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# ENSURING THE ENVIRONMENTAL FRIENDLINESS OF MARINE DIESEL ENGINES OF SPECIALIZED SHIPS

**Statement of the problem in general.** Marine diesel engines (as the main component of a marine power plant) are sources of environmental pollution with exhaust gases, which include toxic components: carbon dioxide CO, hydrocarbons $C_nH_m$, soot C, sulfur oxides $SO_X$, nitrogen oxides $NO_X$ [1-3].

Nitrogen oxides $NO_X$ occupy the first place among harmful emissions in almost all operating modes of diesel engines, regardless of their type, size and design features.

Emission of nitrogen oxides with exhaust gases marine diesel engines is regulated by the requirements of Annex VI MARPOL. In accordance with the Tier-I, Tier-II, Tier-III standards (which apply to diesel engines of ships built after 2000, 2011 and 2016), the maximum amount of $NO_X$ in exhaust gases should not exceed the values determined by special expressions [4, 5].

When operating the power plants of marine transport ships, engineers are faced with various dilemmas, one of which links the environmental and economic performance of heat engines. Stabilization within the required limits or a decrease in the values of almost all environmental indicators of marine diesel engines (emissions of carbon oxides CO, sulfur $SO_X$ and nitrogen $NO_X$) is due to:

- or with changes in the design of engines and systems that ensure their functioning [6];

- or using more expensive (currently) energy sources (for example, hydrogen, natural gas, low-sulphur fuels) [7];

- or the use of solar and wind energy technologies [8].

These methods require not only preliminary development and experimental determination of optimal modes, but also additional financial investments for their implementation, operation and maintenance.

**Analysis of recent researches and publications.**Methods for reducing the concentration of nitrogen oxides in the exhaust gases of marine diesel engines are divided into primary and secondary. Primary methods affect the working process in the diesel cylinder (including the fuel injection process). The main ones are charge air humidification, water injection into the diesel cylinder, the use of water-fuel emulsions, exhaust gas control (due to their recirculation or bypass). According to the theory of combustion, the formation of nitrogen oxides occurs at temperatures above 1500 K. The methods listed above provide a reduction in temperature peaks (which are characteristic of the combustion process), which reduces the intensity of formation and the amount of nitrogen oxides [9-11].

Secondary $NO_X$ reduction methods work directly on the exhaust gases that are already moving in the exhaust line. The most common of the secondary methods is Selective catalytic reduction (SCR). In this case, the exhaust gases enter a special reactor, into which a special reagent (ammonia, ammonium nitrate or urea) is injected [12-14]. As a result of chemical reactions, nitrogen oxides (NO and $NO_2$) are converted into molecular nitrogen $N_2$ and water vapor $H_2O$. The efficiency of the SCR method reaches 95 %. However, SCR reactors are large and heavy. This prevents their placement in the engine room, and (since the SCR reactor is installed above the diesel engine) changes the ship's metacentric height. In addition, the use of ammonia and ammonium nitrate is unsafe for the ship and the ship's crew [15-17].

One of the methods that reduce the emission of nitrogen oxides of marine diesel engines is exhaust gas recirculation (EGR) [4, 5, 18].

One of the features of the operation of sea vessels is their accountability to international classification societies (for example, Lloyd's Register of Shipping – England, Bureau Veritas – France, Det Norske Veritas & Germanischer Lloyd – Germany, The American Bureau of Shipping – USA). Moreover, one sea vessel may be under the supervision of several companies at once. These organizations, based on empirical experience, statistical records, and scientific research, develop their own Rules for the Classification of Sea Vessels, and maintain a system of continuous monitoring of compliance with these rules on classified ships. This limits the possibility of making structural changes in the structure of ship power equipment (both thermal and mechanical engines, and systems that ensure their operation) without appropriate approval from these supervisory authorities. The ship's crew, in the performance of their functional duties, is deprived of the possibility of independent re-equipment of both the power plant itself and the systems that serve it. Therefore, the task of both ship mechanics and representatives of research organizations is to determine the optimal operating conditions for a ship power plant without making any improvements and upgrades to its design.

**Formulation of the problem.** The studies were carried out on a Drillships class vessel with the following main characteristics: Length – 228.1 m, Breadth – 41.8 m, Draft (Operating / Transit) – 11.8 / 8.5 m, Deadweight – 60,086 ton, Drilling Depth – 3660 m.

The ship power plant consisted of six 16V32 STX-MAN diesel engines of the same type with the following main characteristics: bore – 320 mm; stroke – 420 mm; speed – 720 rev/min; output rank – 7000 kW; specific fuel oil consumption – 192 g/(kWh). Diesels served as both main and auxiliary engines.

The objective of the study was to determine the optimal degree of EGR, which ensures the maximum reduction in nitrogen oxide emissions while minimizing changes in the energy and economic performance of the diesel engine.

**Presentation of the main research material.** A feature of the operation of diesel engines 16V32 STX-MAN as part of the ship power plant Drillships is a long operational period of operation in partial modes – in the power range $N_{ework}$=(0.25...0.95)$N_{enom}$. These diesels were equipped with a standard low pressure gas recirculation system (LP-EGR), in which gases after the gas turbine of the turbocharger are returned to the diesel purge receiver through the charge air cooler. A diagram of the gas-air system of a 16V32 STX-MAN diesel engine with a low-pressure gas recirculation system is shown in Fig. 1.

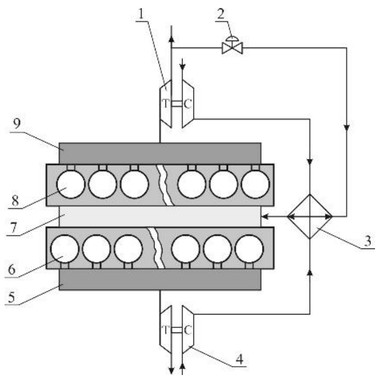



Fig. 1. Scheme of the gas-air system of the 16V32 STX-MAN diesel engine:

1, 4 – turbocharger ; 2 – valve of the recirculation system; 3 – charge air cooler; 5, 9 – exhaust manifold; 6, 8 – working cylinders; 7 – purge air

The design of the diesel engine provides for a two-way arrangement of rows of cylinders 6 and 8. Scavenging air to the cylinders comes from a common receiver 7. Air is injected by gas turbocharger compressors 1 and 4, and it is cooled in a common cooler 3. Exhaust gases from diesel cylinders 6 and 8 enter the manifolds 5 and 9 and further to the gas turbine of the gas turbocharger 1 and 4 (respectively). Exhaust gas recirculation on a diesel engine is provided for one row of cylinders 8 and is carried out using valve 2 controlled by a microcontroller. At the same time, part of the gases (up to 25 %) can return to the purge receiver 7 through the cooler 3. STX-MAN marine diesel engines are characterized by a high degree of boost (with a degree of air pressure increase after the gas turbocharger – up to 3.5...4.5), this ensures a uniform distribution of gases, entering the recirculation, by the volume of the purge receiver and by the working cylinders. During the experiment, the temperature of the air entering after cooler 3 into the purge receiver and further into the diesel cylinders is maintained in the range of 40...45°C with an accuracy of ±1°C by changing the amount of outboard water supplied to cooler 3. Gas flows after gas turbochargers 1 and 4 were combined in one gas outlet pipe with the subsequent use of the energy of the exhaust gases in a waste heat boiler. This contributed to levelling the occurrence of possible deviations in aerodynamic resistance between individual rows of cylinders (for a row of cylinders with gas recirculation and a row without recirculation) and contributed to the same cyclic fuel supply to each row of cylinders [18, 19].

During the research, the following were determined: the degree of recirculation of exhaust gases – $\delta_{EGR}$; concentration of nitrogen oxides in exhaust gases – $NO_X$; specific effective fuel consumption – $b_e$, effective diesel power – $N_e$, exhaust gas temperature – $t$. In addition, according to the operating instructions, all the necessary parameters of the diesel engine were controlled and maintained within the required range.

Gas analysis was performed using a Testo350XL gas analyzer. At the same time, the concentrations in the exhaust gases of the following substances were determined: nitrogen oxides $NO_X$, oxygen $O_{2,Gas}$ and nitrogen $N_{2,Gas}$. Gas analysis of the exhaust gases was carried out in the gas exhaust line at a distance of 10 m from the place where gases exited the gas turbocharger, which complied with the requirements of the Technical Code for $NO_X$ [18, 20, 21].

Exhaust gas recirculation degree $\delta_{EGR}$ during the experiments was calculated by the expression

$$\delta_{EGR} = \frac{\alpha - \alpha_{EGR}}{\alpha} \cdot 100\%,$$

where $\alpha$ – current value of excess air coefficient depending on diesel load;

$\alpha_{EGR}$ – excess air coefficient when using the exhaust gas recirculation system.

Excess air ratio $\alpha$ was determined taking into account volume concentrations $O_{2,Gas}$ and $N_{2,Gas}$ in exhaust gases (measured using the Testo350XL gas analyzer) according to the expression

$$\alpha = \frac{1}{1 - 3{,}76\frac{O_{2,Gas}}{N_{2,Gas}}}.$$

By adjusting the flow area of the exhaust gas recirculation valve (item 2 in Fig. 1), a change in the degree of recirculation of the EGR system was provided in the range $\delta_{EGR}$=0…21 %.

Unitor's ProPower automatic regulation and control system, installed on a diesel engine, made it possible to record the following diesel performance indicators for each of the diesel cylinders: $t$ – exhaust gas temperature, °C; $N_e^{cyl}$ – effective power of the cylinder, kW; $N_e$ – effective diesel power, kW.

The measurements were carried out at a fixed fuel supply and stabilization of the heat fluxes of the cooling media (circulating oil, fresh and sea water).

Throughout the experiment, the engine operated on the same grade of heavy fuel class RMG 380 according to ISO 8217-2020 with the following structural composition: carbon – 86.12 %, hydrogen – 13.42 %, sulfur – 0.32 %, oxygen – 0.06 %, nitrogen – 0.08 %.

High-pressure fuel equipment made it possible to set the cyclic fuel supply $b_{cyc}$, kg/cycle, with an accuracy of 0.5 %, (the same for each of the diesel cylinders), which made it possible to determine the specific effective fuel consumption $b_e$ from known dependencies

$$b_e = \frac{60nzb_{cyc}}{N_e^{cyl}},$$

where $n$ – engine speed, rpm;

$z$ – tact factor [22, 23].

The value of the specific effective fuel consumption obtained in this way for each of the cylinders was averaged and additionally controlled using measuring equipment installed in the booster module of the consumption system, which provides fuel supply to the diesel high-pressure fuel equipment [24].

The studies were carried out at various operating modes of the 16V32 STX-MAN diesel engine – 35...95 % of the load and various degrees of recirculation – 0...21 %. The results of measurements and calculations, which made it possible to determine the values of $NO_X$ emissions in the exhaust gases and the specific effective fuel consumption $b_e$, are shown in Tables 1 and 2.

Table 1. Emission $NO_X$, g/(kWh) marine diesel 16V32 STX-MAN under various loads and degrees recirculation $\delta_{EGR}$

| Diesel load, % | Degree of gas recirculation $\delta_{EGR}$, % | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | 0 | 3 | 6 | 9 | 12 | 15 | 18 | 21 |
| 35 | 8.32 | 7.68 | 7.27 | 6.96 | 6.65 | 6.49 | 6.42 | 6.35 |
| 55 | 8.49 | 8.17 | 7.39 | 7.07 | 6.71 | 6.63 | 6.51 | 6.41 |
| 75 | 8.83 | 8.19 | 7.49 | 7.18 | 6.73 | 6.51 | 6.31 | 6.16 |
| 95 | 8.92 | 8.27 | 7.63 | 7.29 | 7.07 | 6.31 | 6.22 | 5.92 |

Table 2. Specific effective fuel consumption $b_e$, g/(kWh) marine diesel 16V32 STX-MAN under various loads and degrees recirculation $\delta_{EGR}$

| Diesel load, % | Degree of gas recirculation $\delta_{EGR}$, % | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | 0 | 3 | 6 | 9 | 12 | 15 | 18 | 21 |
| 35 | 193.9 | 195.5 | 196.7 | 197.8 | 198.6 | 199.1 | 199.8 | 200.7 |
| 55 | 191.5 | 192.4 | 194.2 | 194.8 | 195.2 | 196.6 | 197.2 | 197.7 |
| 75 | 189.9 | 190.2 | 191.3 | 192.1 | 192.5 | 192.9 | 193.4 | 194.3 |
| 95 | 189.1 | 189.9 | 190.6 | 190.9 | 191.4 | 192.2 | 192.8 | 193.3 |

According to the results of the experiments given in Tables 1 and 2, dependences of the emission of nitrogen oxides $NO_X=f(\delta_{EGR})$ and specific effective fuel consumption $b_e=f(\delta_{EGR})$ – Fig. 2. When building a complex of dependencies $NO_X=f(\delta_{EGR})$ and $b_e=f(\delta_{EGR})$ corresponding to the same load, the dependence $NO_X=f(\delta_{EGR})$. After that, its lower limit was taken as the "base" line to build the dependence $b_e=f(\delta_{EGR})$. The efficiency and economy of using the exhaust gas recirculation system in various modes of its operation can be assessed by determining the area under the dependencies $S_{0,35}^{NO_X}=f(\delta_{EGR})$, $S_{0,55}^{NO_X}=f(\delta_{EGR})$, $S_{0,75}^{NO_X}=f(\delta_{EGR})$, $S_{0,95}^{NO_X}=f(\delta_{EGR})$

та $S_{0,35}^{b_e} = f(\delta_{\text{EGR}})$, $S_{0,55}^{b_e} = f(\delta_{\text{EGR}})$, $S_{0,75}^{b_e} = f(\delta_{\text{EGR}})$, $S_{0,95}^{b_e} = f(\delta_{\text{EGR}})$, where indices 0.35…0.95 correspond to the diesel load.

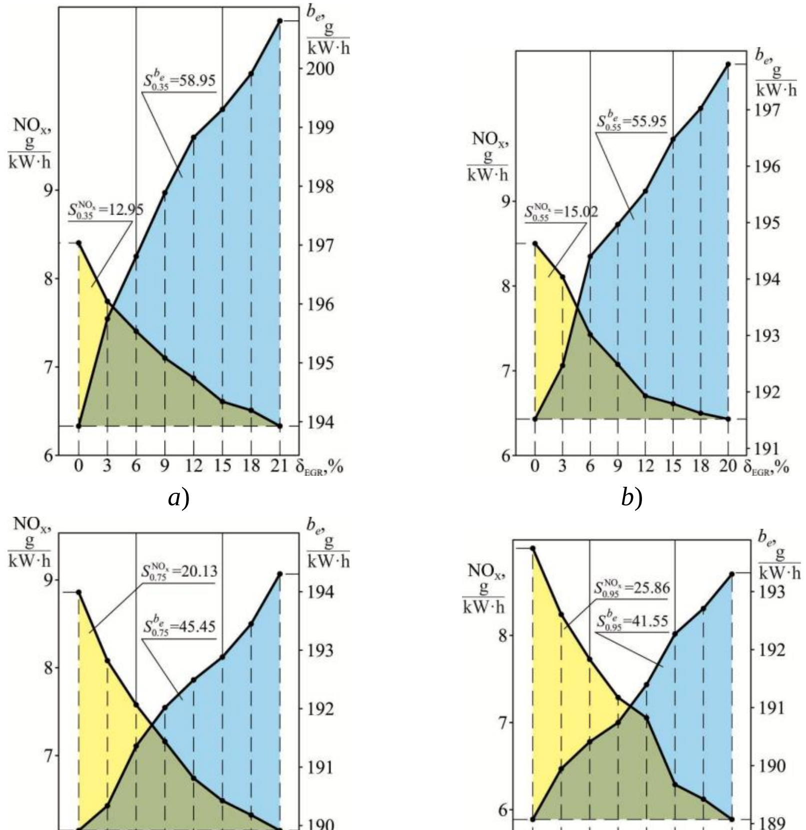



Fig. 2. Emission of nitrogen oxides $NO_X$ and specific effective fuel consumption of a diesel 16V32 STX-MAN under various conditions of the experiment: *a* – load 35 %; *b* – load 55 %; *c* – load 75 %; *d* – load 95 %

The environmental efficiency of a diesel engine in various modes is estimated by the value of the area $S^{NO_X}$, economic – according to the value of the area $S^{b_e}$. Area under dependence $S^{NO_X} = f(\delta_{\text{EGR}})$ directly proportional to the decrease in the environmental friendliness of the diesel engine. The greater the value $S^{\mathrm{NO_X}}$ the more effectively the EGR system provides a reduction in concentration $NO_X$ in diesel exhaust gases. Area under dependence $S^{b_e} = f(\delta_{\mathrm{EGR}})$ inversely proportional to the efficiency of a diesel engine. Increasing value $S^{b_e}$ leads to an increase in the specific effective fuel consumption $b_e$ in the mode under consideration.

EGR System Efficiency $\Delta\mathrm{NO_X}$, %, at different degrees of recirculation $\delta_{\mathrm{EGR}}$ can be evaluated by the expression

$$\Delta\mathrm{NO_X} = \frac{\mathrm{NO_X^0} - \mathrm{NO_X^{EGR}}}{\mathrm{NO_X^0}} \cdot 100\%,$$

where $\mathrm{NO_X^0}$, $\mathrm{NO_X^{EGR}}$ – respectively, the concentration of $NO_X$ in the exhaust gases without and when using the EGR system.

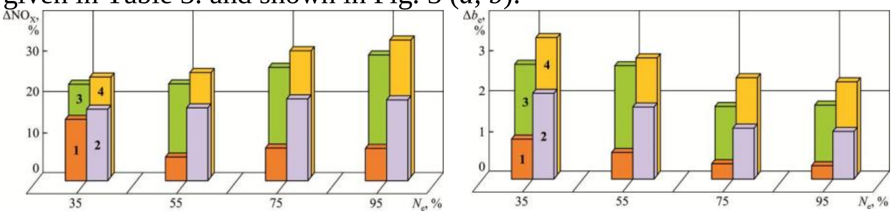
Value $\Delta\mathrm{NO_X}$ also characterizes the environmental friendliness of the operation of maritime transport vessels in various operating conditions. Its increase indicates a decrease in the emission of nitrogen oxides [25].

The decrease in the efficiency of a diesel engine when using the EGR system can be estimated by a relative increase in the specific effective fuel consumption $\Delta b_{\mathrm{e}}$, %, which is defined as

$$\Delta b_{\mathrm{e}} = \frac{b_e^{\mathrm{EGR}} - b_e^0}{b_e^0} \cdot 100\%,$$

where $b_e^0$, $b_e^{\mathrm{EGR}}$ – respectively, the specific effective fuel consumption without and with the use of the EGR system.

Values $\Delta\mathrm{NO_X}$ and $\Delta b_{\mathrm{e}}$ for different conditions of the experiment is given in Table 3. and shown in Fig. 3 (*a*, *b*).




*a*) *b*)

Fig. 3. Relative decrease in $NO_X$ concentration (*a*) and relative increase in the specific fuel consumption (*b*) at different loads of a 16V32 STX-MAN marine diesel engine when using the EGR system:
1 – $\delta_{\mathrm{EGR}}$=3 %; 2 – $\delta_{\mathrm{EGR}}$=9 %; 3 – $\delta_{\mathrm{EGR}}$=15 %; 4 – $\delta_{\mathrm{EGR}}$=21 %

Table 3. Environmental efficiency and fuel efficiency
marine diesel 16V32 STX-MAN when using the EGR system

| Degree of recirculation, % | Diesel load, % | | | |
|---|---|---|---|---|
| | 35 | 55 | 75 | 95 |
| | relative reduction in nitrogen oxide emissions | | | |
| 3 | 7.7 | 3.8 | 7.2 | 7.3 |
| 9 | 16.3 | 16.7 | 18.7 | 18.3 |
| 15 | 22.0 | 21.9 | 26.3 | 29.3 |
| 21 | 23.7 | 24.5 | 30.2 | 33.6 |
| | relative increase in specific effective fuel consumption | | | |
| 3 | 0.83 | 0.47 | 0.16 | 0.42 |
| 9 | 2.01 | 1.72 | 1.16 | 0.95 |
| 15 | 2.68 | 2.66 | 1.58 | 1.64 |
| 21 | 3.51 | 3.24 | 2.32 | 2.22 |

The data presented confirm the thesis about the need for a comprehensive assessment of the environmental and economic performance of a diesel engine.

**Conclusions and prospects for further researches.** Studies that are performed on diesel 16V32 STX-MAN marine class vessel Drillships with deadweights 60,086 ton showed the following.

The use of the exhaust gas recirculation system in the diesel load range of 35...95 % of the rated power and the range of 3...21 % of the degree of exhaust gas recirculation leads to a decrease in nitrogen oxide emissions by 7.7...33.6 %, while increasing the specific effective fuel consumption by 0.2...3.5 % . The deterioration of the combustion process (caused by the intake of not only air, but also exhaust gases into the diesel cylinder) leads to an increase in the temperature of the exhaust gases and increases the temperature tension of the diesel engine. It has been experimentally established that the use of the EGR system in the range of values $\delta_{EGR}$=18...21 % at operating conditions corresponding to 35...55 % load, leads to a critical increase in exhaust gas temperature. In connection, the operation of marine diesel engines in such conditions is possible only in emergency situations, and only for a short period of time.

Recirculation of exhaust gases, as a way to ensure the environmental performance of marine diesel engines, it is advisable to use in the range of values $\delta_{EGR}$=9…15 %. At the same time, in all operating modes of the diesel engine (at loads of 0.35...0.95 % of the rated power), a decrease in nitrogen oxide emissions by 16.3...29.3 % and an increase in specific fuel consumption by 1.6...2.0 % are provided.

The choice of the optimal operating modes of the EGR system and the control of the EGR system can be performed by the ship's crew according to the developed recommendations of research organizations.

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