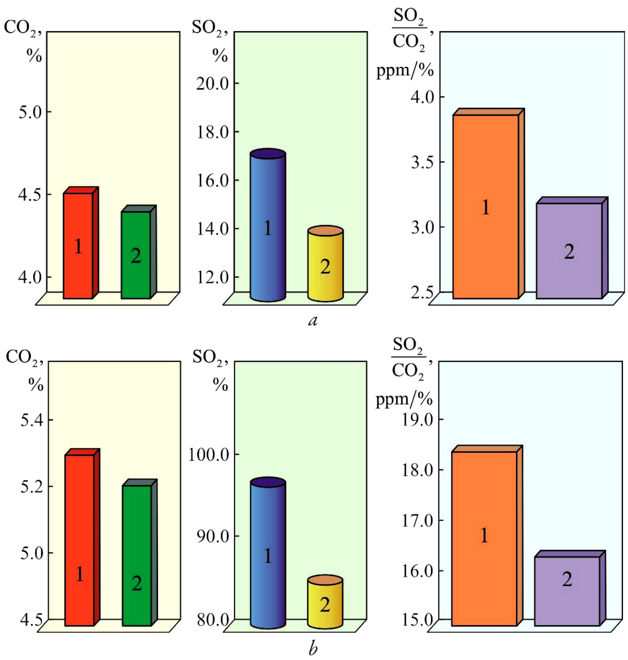


**Fig. 4.** Performance indicators of scrubber exhaust gas cleaning systems (mode 1): 1 – without additional ultrasonic fuel treatment; 2 – with additional ultrasonic fuel treatment; *a* – operation inside SECAs; *b* – operation outside SECAs

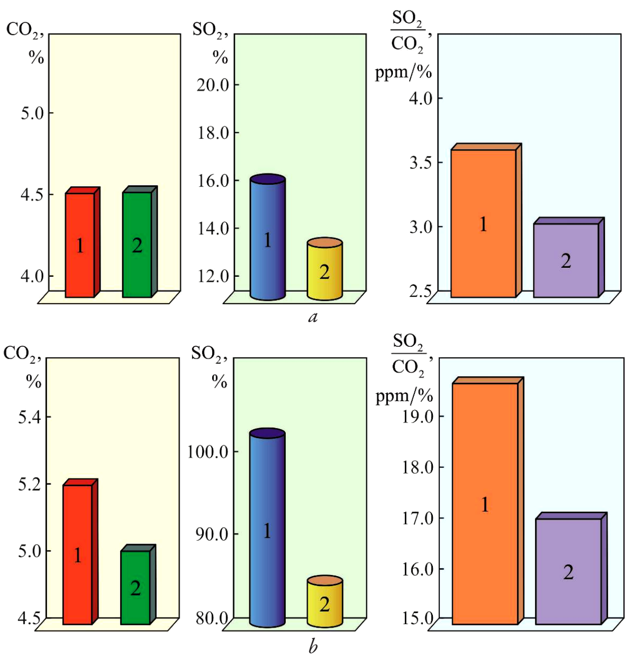


**Fig. 5.** Performance indicators of scrubber exhaust gas cleaning systems (mode 2): 1 – without additional ultrasonic fuel treatment; 2 – with additional ultrasonic fuel treatment; *a* – operation inside SECAs; *b* – operation outside SECAs

The relative reduction in emissions of harmful substances – carbon dioxide $\Delta CO_2$, sulfur dioxide $\Delta SO_2$, as well as their ratio $\Delta(SO_2/CO_2)$, was calculated using the expressions

$$\left.\begin{aligned} \Delta CO_2 &= \frac{CO_2^- - CO_2^{UST}}{CO_2^-}\cdot 100\%,\\ \Delta SO_2 &= \frac{SO_2^- - SO_2^{UST}}{SO_2^-}\cdot 100\%,\\ \Delta\left(SO_2/CO_2\right) &= \frac{\left(SO_2/CO_2\right)^- - \left(SO_2/CO_2\right)^{UST}}{\left(SO_2/CO_2\right)^-}\cdot 100\%, \end{aligned}\right\} \quad (1)$$

where $CO_2^-$, $SO_2^-$, $(SO_2/CO_2)^-$ – emission of carbon dioxide, sulfur dioxide, as well as their ratio for the corresponding operating mode of the exhaust gas cleaning system without the use of additional ultrasonic fuel treatment; $CO_2^{UST}$, $SO_2^{UST}$, $(SO_2/CO_2)^{UST}$ – the values of the same indicators when using additional ultrasonic fuel treatment.

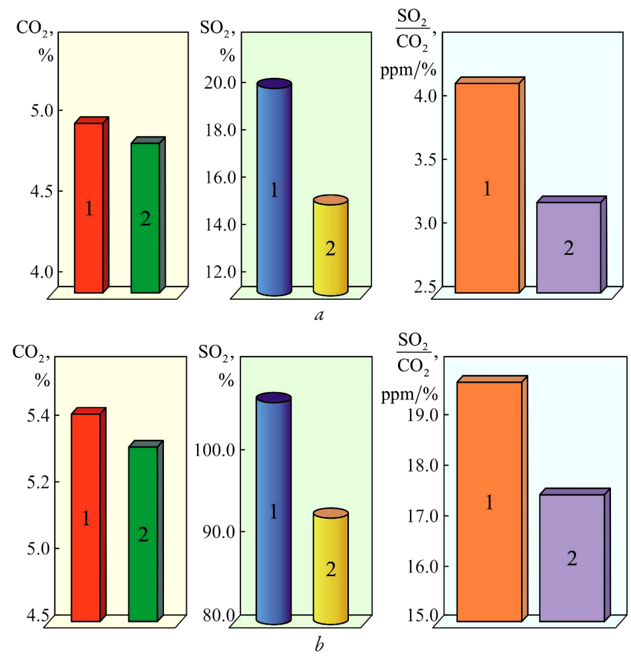


**Fig. 6.** Performance indicators of scrubber exhaust gas cleaning systems (mode 3): 1 – without additional ultrasonic fuel treatment; 2 – with additional ultrasonic fuel treatment; *a* – operation inside SECAs; *b* – operation outside SECAs

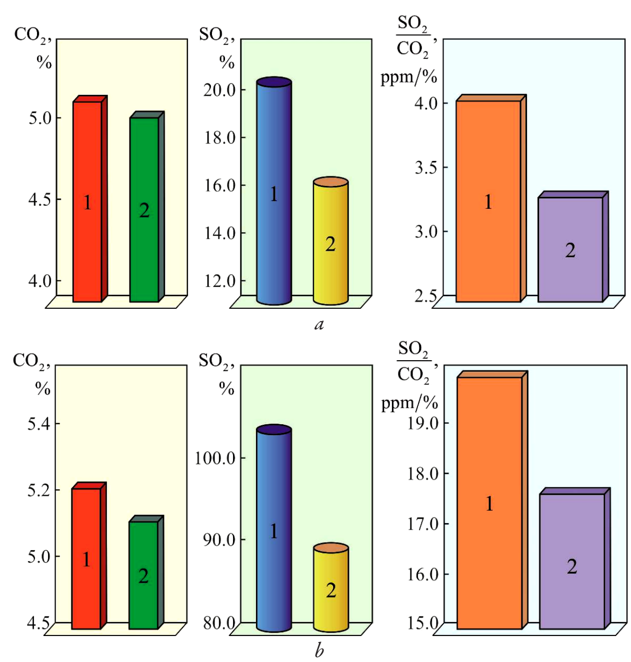


**Fig. 7.** Performance indicators of the scrubber exhaust gas cleaning system (mode 4): 1 – without additional ultrasonic fuel treatment; 2 – with additional ultrasonic fuel treatment; *a* – operation inside SECAs; *b* – operation outside SECAs

Taking into account the numerical values given in Table 4, the values given in Table 5 were obtained using expressions (1).

The use of additional ultrasonic fuel treatment increases the efficiency of the scrubber exhaust gas cleaning system. This is reflected in the improvement of the environmental performance of marine diesel engines – a reduction in carbon dioxide $CO_2$, sulfur dioxide $SO_2$, as well as the $SO_2/CO_2$ ratio. The $SO_2/CO_2$ ratio is the indicator regulated by the requirements of Annex VI MARPOL in the case of using exhaust gas cleaning systems from sulfur oxides. In addition, this ratio is monitored during the environmental performance check of the ship's power plant.

**Table 5**

Relative reduction of emissions of harmful substances when using additional ultrasonic fuel treatment

| Operating mode* | While inside SECAs | | | While outside SECAs | | |
|---|---|---|---|---|---|---|
| | $\Delta CO_2$, % | $\Delta SO_2$, % | $\Delta(SO_2/CO_2)$, % | $\Delta CO_2$, % | $\Delta SO_2$, % | $\Delta(SO_2/CO_2)$, % |
| 1 | 2.22 | 18.60 | 16.75 | 1.89 | 12.24 | 10.56 |
| 2 | 2.22 | 16.77 | 16.77 | 3.85 | 17.35 | 14.04 |
| 3 | 2.04 | 24.12 | 22.54 | 1.85 | 13.17 | 11.53 |
| 4 | 1.96 | 20.49 | 18.90 | 1.92 | 13.97 | 12.28 |

**Note:** modes 1, 2, 3, 4 correspond to those given in Table 3

Ultrasonic fuel treatment has the most effective effect on sulfur-containing fuel components. This is reflected in a significant reduction in sulfur oxide emissions.

During additional ultrasonic treatment of fuel (similar to the case of operating the diesel fuel system without its use), all necessary indicators of the operating cycle were monitored: pressure at the end of compression, maximum combustion pressure, exhaust gas temperature.

Additional ultrasonic treatment of fuel did not affect its viscosity, density, temperature and was not reflected in the cyclic supply. Also, no additional hydraulic losses occurred in the fuel system, which was confirmed by the constancy of pressure and fuel consumption before and after the points of its implementation.

The conducted studies confirm the feasibility of using additional ultrasonic treatment of fuel as a method that contributes to the improvement of the process of cleaning exhaust gases of marine diesel engines from sulfur oxides. The results obtained indicate the effectiveness of the complex action on the emission of sulfur oxides with exhaust gases. In this case, the reduction of sulfur oxides emissions is ensured by a double effect: by activating sulfur-containing components in the fuel composition and direct gas cleaning. The first is performed using additional ultrasonic fuel treatment, the second is performed in the exhaust gas scrubber system installed on the ship. Previous and one-way studies did not take this feature into account, therefore they were characterized by a lower degree of cleaning and forced the use of other types of fuel with a higher cost [38, 39, 47].

*The limitations of research* include the need to install equipment that provides additional ultrasonic fuel treatment. First of all, electrical cables, which are used to power the ultrasonic generator. The compressed volumes of the engine room of seagoing vessels, the increased compactness of the placement of power and auxiliary equipment (including consumable tanks) complicate the performance of such technological operations.

Also, ultrasonic fuel treatment is associated with determining the optimal frequency and amplitude of ultrasonic waves acting on sulfur-containing substances. As a rule, in different bunkering ports, marine fuels are characterized by different component composition, including different sulfur content. This requires additional research to determine the optimal frequency and amplitude of ultrasound for each type of fuel taken on board the ship.

*The development of the considered process* consists in accumulating information on determining the optimal operating modes of ship equipment that provides ultrasonic treatment of different types of fuel. In addition, ultrasonic treatment of fuel requires conducting research aimed at adjusting the operation of the exhaust gas scrubber system. Also, the prospects for further research should include determining the most rational (from the point of view of economic and energy efficiency) modes of joint operation of equipment that provides ultrasonic treatment of fuel and exhaust gas scrubber.

## 4. Conclusions

1. The most rational unit of the ship's fuel preparation system for additional ultrasonic treatment is the consumable tank. It is in this unit that it is necessary to install a generator that provides irradiation of the fuel with ultrasonic waves of a certain frequency and amplitude.

2. Additional ultrasonic treatment of fuel has almost no effect on the emission of carbon dioxide $CO_2$, while it significantly affects compounds containing sulfur. This is reflected in the reduction of sulfur dioxide emissions $SO_2$ and the $SO_2/CO_2$ ratio – an indicator that is the main one when assessing the efficiency of the exhaust gas scrubber system.

For different operating modes of the ship's power plant, it was found that the relative reduction in emissions of harmful substances when using additional ultrasonic treatment of fuel is: while inside SECAs (where, according to the requirements of Annex VI MARPOL, the $SO_2/CO_2$ ratio should not exceed 4.3):
– for sulfur dioxide emissions $SO_2$ 16.77–24.12%;
– for the $SO_2/CO_2$ ratio 16.75–22.54%; while outside SECAs (where, according to the requirements of Annex VI MARPOL, the $SO_2/CO_2$ ratio should not exceed 21.7):
– for sulfur dioxide emissions $SO_2$ 12.24–17.35%;
– for the $SO_2/CO_2$ ratio 10.56–14.04%.

It is also possible to emphasize the greater efficiency of using additional ultrasonic treatment when ships are inside SECAs, i. e. in coastal waters. It is these marine areas that are subjected to the greatest negative impact from means of transport and are subject to the most stringent environmental requirements and standards.

## Conflict of interest

Authors declare that they have no conflict of interest in relation to this research, including financial, personal, authorship, or any other, that could affect the research and its results presented in this article.

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## Data availability

The manuscript has no associated data.

## Use of artificial intelligence

The authors confirm that they did not use artificial intelligence technologies when creating the presented work.

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