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Sergii Sagin,
Oleksiy Kuropyatnyk

DETERMINATION OF OPTIMAL OPERATING MODES OF THE SELECTIVE CATALYTIC REDUCTION SYSTEM FOR MARINE DIESEL EXHAUST GASES

The object of research is the process of ensuring the minimum level of carbon dioxide emissions when using selective catalytic reduction of exhaust gases from nitrogen oxides. It is noted that catalytic reduction systems provide the most effective purification of exhaust gases from nitrogen oxides. At the same time, due to the use of urea as a reagent in these systems, carbon dioxide emissions increase. This increases the greenhouse effect and reduces the energy efficiency of the ship. The research results presented in the work were carried out on a Gas Carrier class ship with a displacement of 127,645 tons with two main engines 5X72DF Hyundai-WinGD and three auxiliary engines 6H35DF Hyundai-HiMSEN. 5X72DF Hyundai-WinGD diesel engines were equipped with a high-pressure catalytic reduction system, 6H35DF Hyundai-HiMSEN diesel engines – with a low-pressure catalytic reduction system. It has been experimentally established that within the recommended range of urea supply to the catalytic reduction system of exhaust gases, there are optimal modes that ensure a minimal increase in carbon dioxide emissions while maintaining a high level of reduction in nitrogen oxide emissions. In these modes, the relative increase in carbon dioxide emissions does not exceed 2.3% for both types of diesel engines. Nitrogen oxide emissions for 5X72DF Hyundai-WinGD diesel engines do not exceed 3.3 g/(kW · h) and do not exceed 2.4 g/(kW · h) for 6H35DF Hyundai-HiMSEN diesel engines, which meets the requirements of Annex VI MARPOL. The relative reduction in nitrogen oxide emissions in these modes is 66.7–83.4% for 5X72DF Hyundai-WinGD diesel engines and 60.8–78.3% for 6H35DF Hyundai-HiMSEN diesel engines. The coincidence of the obtained values for the low-speed diesel engine 5X72DF Hyundai-WinGD and the medium-speed 6H35DF Hyundai-HiMSEN indicates the correctness of the research and the possibility of implementing their results on all types of diesel engines and catalytic reduction systems.

Keywords: *environmental indicators, maritime transport, exhaust gas purification, marine diesel, catalytic reduction system.*

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1. Introduction

Maritime transport is an essential component of the transport infrastructure of any country, which is connected with other sea or ocean routes. At the present stage of development of society, maritime transport is not only a source of financial profit, but also contributes to increasing economic stability and improving national security. For many countries (including developed ones), it is maritime transport that ensures the delivery of energy resources and certain types of food products. The first type of cargo includes gas, oil products and coal. For the second, it includes grain and fruits, as well as frozen meat and fish [1, 2]. It is also necessary to determine that maritime transport is a type of transport that performs many thousands (both in weight and in quantity) transoceanic cargo transportation [3, 4]. It is almost impossible, and in most cases impossible, to carry out similar cargo volumes by other types of transport – by rail and air [5, 6]. This guarantees the constant further development of maritime transport as one of the main sectors of general transport.

The movement of sea transport ships is impossible without the use of power plants, the most common type of which is internal combustion engines [7, 8]. Being a source of useful energy, ship internal combustion engines are simultaneously sources of harmful emissions that enter the atmosphere with their exhaust gases [9, 10]. Most of the exhaust gases are discharged by hazardous and neutral substances and compounds – water vapor H_2O, atomic nitrogen N_2, unburned oxygen O_2. At the same time, the exhaust gases include toxic substances – carbon monoxide CO, sulfur oxides SO_X and nitrogen oxides NO_X [11, 12]. Fuel combustion is also accompanied by the formation of carbon dioxide CO_2, which is not a toxic component of exhaust gases, but belongs to greenhouse gases and affects the increase in the greenhouse effect [13, 14].

Carbon monoxide CO (carbon monoxide) has a negative impact on human health. If the maximum permissible concentration is exceeded, carbon monoxide becomes fatal to health. There are no generally accepted international standards for carbon monoxide emission levels. At the same time, different countries have national standards that set the maximum concentration of carbon monoxide in exhaust gases for various types of heat engines. Carbon monoxide is particularly dangerous in closed rooms (for example, in the engine room of sea ships). The specific gravity of carbon monoxide exceeds the specific gravity of air. Therefore, its entry into the lower part of the engine room and its gradual accumulation subsequently leads to the displacement of air from the bottom to the top and filling the entire volume with this toxic substance. This is the hidden danger of exhaust gas leaks (including carbon monoxide, as one of their components) into closed and air-limited rooms. Separate technologies aimed at removing only carbon monoxide from exhaust gases are not used on marine ships. Reducing CO emissions is considered an additional task when implementing systems and devices that contribute to the reduction of other toxic substances – sulfur oxides SO_X and nitrogen oxides NO_X [15, 16].

The main danger posed by sulfur oxides SO_X is that, after entering the atmosphere, they react with water vapor H_2O and form sulfurous H_2SO_3 and sulfuric H_2SO_4 acids. Subsequently, these substances return to the water and land surface in the form of acid rain, which negatively affects the ecology of these areas. The emission of sulfur oxides is regulated by the percentage of sulfur in the fuel. According to the requirements of Annex VI of the International Convention for the Prevention of Pollution from Ships (MARPOL), the sulfur content in the fuel is limited to 0.1% when ships are in Sulphur Emission Control Areas (SECAs) and to 0.5% when ships are outside SECAs [17, 18]. The reduction of sulfur oxides SOX emissions is ensured through the use of special exhaust gas purification systems. However, the most widespread systems are scrubbers. These systems (provided that special requirements for the quality of exhaust gas purification are met) allow the use of fuel with a sulfur content of up to 3.5%. Similar types of fuels are less expensive than fuels containing 0.5% and especially 0.1% sulfur. This reduces the financial costs of fuel purchase and increases the economic component of the operation of seagoing ships [19, 20].

Nitrogen oxides NO_X are among the pollutants that receive the greatest attention from international and national supervisory organizations and classification societies [21, 22]. This makes research aimed at reducing the concentration of nitrogen oxides in exhaust gases relevant.

The main document regulating the level of NO_X emissions from marine diesel engines is the international MARPOL convention. The requirements of Annex VI MARPOL (which, among other things, limit the value of nitrogen oxide emissions) apply to all engines with a power exceeding 130 kW. The maximum concentration of nitrogen oxides NO_X in the exhaust gases of marine diesel engines depends on the year of construction of the ship and the frequency of rotation of the diesel shaft [23, 24]. Its values are given in Table 1. Compliance with the requirements of Annex VI MARPOL is monitored by the International Maritime Organization (IMO).

Table 1

Annex VI MARPOL requirements for the maximum concentration of nitrogen oxides NO_X, g/(kW · h), in the exhaust gases of marine diesel engines

Level	Shaft rotation frequency, n, min^{-1}		
	$n < 130$	$130 < n < 2000$	$n > 2000$
Tier I – for ships built after 2000	17.0	$45n^{-0.2}$	9.8
Tier II – for ships built after 2011	14.4	$44n^{-0.23}$	7.7
Tier III – for ships built after 2016	3.4	$9n^{-0.2}$	2.0

Note: systematized by the authors based on [24]

Modern ships (the service life of which does not exceed 10 years) belong to Tier III requirements of Annex VI MARPOL. Maintaining the required level of nitrogen oxide emissions for such ships is possible only if additional methods of exhaust gas purification are used, which are divided into primary and secondary [25, 26]. Primary ones provide favorable conditions that prevent the chain reaction of nitrogen oxide formation during fuel combustion [27, 28]. First of all, they are aimed at reducing the maximum combustion temperature in the diesel cylinder. The most common of the primary methods are humidification of the charge air, the use of water-fuel emulsions, direct injection of water into the diesel cylinder, and exhaust gas recirculation. The most common of the secondary methods for reducing nitrogen oxide emissions is selective catalytic reduction [29, 30]. Secondary methods are aimed at directly purification exhaust gases from nitrogen oxides.

During humidification of the charge air, fresh water is injected into the purge receiver or into the air line [31, 32]. This leads to humidification of the charge air entering the diesel engine cylinders and subsequently contributes to a decrease in peak temperatures during fuel combustion. The disadvantage of the charge air humidification technology is the need to constantly monitor the air humidity level in the purge receiver and periodically remove condensed water from its volume. Excessive humidification of the purge air and untimely removal of excess water from the purge receiver can lead to supercooling of the diesel engine. This can result in a temporary or long-term cessation of fuel ignitions injected into the diesel cylinder. Also (due to the formation of additional sulfuric acid) this leads to increased sulfuric wear of the cylinder group and the exhaust gas line of the diesel engine [33, 34].

The use of water-fuel emulsions involves the creation of stable and homogeneous mixtures of water and fuel [35, 36]. The most effective option for producing such mixtures is immediately before their supply to the high-pressure fuel equipment. The water content in the water-fuel emulsion is within 10–30% and depends on the characteristics of the fuel and the operating mode of the diesel engine. The main disadvantages associated with the use of water-fuel emulsions include the need for additional adjustment and control of the equipment that ensures their production. As a rule, water-fuel emulsions are characterized by short stability. Long-term storage leads to their stratification, which can cause disruption or cessation of the supply of the emulsion to the high-pressure fuel equipment. Adding water to the fuel (as the basic principle of creating a water-fuel emulsion) increases the cyclic supply of this mixture. Its volume (due to a constant amount of fuel and a variable amount of water) increases in proportion to the amount of water included in the emulsion. This increases the duration of the emulsion injection compared to the injection of fuel alone, which forces an increase in the injection advance angle of the emulsion. A supercritical increase in the injection advance angle of the emulsion worsens the ignition process of the emulsion and may cause its lack of flashover [37, 38].

Direct injection of water into the diesel cylinder involves the simultaneous injection of water and fuel [39, 40]. At the same time, the most developed and widespread are three methods. The first is provided by injecting water and fuel through separate nozzles. The second is through injecting water and fuel through a common nozzle but through different spray channels and different groups of nozzles. The third is through injecting water and fuel through a common nozzle through common nozzles. In all cases, the supply of water and fuel to the nozzles is provided by a separate high-pressure fuel pump and a separate high-pressure water pump. The main disadvantages of direct injection of water into the diesel cylinder are similar to all methods based on the additional use of water during the diesel engine operating cycle. An increase in the moisture content of the air in the diesel cylinder and the need to adjust the fuel supply phases can cause unstable self-ignition or delayed self-ignition of fuel. This leads to an increase in the unevenness of the shaft rotation and the torque on the diesel engine shaft.

According to various estimates, the use of humidification of the charge air, water-fuel emulsions and direct injection of water into the diesel engine cylinders provides a 15–25% reduction in nitrogen oxide emissions with exhaust gases.

The most effective among the primary methods for reducing nitrogen oxide emissions is exhaust gas recirculation [23, 41]. The basis of this method is the return of part of the exhaust gases that have left the diesel engine cylinder. In this case, when the gases return to the blow-by receiver immediately after they leave the cylinder (before they enter the gas turbocharger), these systems are called high-pressure systems. In the case when the exhaust gases give up their energy in the gas turbocharger and only then return to the blow-by receiver, the systems are called low-pressure systems. Exhaust gas recirculation systems require the installation of an additional gas duct (through which gases are returned to the purge receiver), a scrubber (in which they are cleaned and cooled), a gas supercharger (which provides the necessary gas pressure). It is also necessary to install and constantly adjust the gas bypass valve, which provides the necessary amount of gases returned to the purge receiver. This complicates the design of the diesel engine and requires additional maintenance. Another disadvantage of the gas recirculation system is the increase in specific fuel consumption and, as a result, an increase in the temperature stress of the diesel engine [42, 43]. High- and low-pressure exhaust gas recirculation systems have a unidirectional effect on the process of nitrogen oxide formation and contribute to a 35–40% reduction in their emissions.

It is also possible to use primary methods to reduce nitrogen oxide emissions. An example of this is the use of a recirculation system and direct injection of water into the diesel cylinder, as well as the use of water-fuel emulsions with simultaneous humidification of the charge air.

Selective catalytic reduction (SCR) systems are the most effective among all others used to reduce the concentration of nitrogen oxides in exhaust gases [44, 45]. According to various estimates, they provide a 95–98% reduction in nitrogen oxide emissions entering the atmosphere with exhaust gases from marine diesel engines. That is why SCR is the most common method of reducing nitrogen oxide emissions.

The schematic diagram of exhaust gas purification using the SCR system is given in Fig. 1.

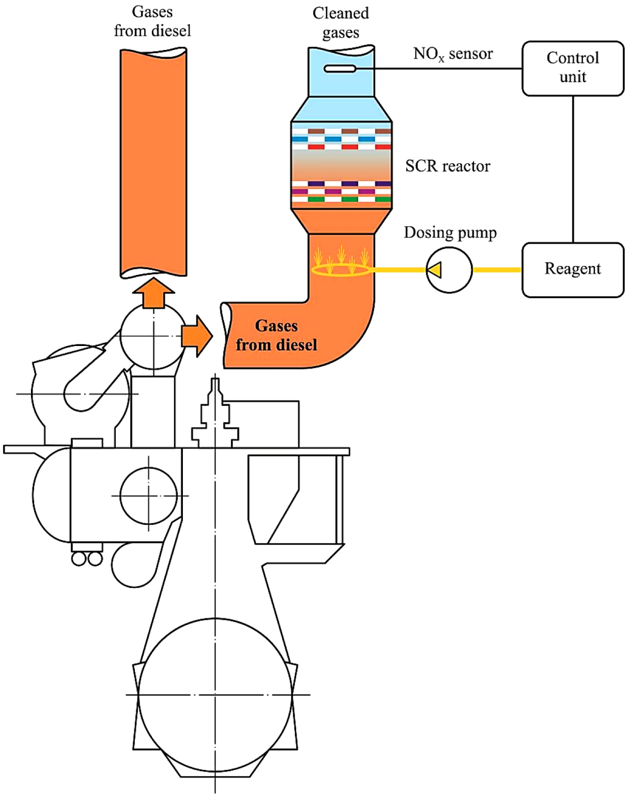

Fig. 1. Purification of marine diesel exhaust gases using a selective catalytic reduction system – SCR (systematized by the authors based on [45, 46], as well as taking into account the design of the marine SCR system on which the research was carried out)

Marine diesel exhaust gases are directed either through the exhaust line or through the SCR system. The main element of the system is the SCR reactor, it is in it that chemical reactions occur that ensure a reduction in nitrogen oxide emissions. The reagent is injected into the exhaust gas flow using a metering pump. In stationary power generation, automobile and rail transport, ammonia NH_3 is usually used as a reagent. In SCR systems installed on seagoing ships, urea $(NH_2)_2CO$ is used as a reagent. The mixture of exhaust gases and reagent enters the SCR reactor, where the following reactions take place on the catalyst:

$$\left.\begin{array}{l} 4NO+2\left(NH_2\right)_2CO+4H_2O+O_2 \rightarrow 4N_2+6H_2O+2CO_2, \\ 6NO_2+2\left(NH_2\right)_2CO+4H_2O+O_2 \rightarrow 7N_2+12H_2O+4CO_2. \end{array}\right\} \quad (1)$$

This leads to the conversion of NO monoxide and NO_2 nitrogen dioxide into atomic nitrogen N_2, which, together with other components of the exhaust gases, is removed to the atmosphere. The final content of nitrogen oxides in the exhaust gases is controlled using a NO_X sensor installed in the exhaust line outside the SCR reactor. Information from the NO_X sensor enters the control unit, which ensures the supply of the required amount of reagent to the metering pump. Equation (1) shows that the process of purification exhaust gases from nitrogen oxides in the SCR reactor is inevitably associated with the formation of carbon dioxide CO_2. Currently, the level of carbon dioxide concentration in the exhaust gases of marine diesel engines is not regulated by the requirements of international or national conventions. At the same time, measures are constantly being implemented to reduce CO_2 emissions [46, 47]. At the same time, the emission of carbon dioxide CO_2 is a component that determines the constructive energy efficiency design index (EEDI). This coefficient is the ratio of carbon dioxide CO_2 emissions with exhaust gases of marine diesel engines installed on the ship to the transport work of the ship. The general formula for determining EEDI has the form

$$EEDI = \frac{\text{Emission } CO_2}{\text{Capacity} \cdot v} \left[\frac{g}{\text{ton} \cdot \text{nm}}\right], \quad (2)$$

where Emission CO_2 – total carbon dioxide emissions of main and auxiliary diesel engines, g; Capacity – deadweight of the ship, tons; v – ship speed, knots.

In accordance with IMO requirements, the EEDI value is calculated for all ships built after 01.01.2013. For each ship, the maximum possible coefficient $EEDI_{max}$ is determined, the excess of which indicates that the ship does not meet the requirements for energy efficiency.

Thus, the use of SCR as a method that ensures the maximum reduction in nitrogen oxide emissions leads to an increase in the emission of another negative component of exhaust gases – carbon dioxide. This causes a decrease in the energy efficiency of the ship [48, 49].

In this regard, *the aim of the research* is to determine the optimal operating modes of the ship's SCR system. In this case, optimal ones are understood as those that ensure a minimal increase in carbon dioxide emissions while maintaining a high level of reduction in nitrogen oxide emissions.

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

- determining the effect of urea supply (as a reagent used in the SCR system) on increasing carbon dioxide emissions with exhaust gases;
- determining the effect of urea supply on nitrogen oxide emissions with exhaust gases;
- determining the effect of urea supply on the environmental sustainability of the ship in terms of nitrogen oxide emissions.

2. Materials and Methods

The object of research is the process of ensuring the minimum level of carbon dioxide emissions when using selective catalytic reduction of exhaust gases from nitrogen oxides.

As a scientific hypothesis, the thesis was adopted that the minimum level of carbon dioxide emissions is ensured by choosing the optimal value of urea supply to the selective catalytic reduction system.

The research was carried out on a Gas Carrier class ship with a displacement of 127,645 tons. As the main engines on the ship, two identical low-speed diesel engines 5X72DF Hyundai-WinGD (Winterthur Gas & Diesel Ltd. Winterhur, Switzerland) were installed. As auxiliary engines, three identical medium-speed diesel engines 6H35DF Hyundai-HiMSEN, Hyundai Global Service, Busan, Korea). The main characteristics of the ship on the power plant are given in Table 2.

Table 2

Main characteristics of the ship on the power plant

Characteristics	Dimension	Value
Ship		
Maximum length	m	299.0
Breadth at midship	m	46.4
Draft	m	12.5
Displacement	ton	127,645
Speed	knots	19.5
Propeller, type – Fixed Pitch Propeller		
Diameter	m	8.4
Number of blades	–	3
Speed	$\min^{-1}$	73
Quantity	–	2
Main engine 5X72DF Hyundai-WinGD		
Cylinder diameter	m	0.72
Piston stroke	m	3.155
Number of cylinders	–	5
Nominal speed	$\min^{-1}$	73
Nominal power	kW	11,000
Specific fuel consumption	kg/(kW · h)	0.168
Quantity	–	2
Auxiliary engines 6H35DF Hyundai-HiMSEN		
Cylinder diameter	m	0.35
Piston stroke	m	0.4
Number of cylinders	–	6
Nominal speed	$\min^{-1}$	720
Nominal power	kW	2,880
Specific fuel consumption	kg/(kW · h)	0.183
Quantity	–	3

The design perfection of diesel engines (both main and auxiliary) and the organization of the working cycle running in their cylinders ensured the requirements of Tier II MARPOL, therefore, did not require additional technical measures to reduce nitrogen oxide emissions. While the ship was in special environmental areas, its environmental indicators (primarily regarding the concentration of nitrogen oxides in exhaust gases) met the requirements of Tier III MARPOL. This was achieved using the SCR system. At the same time, each of the two main engines 5X72DF Hyundai-WinGD and each of the three auxiliary engines 6H35DF Hyundai-HiMSEN were equipped with a separate SCR reactor. One of the main conditions for ensuring high-quality purification of exhaust gases from nitrogen oxides using SCR technology is to maintain the temperature at the level of the gas temperature at the inlet to the SCR reactor required for this process. Its value should not be less than 320°C. Marine internal combustion engines 5X72DF Hyundai-WinGD belong to the series of long-stroke diesel engines. The increased piston stroke of such diesel engines ensures a more complete use of the energy of the gases to create torque on the shaft, but at the same time the temperature of the gases decreases during their release from the cylinders. It is because of this that long-stroke internal combustion engines (to which 5X72DF diesel engines belong) are equipped with a high-pressure SCR system (HP-SCR). A design feature of these systems is the installation of the SCR reactor immediately after the diesel cylinders, i. e. before the gas turbocharger. This ensures that exhaust gases with high pressure (those that have not yet given up most of the energy on the gas turbocharger blades) and with the maximum possible temperature for these conditions enter the SCR reactor. In case of a decrease in the temperature of the gases at the outlet of the cylinders, the exhaust control system changes the opening angle of the exhaust valve, thereby helping to maintain the required temperature level.

Unlike the main engines, each of the Hyundai-HiMSEN 6H35DF auxiliary engines is equipped with a low-pressure SCR system (LP-SCR), the SCR reactor of which is installed after the gas turbocharger. At the same time, the temperature of the gases entering the SCR reactor after the gas turbocharger is sufficient to ensure the process of selective catalytic purification of exhaust gases from nitrogen oxides. The manufacturer of HP-SCR and LP-SCR is Hyundai Global Service Co., Ltd., Busan, Korea.

Each of the SCR systems (HP-SCR for each of the two main 5X72DF engines and LP-SCR for each of the three auxiliary 6H35DF engines) operates separately from the others, has its own parameter control system and urea supply control.

The main components of the SCR system are shown in Fig. 2 as a screenshot of the control panel.

The SCR system (both for the main 5X72DF Hyundai-WinGD and for the auxiliary 6H35DF Hyundai-HiMSEN engines) consists of three circuits:

- chemical, which supplies urea to the SCR reactors of the main and auxiliary engines (purple in Fig. 2);
- gas, which supplies exhaust gases to the SCR reactors of the main and auxiliary engines (orange in Fig. 2);
- air, which supplies compressed air to the system elements (blue in Fig. 2).

The main elements that make up the chemical circuit (blue designations 1–4 in Fig. 2):

- Urea storage tank (1) – designed to accumulate and supply urea to the purification system. The tank capacity is sufficient for the simultaneous operation of the SCR reactors of the main and auxiliary diesel engines. In order to maintain the operational properties of urea, the storage tank is equipped with a steam heating coil, a thermometer, a level sensor and an alarm system;
- Urea supply unit (2) – ensures the supply of urea to the SCR reactors of the main and auxiliary diesel engines, as well as the recirculation of urea to the storage tank in the event of low loads in the system;
- Urea dosing unit (3) – ensures the accurate supply of urea to the injector. The dosing unit also includes an air supply unit, which ensures the formation and dispersion of a mixture of urea and air. A similar unit with a similar functional purpose is included in the exhaust gas purification system of auxiliary diesel engines;
- Mixing tank (4) – a system unit in which the urea supply nozzles are located. Exhaust gases from the main engine also enter the mixing tank. Next, the mixture of urea and gases is sent to the SCR reactor. A similar unit with a similar functional purpose is included in the exhaust gas purification system of auxiliary diesel engines.

The main elements that make up the gas circuit (blue designations 5, 6 in Fig. 2):

- SCR chamber for M/E (5) – a system element in which nitrogen oxides NO_X are directly reduced to atomic nitrogen N_2. Equipped with temperature and pressure sensors, as well as purging and heating devices. Similar functions are performed by the SCR chamber for M/E of auxiliary engines;
- exhaust manifold of the main engine (6) – into which the purified gases after the SCR reactor enter. From the exhaust manifold, the gases are directed to the gas turbocharger and then to the utilization boiler of the main engine / M/E Exhaust Gas Economizer.

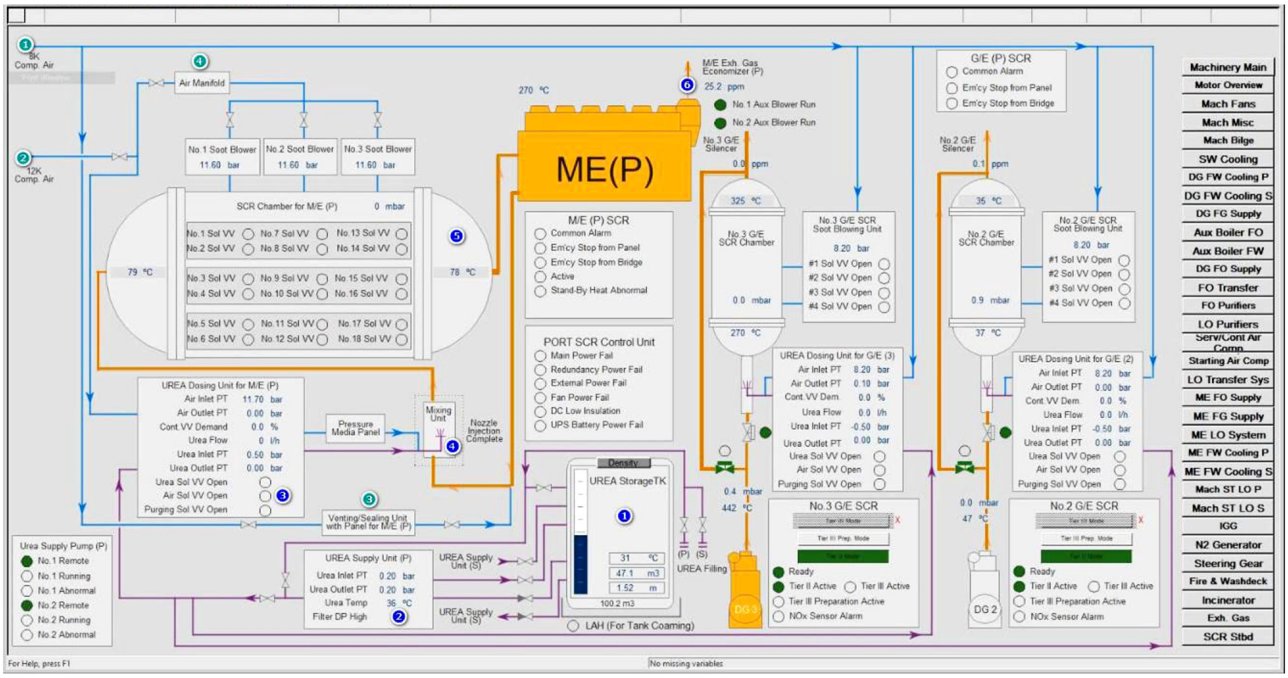

Fig. 2. Main components of the SCR system of the main 5X72DF Hyundai-WinGD and auxiliary 6H35DF Hyundai-HiMSEN engines of a Gas Carrier class ship with a displacement of 127,645 tons

The main elements that make up the air circuit (blue designations 1–4 in Fig. 2):

- medium-pressure air line (1) – provides purging and ventilation of the system from urea vapors. Uses air with a pressure of 8 bar;
- high-pressure air line (2) – provides blowing and removal of dust, soot and unburned particles included in the exhaust gases from the surface of the SCR catalyst. Uses air with a pressure of 12 bar;
- SCR reactor blowing system Venting/Sealing unit (3) – is an integral part of both HP-SCR and LP-SCR systems and ensures purification of the catalyst surface from contaminants (such as soot, dust and other solid particles that accumulate during gas purification in the SCR reactor). Blowing is carried out using compressed air supplied under a pressure of 12 bar by a specially designed compressor for the SCR system;
- Air Manifold (4) – provides air supply to various cells of the SCR catalyst through specially laid pipelines. Distribution nozzles installed inside the SCR reactor direct the air flow to the active surface of the catalyst, purification it of soot and contaminants. The removal of contaminants from the SCR reactor circuit is carried out automatically according to the software at a specified interval.

When the SCR system is not used, the air acts as a sealing barrier. In this case, the air prevents exhaust gases and moisture from entering the sensitive parts of the catalyst and its equipment. These include temperature and pressure sensors. At the same time, a constant air flow creates excess pressure in the cavities where the ingress of an aggressive environment is undesirable.

Urea (which is subsequently used in the exhaust gas purification system) is a disposable component of the SCR system. After entering the SCR reactor, it evaporates in the exhaust gas stream, is converted into other substances and is removed to the atmosphere as a new component of the exhaust gases. In this way, the SCR reactor operates in a "dry" mode, in which no liquid or solid sediment is formed during its operation.

Replenishment of ship urea reserves is carried out during the bunkering of the ship. The amount of urea taken on board the ship (as well as the amount of fuel) is calculated depending on the duration of the navigation passage and the possibility of replenishing its reserves in the ports of call. In this case, the probable time of the ship's stay in special ecological areas – sea or ocean water areas, in which the operation of the SCR system is mandatory.

Urea is stored during sea crossings in specially designed tanks. These tanks are used exclusively in the SCR system and do not provide for the storage or pumping through them of other substances (water, fuel or lubricant). Maintaining the operational characteristics of urea is ensured by its circulation between tanks located next to each other, or in the volume of one tank.

3. Results and Discussion

The studies were carried out at modes corresponding to 25%, 50%, 75% and 100% load on the main engines 5X72DF Hyundai-WinGD and on the auxiliary engines 6H35DF Hyundai-HiMSEN. During the studies, the main engines 5X72DF Hyundai-WinGD operated with the same power, each on its own propeller. Also, the same power was maintained on the auxiliary engines 6H35DF Hyundai-HiMSEN in case of their parallel operation.

The test cycle began with an operating mode corresponding to 25% load, and gradually changed to 50% and then to 75% and 100%. The main indicators, the determination of which was devoted to the study, were the concentration of carbon dioxide CO_2 and nitrogen oxides NO_X in exhaust gases. The fixation of these indicators was carried out only at stable operating modes of diesel engines, which were determined unchanged for at least 30 minutes:

- exhaust gas temperature;
- cooling water temperature;
- circulating oil temperature;
- maximum combustion pressure;
- pressure at the end of compression;
- average indicator pressure [50–52].

The specified indicators were monitored using the Doctor ship diagnostic system.

The range of urea supply to the SCR reactor circuit of the main 5X72DF Hyundai-WinGD and auxiliary 6H35DF Hyundai-HiMSEN engines is limited by minimum G_{ur}^{min} and maximum G_{ur}^{max} values. The values of these indicators depending on the load on the diesel engines are given in Table 3.

Table 3

Recommended range of urea supply to the SCR reactor circuit

Indicator	Value			
Diesel load, %	25	50	75	100
Urea consumption in the HP-SCR system of the 5X72DF Hyundai-WinGD diesel, l/h	60–80	95–130	135–180	150–200
Urea consumption in the LP-SCR system of the 6H35DF Hyundai-HiMSEN diesel, l/h	8–12	10–16	14–22	18–28

Let's define that each of the loads has its own recommended range of urea supply. Reducing the supply below the recommended one does not provide the required degree of purification of exhaust gases from nitrogen oxides. Increasing it above the recommended one leads to an increase in hydraulic resistance inside the SCR reactor (due to the liquid phase of the reagent). This additionally increases the backpressure in the gas exhaust line, which can cause exhaust gases to be thrown back into the diesel cylinder.

During the study, the urea supply at each of the loads specified in Table 3 on marine diesel engines varied in the range of 75%, 80%, 85%, 90%, 95%, 100% of the maximum value G_{ur}^{max}. The numerical values of urea supply for these conditions are given in Tables 4, 5.

Table 4

Urea consumption G_{ur}, l/h at different operating modes of HP-SCR main engines 5X72DF Hyundai-WinGD

Relative urea supply, %	Diesel load, %			
	25	50	75	100
75	60	97.5	135	150
80	64	104	144	160
85	68	110.5	153	170
90	72	117	162	180
95	76	123.5	171	190
100	80	130	180	200

Table 5

Urea consumption G_{ur}, l/h at different operating modes of LP-SCR auxiliary engines 6H35DF Hyundai-HiMSEN

Relative urea supply, %	Diesel load, %			
	25	50	75	100
75	9.0	12.0	16.5	21.0
80	9.6	12.8	17.6	22.4
85	10.2	13.6	18.7	23.8
90	10.8	14.4	19.8	25.2
95	11.4	15.2	20.9	26.6
100	12.0	16.0	22.0	28.0

In the HP-SCR and LP-SCR systems, at each load on the 5X72DF Hyundai-WinGD and 6H35DF Hyundai-HiMSEN diesel engines, the studies were carried out under the condition of 75%, 80%, 85%, 90%, 95% and 100% urea supply. The duration of operation of diesel engines and their SCR systems at each of the modes was 0.5–1.0 h. This ensured the uniformity of thermal and dynamic loads, as well as the constancy of the controlled indicators. After this period of time, the values of carbon dioxide CO_2 and nitrogen oxides NO_X emissions were recorded. The values obtained in this way are given in Tables 6–9.

For better visualization, the results given in Tables 6–9 are displayed in the form of diagrams – Fig. 3, 4.

Table 6

Carbon dioxide CO_2 emission, %, when using the HP-SCR system on the 5X72DF Hyundai-WinGD diesel engine

Diesel load, %	Relative urea consumption, %						
	0	75	80	85	90	95	100
25	5.68	5.71	5.74	5.76	5.72	5.73	5.81
50	6.16	6.19	6.22	6.25	6.20	6.21	6.29
75	6.78	6.81	6.84	6.87	6.82	6.83	6.91
100	7.32	7.35	7.38	7.41	7.36	7.37	7.46

Note: 0 – operation of the 5X72DF Hyundai-WinGD diesel engine without using the HP-SCR system

Table 7

Nitrogen oxides NO_X emission, g/(kW · h), when using the HP-SCR system on a 5X72DF Hyundai-WinGD diesel engine

Diesel load, %	Relative urea consumption, %						
	0	75	80	85	90	95	100
25	9.82	3.33	3.31	3.28	3.27	3.26	3.25
50	10.36	3.18	3.14	3.08	2.99	2.96	2.95
75	12.15	2.82	2.52	2.32	2.12	1.98	1.88
100	13.64	3.08	2.84	2.58	2.31	2.26	2.21

Note: 0 – operation of the 5X72DF Hyundai-WinGD diesel engine without using the HP-SCR system

Table 8

Carbon dioxide CO_2 emission, %, when using LP-SCR system on 6H35DF Hyundai-HiMSEN diesel engine

Diesel load, %	Relative urea consumption, %						
	0	75	80	85	90	95	100
25	6.14	6.19	6.20	6.23	6.21	6.21	6.28
50	6.25	6.29	6.31	6.34	6.32	6.33	6.36
75	6.48	6.52	6.54	6.55	6.52	6.53	6.61
100	6.85	6.88	6.91	6.93	6.88	6.91	6.97

Note: 0 – operation of the 6H35DF Hyundai-HiMSEN diesel engine without using the LP-SCR system

Table 9

Nitrogen oxides NO_X emission, g/(kW · h), when using the LP-SCR system on the 6H35DF Hyundai-HiMSEN diesel engine

Diesel load, %	Relative urea consumption, %						
	0	75	80	85	90	95	100
25	5.82	2.37	2.33	2.30	2.28	2.26	2.24
50	6.62	2.24	2.19	2.15	2.12	2.10	2.07
75	7.53	2.14	2.09	2.03	2.00	1.98	1.97
100	8.93	2.09	2.06	2.02	1.98	1.94	1.91

Note: 0 – operation of the 6H35DF Hyundai-HiMSEN diesel engine without using the LP-SCR system

According to the requirements of Annex VI MARPOL (given in Table 1), the maximum possible concentration of nitrogen oxides in exhaust gases should not exceed:

1) for 5X72DF Hyundai-WinGD diesel engines:
   - 14.4 g/(kW · h) for Tier II (namely without using HP-SCR);
   - 3.4 g/(kW · h) for Tier III (namely with using HP-SCR);
2) for 6H35DF Hyundai-HiMSEN diesel engines:
   - g/(kW · h) for Tier II (namely without using LP-SCR);
   - g/(kW · h) for Tier III (namely with using LP-SCR).

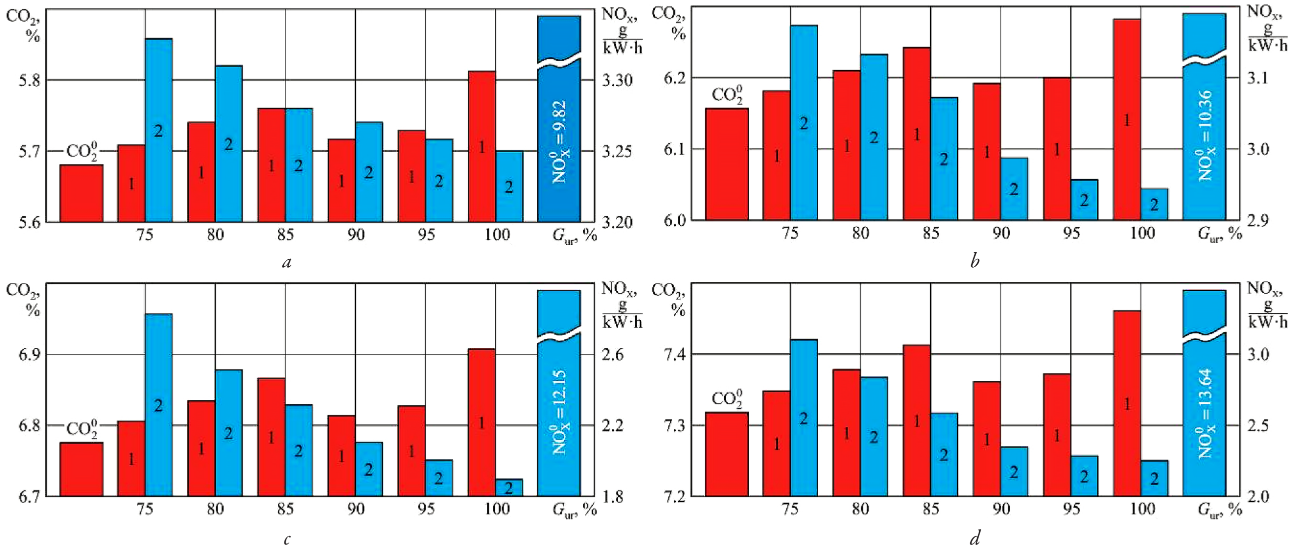

Fig. 3. Change in emissions of carbon dioxide CO_2 and nitrogen oxides NO_X when using the HP-SCR system on a 5X72DF Hyundai-WinGD diesel engine: *a* – 25% load; *b* – 50% load; *c* – 75% load; *d* – 100% load (CO_2^0, NO_X^0 – emissions without using HP-SCR)

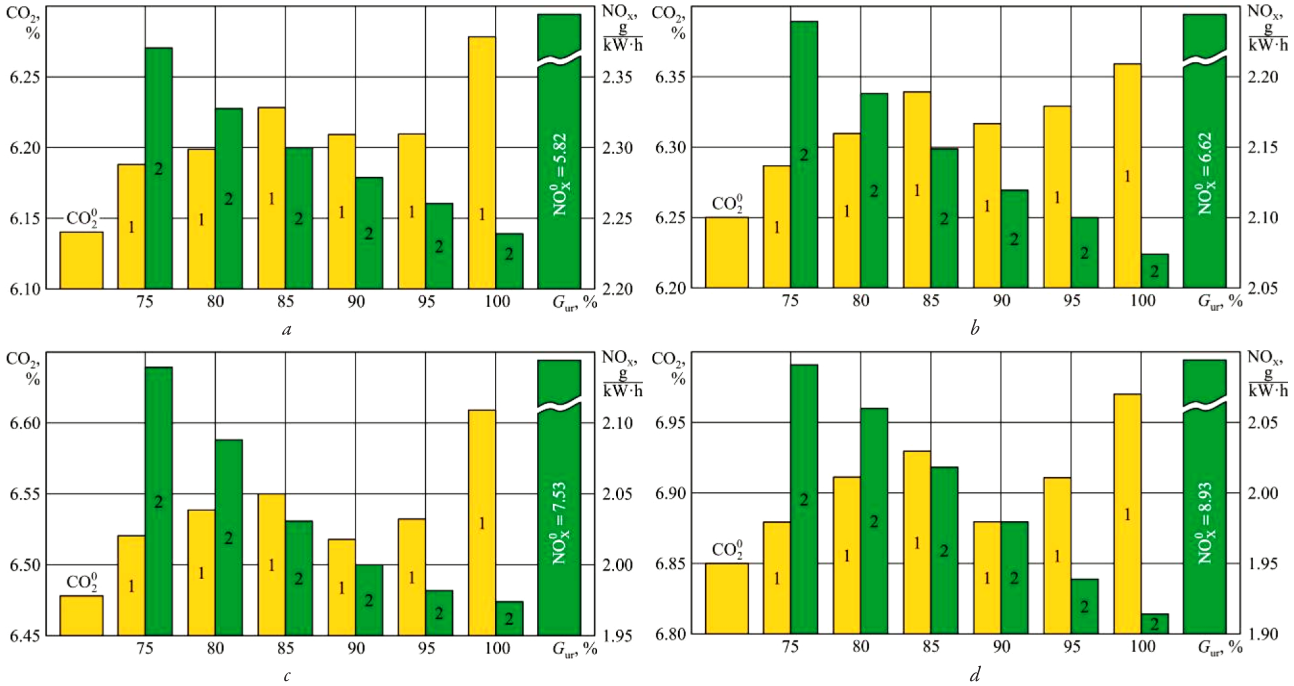

Fig. 4. Change in emissions of carbon dioxide CO_2 and nitrogen oxides NO_X when using the LP-SCR system on a 6H35DF Hyundai-HiMSEN diesel engine: *a* – 25% load; *b* – 50% load; *c* – 75% load; *d* – 100% load (CO_2^0, NO_X^0 – emissions without using LP-SCR)

The results of the studies given in Tables 6–9 and Fig. 3, 4 show that the requirements of Annex VI MARPOL were met in all operating modes of the 5X72DF Hyundai-WinGD and 6H35DF Hyundai-HiMSEN diesel engines.

The quality of the exhaust gas purification process of marine diesel engines 5X72DF Hyundai-WinGD and 6H35DF Hyundai-HiMSEN when using the HP-SCR and LP-SCR systems can be assessed by the following indicators:

- relative increase in carbon dioxide emissions ΔCO_2

$$\Delta CO_2^0 = \frac{CO_2^0 - CO_2^i}{CO_2^0}; \qquad (3)$$

- relative decrease in nitrogen oxide emissions ΔNO_X

$$\Delta NO_X = \frac{NO_X^0 - NO_X^i}{NO_X^0}. \qquad (4)$$

HP-SCR and LP-SCR systems also affect the environmental sustainability of the ship in terms of nitrogen oxide ΔNO_X^+ emissions. This indicator is proposed to be understood as the relative difference between the maximum possible (according to IMO requirements) and the current value of the concentration of nitrogen oxides in exhaust gases

$$\Delta NO_X^+ = \frac{NO_X^{IMO} - NO_X^i}{NO_X^{IMO}}. \qquad (5)$$

In expressions (3)–(5):

- CO_2^0, NO_X^0 – carbon dioxide and nitrogen oxide emissions during operation of 5X72DF Hyundai-WinGD and 6H35DF Hyundai-HiMSEN diesel engines without using SCR;
- CO_2^i, NO_X^i – carbon dioxide and nitrogen oxide emissions during operation of 5X72DF Hyundai-WinGD and 6H35DF Hyundai-HiMSEN diesel engines with using SCR;

– NO_X^{IMO} – maximum possible nitrogen oxide emissions according to IMO requirements (depending on Tier II or Tier III, which are given in Table 1).

The calculated values obtained from expressions (2)–(4) for different operating modes of 5X72DF Hyundai-WinGD and 6H35DF Hyundai-HiMSEN diesel engines, as well as their HP-SCR and LP-SCR systems, are given in Tables 10–15.

For better visualization, the results of the studies presented in Tables 10–15 are displayed in the form of diagrams – Fig. 5, 6.

Table 10

Relative increase in carbon dioxide emissions ΔCO_2, %, for different operating modes of the 5X72DF Hyundai-WinGD marine diesel engine and its HP-SCR

Diesel load, %	Relative urea consumption, %					
	75	80	85	90	95	100
25	0.53	1.06	1.41	0.70	0.88	2.29
50	0.49	0.97	1.46	0.65	0.81	2.11
75	0.44	0.88	1.33	0.59	0.74	1.92
100	0.41	0.82	1.23	0.55	0.68	1.91

Table 11

Relative increase in carbon dioxide emissions ΔCO_2, %, for different operating modes of the 6H35DF Hyundai-HiMSEN marine diesel engine and its LP-SCR

Diesel load, %	Relative urea consumption, %					
	75	80	85	90	95	100
25	0.81	0.98	1.47	1.14	1.16	2.28
50	0.64	0.96	1.44	1.12	1.28	1.76
75	0.62	0.93	1.08	0.62	0.77	2.01
100	0.44	0.88	1.17	0.44	0.88	1.75

Table 12

Relative reduction of nitrogen oxide emissions ΔNO_X, %, for different operating modes of the 5X72DF Hyundai-WinGD marine diesel engine and its HP-SCR

Diesel load, %	Relative urea consumption, %					
	75	80	85	90	95	100
25	66.09	66.29	66.60	66.70	66.80	66.90
50	69.31	69.69	70.27	71.14	71.43	71.53
75	76.79	79.26	80.91	82.55	83.70	84.53
100	77.42	79.18	81.09	83.06	83.43	83.80

Table 13

Relative reduction of nitrogen oxide emissions ΔNO_X, %, for different operating modes of the 6H35DF Hyundai-HiMSEN marine diesel engine and its LP-SCR

Diesel load, %	Relative urea consumption, %					
	75	80	85	90	95	100
25	59.28	59.97	60.48	60.82	61.17	61.51
50	66.16	66.92	67.52	67.98	68.28	68.73
75	71.58	72.24	73.04	73.44	73.71	73.84
100	76.60	76.93	77.38	77.83	78.28	78.61

Table 14

Environmental sustainability of the ship by nitrogen oxide emissions ΔNO_X^+, %, for different operating modes of the 5X72DF Hyundai-WinGD marine diesel engine and its HP-SCR

Diesel load, %	Relative urea consumption, %					
	75	80	85	90	95	100
25	2.06	2.65	3.53	3.82	4.12	4.41
50	6.47	7.65	9.41	12.06	12.94	13.24
75	17.06	25.88	31.76	37.65	41.76	44.71
100	9.41	16.47	24.12	32.06	33.53	35.00

Table 15

Environmental sustainability of the ship by nitrogen oxide ΔNO_X^+ emissions, %, for different operating modes of the 6H35DF Hyundai-HiMSEN marine diesel engine and its LP-SCR

Diesel load, %	Relative urea consumption, %					
	75	80	85	90	95	100
25	1.25	2.92	4.17	5.00	5.83	6.67
50	6.67	8.75	10.42	11.67	12.50	13.75
75	8.00	12.92	15.42	16.67	17.50	17.92
100	12.92	14.17	15.83	17.50	19.17	20.42

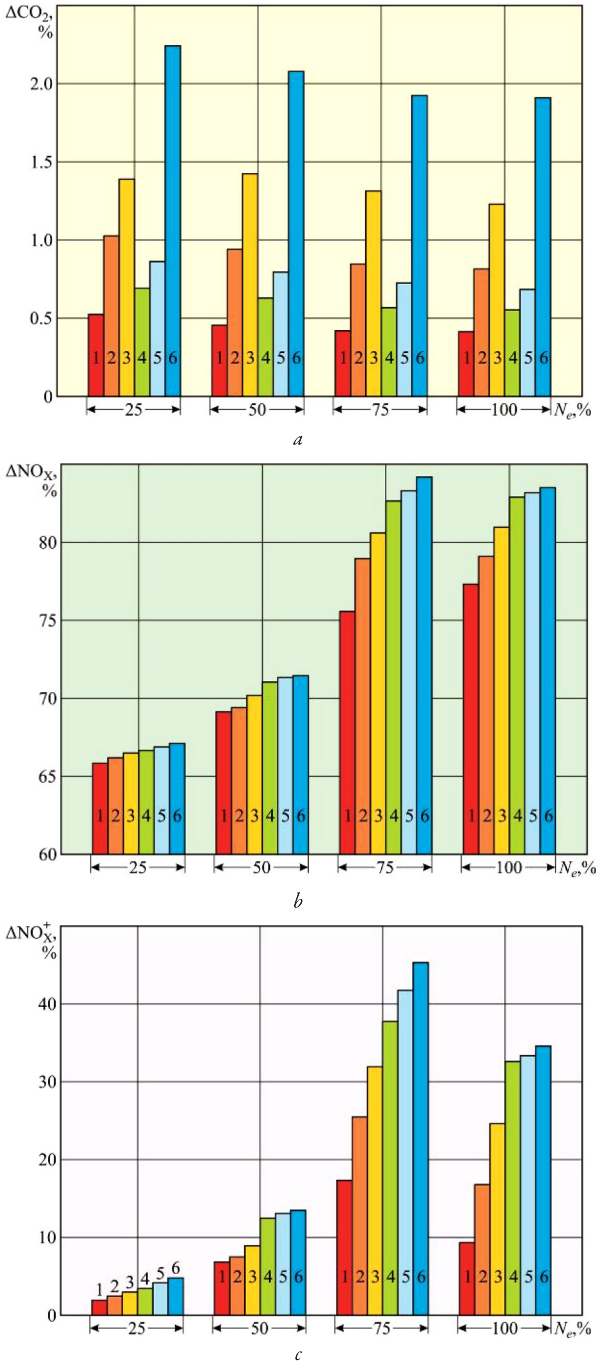

Fig. 5. Quality indicators of the exhaust gas purification process of the 5X72DF Hyundai-WinGD marine diesel engine under the condition of different urea supply to the SCR reactor: 1 – 75%; 2 – 80%; 3 – 85%; 4 – 90%; 5 – 95%; 6 – 100%; *a* – relative increase in carbon dioxide emissions ΔCO_2; *b* – relative decrease in nitrogen oxide emissions NO_X; *c* – environmental sustainability of the ship in terms of NO_X emissions

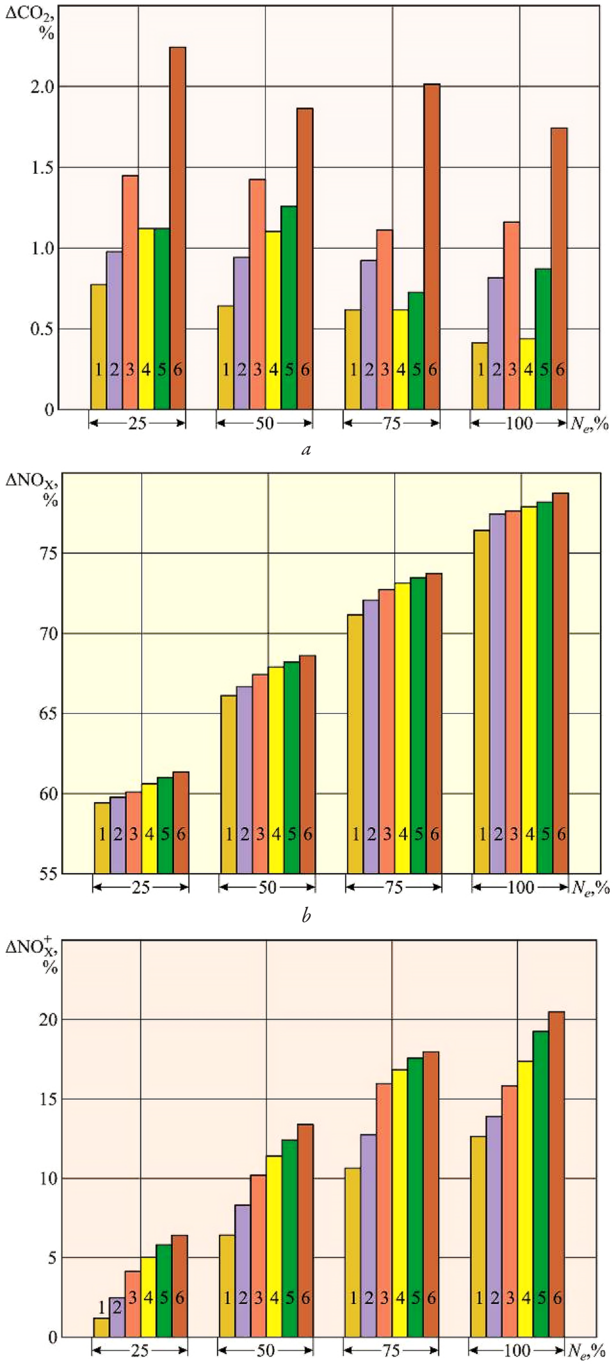

Fig. 6. Quality indicators of the exhaust gas purification process of the 6H35DF Hyundai-HiMSEN marine diesel engine under the condition of different urea supply to the SCR reactor: 1 – 75%; 2 – 80%; 3 – 85%; 4 – 90%; 5 – 95%; 6 – 100%; *a* – relative increase in carbon dioxide emissions $\varDelta CO_2$; *b* – relative decrease in nitrogen oxide emissions NO_X; *c* – environmental sustainability of the ship in terms of NO_X emissions

High and low pressure SCR systems provide exhaust gas purification of marine diesel engines 5X72DF Hyundai-WinGD and 6H35DF Hyundai-HiMSEN to Tier III MARPOL standards. However, SCR systems have a negative feature, which is an increase in carbon dioxide emissions during their use. This is due to the chemical reaction between nitrogen oxides NO_X (formed during fuel combustion) and urea $(NH_2)_2CO$ (used as a reagent in the SCR reactor). An increase in CO_2 emissions contributes to an increase in the greenhouse effect, and also reduces the constructive coefficient of energy efficiency of the ship [53, 54]. The dependence of carbon dioxide emissions on the supply of urea to the SCR reactor is nonlinear. This is due to the complex thermochemical reactions occurring in the SCR reactor. First of all, these include afterburning of fuel in the exhaust gas main and the SCR reactor, which is located near the gas turbocharger. Also, the nonlinearity of CO_2 formation is affected by the additional supply of air to the SCR reactor, which is used to spray urea. At the same time, there are optimal modes of urea supply to the SCR reactor. These modes ensure a minimum or close to the minimum value of carbon dioxide emissions while maintaining a high degree of exhaust gas purification from nitrogen oxides.

The limitations of research include the impossibility of analytically determining the specified optimal modes of urea supply to the SCR reactor. The development of such mathematical models is associated with the need to take into account a large number of additional indicators:

- *structural* – geometric dimensions of the cylinder, exhaust manifold, gas exhaust main, as well as the gas turbine of the gas turbocharger [55, 56];
- *physical* – additional aerodynamic resistance in the SCR reactor, pressure changes in the SCR reactor due to urea spraying with compressed air, temperature fluctuations in the SCR reactor [26, 57];
- *chemical* – unforeseen reactions in the SCR reactor between the multicomponent composition of exhaust gases, urea and the catalyst [58, 59].

The amount of carbon dioxide is also affected by the gradual contamination of the catalyst surface, on the surface of which the process of selective catalytic reduction of nitrogen oxides is carried out.

In this case, it is possible to experimentally determine the optimal operating modes of the SCR system for each of the operating modes of the diesel engine.

The development of the proposed method consists in determining the complex influence of the amount of urea supplied to the SCR reactor and the temperature of the exhaust gases entering the SCR reactor on the emission of CO_2 and NO_X. Also, additional attention is required for studies to determine the impact of fuel structural characteristics (primarily the percentage of carbon and nitrogen) on CO_2 and NO_X emissions when using SCR systems.

4. Conclusions

1. The use of urea as a reagent in SCR systems leads to an increase in carbon dioxide emissions in all operating modes of marine diesel engines. The relative increase in CO_2 emissions for the 5X72DF Hyundai-WinGD diesel engine equipped with the HP-SCR system is in the range of 0.41–2.29% and depends on the relative urea consumption. The similar indicator for the 6H35DF Hyundai-HiMSEN diesel engine equipped with the LP-SCR system is in the range of 0.44–2.28%. At the same time, for both diesel engines and their SCR systems there are urea supply modes in which the minimum level of CO_2 emissions is observed. It has been experimentally established that for both diesel engines these modes correspond to the case of 90–95% relative urea consumption.

2. An increase in the relative urea consumption contributes to a decrease in nitrogen oxide emissions in all operating modes of diesel engines. The use of the HP-SCR system on the 5X72DF Hyundai-WinGD marine diesel engine provides a reduction in nitrogen oxide emissions by 66.09–83.80%. The use of the LP-SCR system on the 6H35DF Hyundai-HiMSEN marine diesel engine provides a reduction in nitrogen oxide emissions by 59.28–78.61%. At the same time, for both diesel engines, the greatest reduction in NO_x emissions is observed in modes corresponding to 90–100% of the relative urea consumption.

3. HP-SCR and LP-SCR systems increase the environmental sustainability of the ship in terms of nitrogen oxide emissions. For the HP-SCR system, this indicator is 2.06–44.71%; for the LP-SCR

system – 1.25–17.92%. At the same time, the maximum value of the environmental sustainability of the ship in terms of nitrogen oxide emissions is ensured under the condition of 90–100% of the relative urea consumption.

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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✉***Sergii Sagin,*** *Doctor of Technical Sciences, Professor, Head of Department of Ship Power Plant, National University "Odessa Maritime Academy", Odesa, Ukraine, e-mail: saginsergii@gmail.com, ORCID: https://orcid.org/0000-0001-8742-2836*

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Oleksiy Kuropyatnyk, *PhD, Department of Ship Power Plant, National University "Odessa Maritime Academy", Odesa, Ukraine, ORCID: https://orcid.org/0009-0008-2565-5771*

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✉*Corresponding author*