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Article

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ANALYSIS OF METHODS OF MANAGING THE ENVIRONMENTAL SAFETY OF THE NAVIGATION PASSAGE OF SHIPS OF MARITIME TRANSPORT

The requirements of the MARPOL international convention on ensuring the environmental performance of marine diesel engines in relation to the emission of sulfur oxides, as well as marine fuels during navigation passages of sea transport vessels in special ecological areas, are given. The use of scrubber cleaning of exhaust gases and the use of fuel mixtures, which include biodiesel fuel, are considered as methods that meet these requirements. The research was carried out on ships of the Bulker Carrier class with deadweight of 63,246 tons during the navigation transition between the ports of Northern Europe. One of the vessels used scrubber cleaning of exhaust gases as a method of environmental safety management. The other is the use of fuel mixtures, which include biodiesel fuel. Both vessels are equipped with a 5S60ME-C8.2 MAN-Diesel&Turbo marine diesel engine as the main engine, and three 6EY18ALW Yanmar diesel engines as auxiliary engines. The ratio of sulfur oxides to carbon oxides – SO_2/CO_2 – was chosen as an indicator for evaluating the effectiveness of environmental safety management methods. This value was monitored and regulated by an automatic monitoring system. It was found that both methods meet the requirements of the MARPOL convention, namely, they will support the SO_2/CO_2 ratio in the range of 2.29–4.17 (when in special environmental control zones) and in the range of 6.46–20.83 (when in outside the zone of special environmental control). The use of environmental safety management methods increases energy costs for ensuring this process. When using exhaust gas scrubbing, additional power losses reach 237–278 kW. In the case of using a fuel mixture that includes biodiesel fuel, power losses amount to 18–20 kW. It has been experimentally confirmed that the use of a fuel mixture that includes biodiesel fuel is characterized by a lower level of environmental sustainability. At the same time, compared to the use of scrubber cleaning of exhaust gases, this method requires less energy consumption and is also characterized by simpler additional equipment. In this regard (and also taking into account that all the requirements of Annex VI MARPOL are provided), it is recommended as the main one to ensure the environmental safety of navigation passages of sea transport vessels.

Keywords: *biodiesel fuel, environmental safety, emission of sulfur oxides, sea transport, navigation passage, exhaust gas scrubbing.*

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1. Introduction

Ensuring the commercial operation of sea transport vessels is impossible without maintaining the safety of navigation passages. At the same time, it is necessary to guarantee not only the safety of navigation and the operation of the ship's power plant, but also the environmental safety of the sea ship. Environmental safety of the ship is a complex indicator and includes: safe management of ballast operations, maintaining a safe technical condition of the ship's hull, ensuring the requirements of international conventions on environmental protection from pollution. Management of ecological safety of navigation crossings is especially relevant when sea transport vessels are in the 12-mile coastal zone, in special ecological areas and water areas of inland seas.

Navigation of marine vessels is impossible without the use of a source of thermal energy. Even for small sailing ships, sails are used as an additional source that provides movement, and a heat engine is installed as the main one. Internal combustion engines (diesels) are the most common heat engines used in transport [1, 2]. Diesels are sources of mechanical energy for automobile, railway, sea and inland water transport, as well as agricultural and mobile (small or portable) equipment [3, 4]. It is diesel engines that are currently dominant on all sea and inland water transport vessels without exception, regardless of their displacement, type and purpose. Leading diesel engineering concerns and companies produce marine diesels in a wide range of sizes (cylinder diameter from 0.1 m to 0.98 m), number of cylinders (from 4 to 18) and power (from 100 kW to almost 100,000 kW) [5–7].

Providing the ship with the necessary energy (which is used both for movement and for the operation of all ship machines, mechanisms, equipment and devices), diesel engines emit a large amount of exhaust gases into the atmosphere. Most of the exhaust gases are non-toxic components (carbon dioxide CO_2, water vapor H_2O, as well as atomic oxygen O_2 and nitrogen N_2). However, along with it, toxic impurities harmful to the environment and humans enter the atmosphere. These include nitrogen oxides NO_X, sulfur oxides SO_X, carbon monoxide CO, and unburned hydrocarbons C_nH_m. The minimization of NO_X, SO_X, CO emissions that enter the atmosphere with the exhaust gases of marine diesels is an urgent task, many studies and developments are directed to its solution [8–10].

The solution to the problem of managing the environmental safety of navigation crossings was considered by various researchers.

To reduce the emission level of nitrogen oxides, it was proposed to use recirculation of exhaust gases [11, 12], additional purification in special catalytic reactors [13, 14], as well as to apply technologies of humidification of supercharged air and water supply to the diesel cylinder [15, 16]. However, at the same time, the effective power of the diesel engine decreases and the specific fuel consumption increases [17, 18].

Studies [19, 20] have shown that a decrease in the concentration of carbon monoxide in exhaust gases is possible due to their additional filtration and cooling. At the same time, it was established that similar technological solutions increase aerodynamic resistance in the exhaust pipe. This is the reason for the decrease in the energy efficiency of the working cycle of the diesel engine [21, 22]. One of the options for reducing carbon monoxide emissions is the adjustment of the navigation passage taking into account the current and air currents [23, 24]. This method reduces the total fuel consumption per mile of sailing, however, its use is possible only in limited sea and ocean water areas [25, 26].

A reduction in the emission of sulfur oxides is provided by fuel desulfurization [27, 28]. In marine conditions, this is achieved by ultrasonic or hydrodynamic fuel treatment. However, at the same time, only the technical condition of the cylinder group and the gas exhaust line of the diesel engine improves significantly. The concentration level of sulfur oxides in the exhaust gases decreases slightly with similar fuel processing. The main method of reducing the emission of sulfur oxides with exhaust gases is the use of fuel with a sulfur content of up to 0.1 % by mass. In accordance with the international standard ISO 8217 «Fuel Standard for marine distillate fuels», these types of marine fuels belong to the Marine Gas Oil class and are characterized by the highest cost compared to fuels of other classes. The use of such fuels reduces the economic efficiency of sea transport vessels. This is one of the reasons for using scrubber cleaning of exhaust gases, in which it is possible to use fuel with a sulfur content of up to 3.5 %.

One of the methods of ensuring the environmental safety of marine and inland water transport vessels is the use of fuel of biological origin [29, 30]. The sulfur content in these types of fuel does not exceed 0.03 % by mass (which significantly reduces emissions of sulfur oxides). The cost of biofuel is less than the cost of Marine Gas Oil fuel with a sulfur content of 0.1 %. Biofuel is actively used in diesel engines of automobile and railway transport, as well as in stationary power generation [31, 32]. The use of biofuel on marine vessels has few examples and is based on operational experience for certain diesel engines and their specific operating modes [33, 34]. At the same time, in many ports there is already the possibility of bunkering with biofuel, which expands the prospects of its use both as part of fuel mixtures with fuel of petroleum origin, and as an independent fuel.

In this regard, *the aim of research* was to assess the possibility of using biofuel in marine diesel engines, as well as to compare its effectiveness with other methods that ensure the maintenance of ecological safety of navigation passages of sea vessels. At the same time, it is necessary to establish the influence of biofuel on the emission of sulfur oxides with the exhaust gases of marine diesel engines. From a practical point of view, this will make it possible to recommend the use of fuel mixtures that contain biofuel as one of the methods of managing the environmental safety of marine transport vessels.

2. Materials and Methods

The object of research is the process of ensuring the necessary concentration of sulfur oxides in the exhaust gases of marine diesel engines.

The main environmental indicators of marine diesels are determined by the emission of nitrogen oxides NO_X and sulfur oxides SO_X, which enter the environment with exhaust gases. NO_X and SO_X emission values are regulated by the requirements of Annex VI MARPOL [17, 23, 35]. The maximum permissible concentration of NO_X in exhaust gases is determined by special expressions depending on the year of construction of the ship and the characteristics of the diesel engine. SO_X emissions are regulated by the mass content of sulfur in marine fuel. From 01.01.2020, in accordance with Annex VI MARPOL, the sulfur content in the fuel should not exceed 0.1 % under the condition that the ship is operated in Sulfur Emission Control Areas (SECAs) and no more than 0.5 % during operation vessels outside the SECAs. The special zones of SECAs are defined by the International Maritime Organization (IMO) and are shown in Fig. 1. For European countries, these include the waters of the North and Baltic Seas, as well as Mediterranean ports.

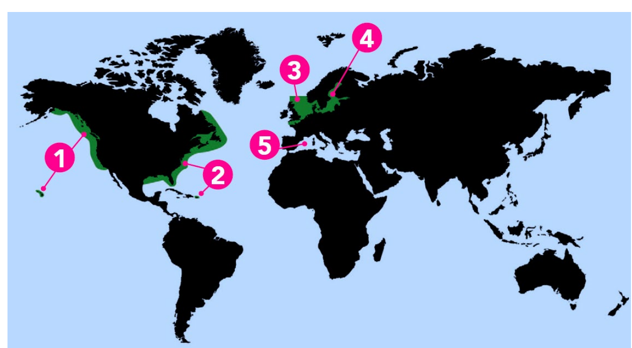

Fig. 1. Areas of SECAs in accordance with IMO requirements: 1 – The North American SECA, including most of the US, Canadian coast and Hawaii; 2 – The US Caribbean SECA, including Puerto Rico and the US Virgin Islands; 3 – The North Sea SECA, including The English Channel; 4 – The Baltic Sea SECA; 5 – All EU Ports

The use of fuel with a sulfur content of more than 0.5 % by mass is possible only under the condition of additional cleaning of the exhaust gases in special technical devices (as scrubbers are usually installed) [36, 37].

In the case of managing the environmental safety of the navigation crossing with the help of additional exhaust gas cleaning, the SO_2 (ppm)/CO_2 (%) ratio after the scrubber is controlled. This value should not exceed the value of 4.1 SO_2/CO_2 when the ship is in the SECAs and the value of 21.7 SO_2/CO_2 when the ship is outside the SECAs.

The requirements of Annex VI MARPOL regarding the control of the emission of sulfur oxides are shown in the Table 1.

Table 1

Annex VI MARPOL requirements regarding the emission of sulfur oxides

Where and when applicable	Fuel oil sulphur content, %	Ratio emission SO_2 (ppm)/CO_2 (%)
Outside an Emission Control Areas (ECA) or EU port starting from 1 Jan 2020	0.5	21.7
Inside an Emission Control Areas (ECA) or EU port starting from 1 Jan 2015	0.1	4.3

Maintenance of ecological safety of power plants of marine transport vessels is possible due to the use of alternative fuels.

One of the types of ecologically clean fuel of biological origin is biodiesel fuel (biodiesel), which is obtained from vegetable fats and oils by treating them with methanol or ethanol [38, 39]. According to the Eurostandard DIN EN 14214-2019 «Liquid petroleum products. Fatty acid methyl esters for use in diesel engines and heating applications», such fuel is classified as FAME. Ego is recommended for use in diesel engines of automobile and railway transport, and diesel power plants. At the same time, the restriction of the use of biodiesel fuel on ships is due to its short shelf life. This limits its use during long ocean or sea crossings [1, 23].

Another disadvantage of biodiesel fuel is its lower energy efficiency compared to petroleum fuel, which does not allow it to be used as an independent source of energy, and requires the creation of fuel mixtures in which the majority consists of petroleum fuel, and biodiesel fuel is used as an additive [6, 14].

However, the experience of using such mixtures allows for the gradual introduction of biodiesel fuel on ships with diesel engines. This is also facilitated by comparable values of density and viscosity of biodiesel and petroleum fuel [25, 40]. One of the indisputable advantages of using mixtures of biodiesel and petroleum fuel is the improvement of the environmental performance of diesel engines on ships, especially the reduction of the concentration of sulfur and nitrogen oxides in the exhaust gases [8].

The research was carried out on two specialized ships of the Bulker Carrier class of the same type with deadweight of 63,246 tons. The ship's power plant included 5S60ME-C8.2 MAN-Diesel&Turbo and 6EY18ALW Yanmar diesels. The main characteristics of diesel engines are presented in Table 2.

One of the vessels used a scrubber system for additional purification of exhaust gases from sulfur oxides (Fig. 2). This made it possible to use fuel with a sulfur content of up to 3.5 % by mass for marine diesel engines.

Table 2

The main characteristics of the diesel engines of the Bulker Carrier class ship with a deadweight of 63,246 tons

Parameter	5S60ME-C8.2 MAN-Diesel&Turbo	6EY18ALW Yanmar
Cylinder diameter, m	0.6	0.18
Piston stroke, m	2.4	–
Number of cylinders	5	6
Power at nominal load, kW	8050	800
Shaft rotation frequency, min^{-1}	89	900
Specific fuel consumption in the range of operating loads 45–100 %, kg/(kW·h)	0.187–0.174	0.198–0.183
Quantity in the composition of the ship's power plant	1	3

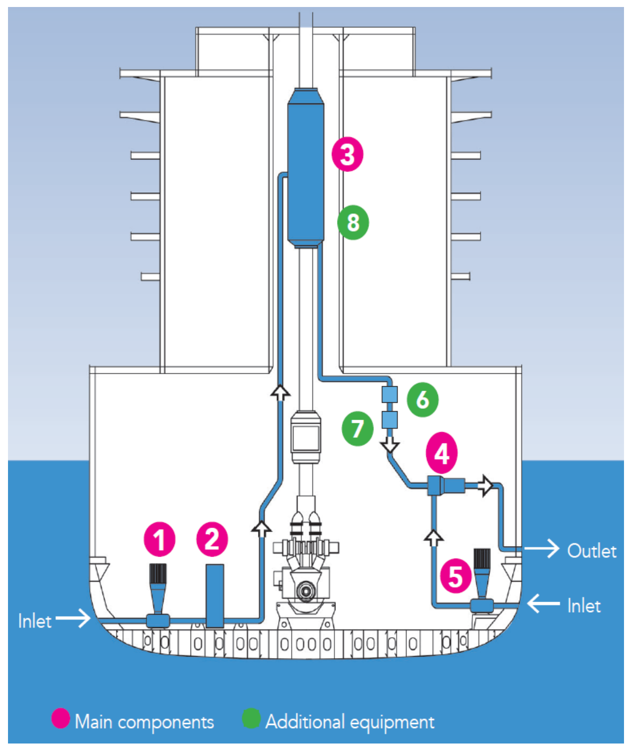

Fig. 2. Completion of the ship exhaust gas purification system: 1 – intake (sea) water pump; 2 – intake (sea) water filter; 3 – scrubber; 4 – mixer; 5 – buffer pump; 6 – degassing unit; 7 – filtration unit; 8 – exhaust gas cooler

Exhaust gas cleaning was carried out in the open type. Gases from the main engine and three auxiliary engines (not shown in Fig. 2) entered scrubber 3. Seawater was used to clean the gases, which was supplied to scrubber 3 by seawater pump 1 through filter 2. The performance of pump 1 (depending on the sulfur content in fuel, power of the main engine, as well as the number of working auxiliary engines) varied in the range of 200–550 kg/h. The temperature of gases in scrubber 3 was maintained in the range of 200–300 °C. In case of exceeding this value, the gases were cooled with the help of the cooler 8. After the scrubber 3, the water entered the degassing block 6 and the filtration block 7, in which gases and solid impurities were separated from the water. Then the water poured overboard. In order to maintain the necessary level of acidity (the level of which was maintained in the range of pH=6.8–7.0), sea water was added to the water flowing overboard in mixer 4. The supply of seawater to mixer 4 was carried out by buffer pump 5. The capacity of the buffer pump varied in the range of 200–300 kg/h. The operation of all system elements was controlled automatically. The required SO_2/CO_2 ratio was also automatically maintained. This was achieved by changing the output of the seawater pump 1.

The system provides the required level of exhaust gas purification in the following operating range of the ship's power plant:

– minimum operating mode – operation of one 6EY18ALW Yanmar auxiliary engine at any load;

– the maximum operating mode – operation of the main engine 5S60ME-C8.2 MAN-Diesel&Turbo at a load of 85 % and two auxiliary engines 6EY18ALW Yanmar at a load of 85 %.

Also, the system can be operated under the condition of 105 % load of the main 5S60ME-C8.2 MAN-Diesel&Turbo engine and a total load of 6EY18ALW Yanmar auxiliary engines of 150 %.

The system provides automatic registration of the location of the ship, the load on the main engine and auxiliary engines, parameters of sea water in the purification circuit, as well as the current value of SO_2/CO_2. Registration of these data is performed at 3-minute intervals. A fragment of the table with the registration of system parameters is shown in Fig. 3.

In all operational modes, as well as in all areas of navigation (inside and outside SECAs), the main engine 5S60ME-C8.2 MAN-Diesel&Turbo and auxiliary engines 6EY18ALW Yanmar were operated using RMG380 fuel [41, 42].

On the second ship, additional cleaning of exhaust gases was not carried out. In this regard, DMA fuel was used when diesel engines were operated in SECAs, RME180 fuel was used when diesel engines were operated outside SECAs [43, 44]. On the same ship, a technology was implemented that allows the use of biodiesel fuel, which used B30 fuel of the FAME class [45, 46].

The main characteristics of fuels are shown in the Table 3.

The schematic diagram of the fuel system, which allowed the use of marine engine fuels DMA and RME180, as well as biodiesel fuel FAME B30, is shown in Fig. 4.

The operation of the main engine 16 and auxiliary engines 10, 11, 12 was possible on DMA fuel (while the ship was in SECA) and RME180 fuel (when the ship was outside SECA). In addition, diesel engines could run on a mixture of DMA, RME180 and FAME B30 biodiesel fuel. The content of FAME B30 biodiesel fuel in its mixture with DMA or RME180 fuel was 20 %. This concentration was determined as optimal during previous studies. Fuel supply to the engines was carried out by fuel pump 3 (from the RME180 fuel tank), fuel pump 6 (from the DMA fuel tank), fuel pump 9 (from the FAME B30 fuel tank). Fuel purification was provided in filters 2, 5, 8. The necessary concentration of FAME B30 biodiesel fuel in its mixture with DMA or RME180 fuel was provided by the dispenser 15 depending on the readings of the flow meter 13 and controlled by the microcontroller 14 [47, 48].

At the time of research, both ships were making a navigational transition between the ports of Aughinish (Ireland) and Tallinn (Estonia). With an intermediate call at the ports of Scagen (Denmark), Kalundborg (Denmark), Gdynia (Poland). When moving from the port of Aughinish to the port of Scagen, ships entered the Baltic SECA. The plan of the navigation transition is shown in Fig. 5. The characteristics of the navigation transition are given in the Table 4.

Data and Time UTC	Latitude			Longitude			Load, %				Parameters of sea water in the treatment system			Ratio SO_x/CO_2 [ppm/%]
	degrees	minutes	seconds	degrees	minutes	seconds	ME	AE No. 1	AE No. 2	AE No. 3	Flow [m^3/h]	Temperature at overboard discharge [°C]	Ph at overboard discharge	
12/07/20 2309:02	58	28	78	1	29	87	78	68	0	0	171	25	6.9	2.43
12/07/20 2309:05	58	28	78	1	28	87	78	54	0	55	302	25	6.9	2.48
12/07/20 2309:08	58	28	78	1	27	87	77	55	0	55	306	25	6.9	2.45
12/07/20 2309:11	58	27	78	1	26	87	77	55	0	55	307	25	7.0	2.45

Fig. 3. Fragment of the table with the registration of the parameters of the exhaust gas cleaning system of the Bulker Carrier class ship with a deadweight of 63,246 tons (ME – mean engine; AE – auxiliary engine; Ph – acid number)

Table 3

Characteristics of fuels

Parameter	RMG380	RME180	DMA	FAME B30
Viscosity at 50 °C, sSt	329	184	12.8	36.3
Density at 15 °C, kg/m^3	986	928	896	914
Sulfur content, %	2.7	0.48	0.082	0.018
Flash temperature, °C	81	73	67	71
Calorific value, kJ/kg	39070	40480	43420	36890

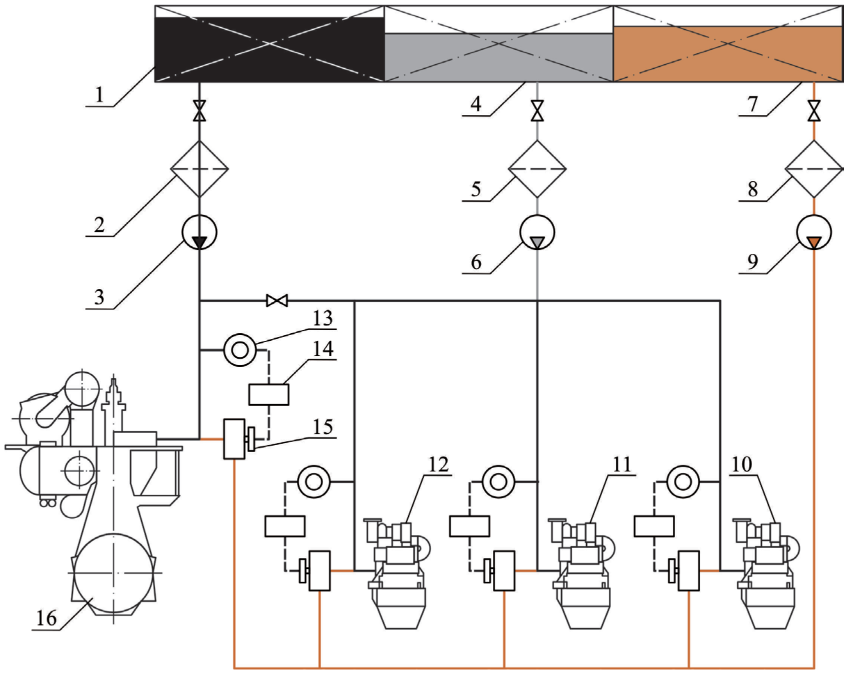

Fig. 4. Schematic diagram of the fuel system: 1 – RME180 fuel tank; 2, 5, 8 – fuel filter; 3, 6, 9 – fuel pump; 4 – DMA fuel tank; 7 – FAME B30 fuel tank; 10 – auxiliary engine No. 3; 11 – auxiliary engine No. 2; 12 – auxiliary engine No. 1; 13 – flow meter; 14 – microcontroller; 15 – dispenser; 16 – main engine

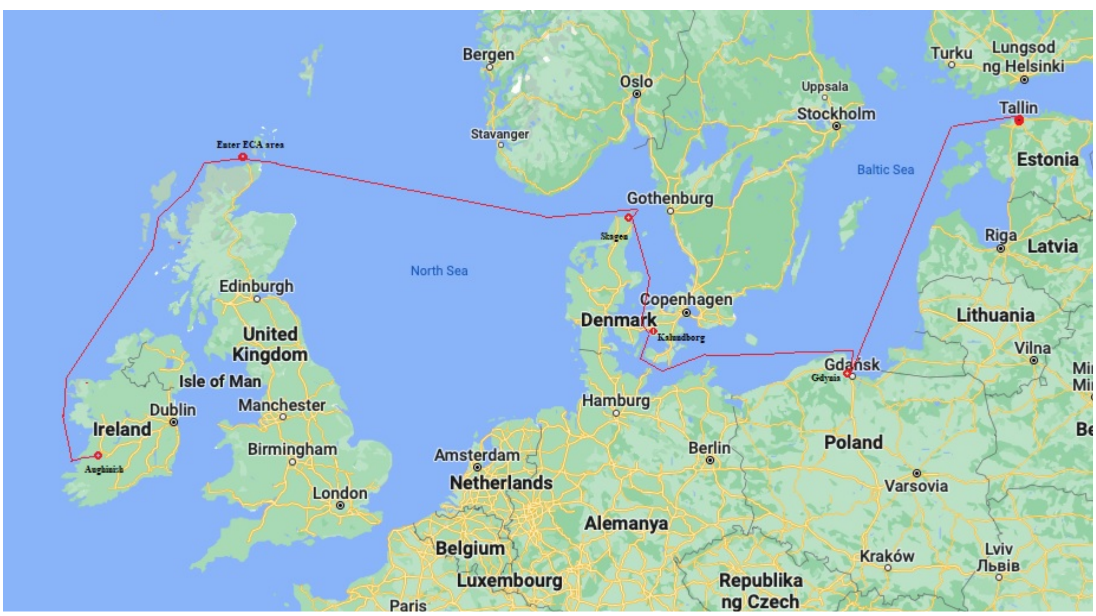

Fig. 5. Plan of the navigation transition

Table 4

Characteristics of the navigation transition

Port of departure	Port of arrival	Distance, nautical miles	Time to go, hours
Aughinish (Ireland)	Enter Baltic SECA	519	47
Enter Baltic SECA	Scagen (Denmark)	508	46
Scagen (Denmark)	Kalundborg (Denmark)	155	14
Kalundborg (Denmark)	Gdynia (Poland)	397	36
Gdynia (Poland)	Tallinn (Estonia)	419	38

During the entire navigation passage, both ships carried the same cargo and performed the same cargo operations in the unloading ports. This ensured the identity of the external conditions during the experiments and the identity of the loads on the main engine of the ships. The loads on the auxiliary engines were also maintained identically for each of the vessels. This was ensured by the same loads on marine energy consumers.

3. Results and Discussion

The automatic monitoring program of the exhaust gas cleaning system (a fragment of which is shown in Fig. 3) made it possible to control its main parameters. However, for the analysis of the efficiency of the exhaust gas cleaning system, only the change in the ratio of the emission

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of sulfur oxides to carbon oxides in time $SO_2/CO_2 = f(t)$ was considered.

The results of these studies (for the navigation transition, the characteristics of which are indicated in Table 4) are shown in Table 5. The values of the relation SO_2/CO_2 were recorded by the monitoring system every 3 minutes. To reduce the volume of information, the values in Table 5 are shown after 5 hours (when working outside SECA) and after 10 hours (when working in SECA).

For better visualization, the obtained values are presented in the form of Fig. 6.

The effectiveness of the ecological safety management method can be estimated by the expression that characterizes the environmental sustainability of the ship:

$$Eco^{+} = \frac{\left(\frac{SO_2}{CO_2}\right)_{max} - \left(\frac{SO_2}{CO_2}\right)_{t}}{\left(\frac{SO_2}{CO_2}\right)_{max}} \cdot 100\%,$$

where $(SO_2/CO_2)_{max}$ – the maximum value for the ship's operating conditions (in SECA or outside SECA) SO_2/CO_2; $(SO_2/CO_2)_t$ – the ratio at time t.

The larger the value of Eco^{+}, the farther the dependence is from the maximum permissible value $SO_2/CO_2 = f(t)$ – Fig. 6, the environmental sustainability of the ship and the environmental safety of the navigation crossing are higher.

The values of environmental sustainability for different methods of managing environmental safety are shown in the Table 6.

The nomograms are constricted for better visualization according to the results of the Table 5 – Fig. 7.

The use of ecological safety management methods is always associated with an increase in energy costs for their maintenance.

In the case of the scrubber cleaning system, additional energy costs are associated with the use of sea water pumps and buffer pumps (items 1 and 5 in Fig. 2). In addition, the use of scrubber cleaning reduces the power of the main and auxiliary engines by 1.0–1.5 %. This is due to the increase in aerodynamic resistance in the gas exhaust line of diesel engines.

In the case of using a fuel mixture that contains biodiesel fuel, additional energy costs are associated with the operation of the biodiesel fuel pump (item 9 in Fig. 4).

Table 5

SO_2/CO_2 monitoring during a navigation transition

Work outside SECA			Work in SECA					
Time, hours	SO_2/CO_2		Time, hours	SO_2/CO_2		Time, hours	SO_2/CO_2	
	1	2		1	2		1	2
5	7.22	18.72	50	2.51	3.75	120	2.47	3.80
10	6.82	19.21	60	2.48	4.02	130	2.48	4.05
15	6.94	17.72	70	2.48	3.72	140	2.47	3.72
20	7.74	18.68	80	2.45	3.18	150	2.44	3.63
25	7.78	20.02	90	2.47	3.82	160	2.29	3.53
30	7.62	20.83	100	2.49	4.17	170	2.34	3.61
35	6.53	19.22	110	2.48	4.15	180	2.32	3.68
40	6.55	18.32	–	–		–	–	
45	6.46	18.82	–	–		–	–	

Notes: 1 – use of scrubber cleaning system; 2 – use of a fuel mixture with biodiesel fuel

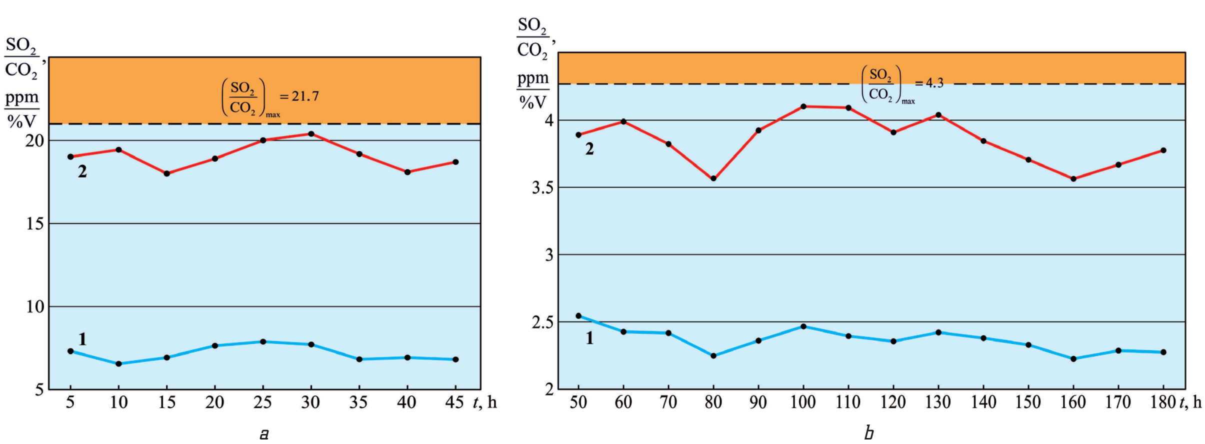

Fig. 6. Changing the relationship with different methods of managing the environmental safety of the navigation passage of a Bulker Carrier class ship with deadweight of 63,246 tons: 1 – use of the scrubber cleaning system; 2 – use of a fuel mixture with biodiesel fuel; *a* – work outside SECA; *b* – work in SECA

Table 6

Ecological sustainability of the ship during the navigation transition Aughinish – Tallinn for different ways of managing environmental safety

Work outside SECA			Work in SECA					
Time, hours	Eco^+, %		Time, hours	Eco^+, %		Time, hours	Eco^+, %	
	1	2		1	2		1	2
5	66.73	15.92	50	41.63	12.79	120	42.56	11.63
10	68.57	12.96	60	42.33	6.51	130	42.33	5.81
15	68.02	22.46	70	42.33	13.49	140	42.56	13.49
20	64.33	16.17	80	43.02	26.05	150	43.26	15.58
25	64.15	8.39	90	42.56	11.17	160	46.75	17.91
30	64.88	4.18	100	42.09	3.02	170	45.58	16.05
35	69.91	12.90	110	42.33	3.49	180	46.05	14.42
40	69.82	18.46	–	–		–	–	
45	70.23	15.30	–	–		–	–	

Notes: 1 – use of scrubber cleaning system; 2 – use of a fuel mixture with biodiesel fuel

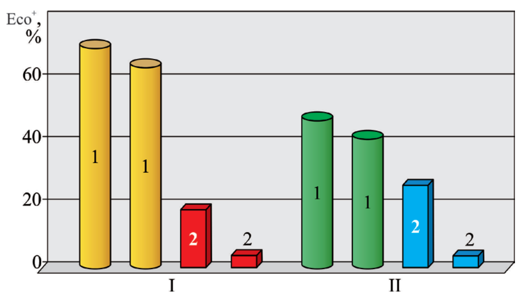

Fig. 7. Changing the environmental sustainability of a Bulker Carrier class ship with deadweight of 63,246 tons with different methods of environmental safety management: 1 – use of a scrubber cleaning system; 2 – use of a fuel mixture with biodiesel fuel; I – work in SECA; II – work outside SECA

For the considered scrubbing system for cleaning exhaust gases, the power required to ensure the operation of two sea water pumps:

$$N_p^{sw} = 2 \cdot 40 = 80 \text{ kW},$$

where 40 kW – the power of one sea water pump;

$$N_p^{bw} = 2 \cdot 35 = 70 \text{ kW},$$

where 35 kW – the power of one buffer pump.

Loss of 1.0–1.5 % of the power of the main engine 5S60ME-C8.2 MAN-Diesel&Turbo under the condition of its operation at a load of 0.85 %:

$$N_e^{ME} = 0.85 \cdot 8050 \cdot 0.01 = 68.4 \text{ kW},$$

$$N_e^{ME} = 0.85 \cdot 8050 \cdot 0.015 = 102.6 \text{ kW}.$$

Loss of 1.0–1.5 % of power under the condition of their operation at a load of 0.85 %:

$$N_e^{AE} = 0.85 \cdot 2 \cdot 800 \cdot 0.01 = 13.6 \text{ kW},$$

$$N_e^{AE} = 0.85 \cdot 2 \cdot 800 \cdot 0.015 = 20.4 \text{ kW}.$$

Total power losses when using a scrubber exhaust gas cleaning system:

$$\Delta N^{sc} = N_p^{sw} + N_p^{bw} + N_e^{ME} + N_e^{AE}.$$

Depending on the power losses of the main engine 5S60ME-C8.2 MAN-Diesel&Turbo and auxiliary engines 6EY18ALW Yanmar, the range of total power losses is:

$$\Delta N^{sc} = 237–278 \text{ kW}.$$

Total power losses when using a fuel mixture that contains biodiesel fuel are determined by the power of the biodiesel fuel pump:

$$\Delta N^{bio} = N_p^{bf}.$$

Given the characteristics of the biodiesel fuel pump, the range of total power losses is:

$$\Delta N^{bio} = 18 - 20 \text{ kW}.$$

The nomogram, which displays power losses when using various methods of managing environmental safety, is shown in Fig. 8.

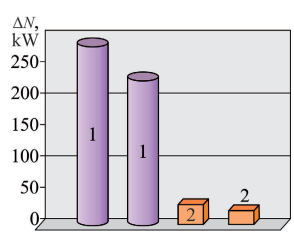

Fig. 8. Power losses with different methods of managing the environmental safety of a Bulker Carrier class ship with a deadweight of 63,246 tons: 1 – use of the scrubber cleaning system; 2 – use of a fuel mixture with biodiesel fuel

During the research, all the main operating parameters of the main and auxiliary engines were controlled and maintained within the required range [49, 50], as well as parameters in the systems that ensure their functioning [51, 52].

Environmental safety management of navigation passages is one of the components that determine the operation of maritime transport. It is especially important to maintain ecological safety for the regions of Northern Europe, in which special ecological regions for the control of sulfur oxide emissions have been created. Fulfillment of international requirements for the level of SO_X emissions is possible by additional purification of exhaust gases, as well as by using fuel with low sulfur content. In the first case, exhaust gases are cleaned in special scrubbers, in the second case, biodiesel fuel is used, the sulfur content of which does not exceed 0.02 %.

The effectiveness of the use of ecological safety management methods can be assessed by the environmental sustainability of the ship. The higher the environmental sustainability value, the further the current SO_X emission values are from the maximum possible SO_X emission values. The method of using additional cleaning of exhaust gases in scrubbers is characterized by the highest environmental efficiency. At the same time, the use of biodiesel fuel as a method of controlling environmental safety also provides a high level of environmental sustainability.

Disadvantages of environmental safety management methods include diesel power losses, which are associated with additional aerodynamic resistance in the gas exhaust line. Additional equipment that ensures the functioning of gas purification systems or fuel preparation also requires additional energy costs. In the case of using scrubber cleaning of gases, these are sea water pumps and buffer pumps. In the case of using biodiesel fuel, additional energy costs are required to ensure the operation of the biodiesel fuel pump. In addition, it is necessary to equip the fuel system with biodiesel fuel dispensers.

The economic efficiency of exhaust gas scrubber cleaning is determined by the possibility of using fuel in marine diesel engines. The sulfur content in which reaches 3.5 %. These types of fuel (compared to fuel with a sulfur content of up to 0.5 %) have a lower cost. Therefore, the use of scrubber cleaning of exhaust gases is most rational for marine vessels with powerful power plants and, accordingly, increased fuel consumption.

The use of biodiesel fuel is possible for diesel engines of any capacity, performing the functions of both main and auxiliary engines.

However, environmental safety management methods are characterized by additional risks and threats. For the exhaust gas scrubber cleaning system, this is work on an open circuit, in which the water from the scrubber flows overboard without additional cleaning. This requires constant monitoring and constant control of its acid number. The main risk when using biodiesel fuel is the impossibility of bunkering with this type of fuel in some seaports. At the same time, there is a need to increase the amount of biodiesel fuel received in the ports of possible bunkering. Taking into account the gradual stratification of biofuel over time, this reduces the reliability of its storage and the efficiency of its use.

4. Conclusions

1. It is shown that environmental safety management of navigation passages of sea vessels is possible with the help of additional cleaning of exhaust gases of ship diesels in scrubbers, as well as by using biodiesel fuel. One of the sea water areas in which the management of the environmental safety of navigation crossings is of the greatest importance are the special sulfur emission control areas – SECAs. Such areas include the North and Baltic Seas – European sea areas with increased shipping intensity, which are characterized by the proximity of the mainland.

2. The criterion for the degree of purification of exhaust gases from sulfur impurities is the ratio of sulfur oxide to carbon oxide – SO_2/CO_2. It is determined that for a ship of the Bulker Carrier class with a deadweight of 63,246 tons:

1) the use of scrubber cleaning ensures the SO_2/CO_2 ratio:
– when the ship is in SECA in the range of 2.29–2.51 (at the maximum permissible value of 4.3);
– when the ship is outside the SECA in the range of 6.46–7.78 (with the maximum permissible value of 21.7);

2) the use of a fuel mixture, which includes biodiesel fuel, ensures the SO_2/CO_2 ratio:
– when the ship is in SECA in the range 3.18–4.17;
– when the ship is outside the SECA in the range 17.72–20.83.

3. Environmental sustainability of the ship:

1) when using scrubber cleaning:
– when the ship is in SECA in the range of 41.63–46.75;
– when the ship is outside the SECA in the range 64.15–70.23;

2) when using a fuel mixture that includes biodiesel fuel:
– when the ship is in SECA in the range 3.02–26.05;
– when the ship is outside the SECA in the range 4.18–22.46.

4. It was revealed that the use of ecological safety management methods increases energy costs for ensuring this process. When using scrubber cleaning and additional cleaning in scrubbers, power losses amount to 237–278 kW. When using a fuel mixture that includes biodiesel fuel, power losses amount to 18–20 kW.

5. It is shown that the use of a fuel mixture, which includes biodiesel fuel, is characterized by a lower level of environmental sustainability. At the same time, compared to the use of scrubber cleaning of exhaust gases, this method requires less energy and is characterized by simpler additional equipment. Due to this (and also taking into account that all the requirements of Annex VI MARPOL are provided), it is recommended as the main one for ensuring environmental safety of navigation crossings of sea transport vessels.

Conflict of interest

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

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