Exhaust Gas Recirculation as a Major Technique Designed to Reduce NO\textsubscript{x} Emissions from Marine Diesel Engines

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Summary

The study objective is to identify to what extent the recirculation of exhaust gas from a low-speed marine diesel engine affects environmental, economic and power-related parameters in engine operation. Concentration of nitrogen oxides in exhaust gases was assumed to be the environmental parameter of an engine, specific fuel consumption as its economic parameter while effective (brake) power as its power-related parameter. Content of nitrogen oxides in exhaust gases discharged by low-speed marine diesel engines shall remain within the range of 3.4…14.4 g/(kW\cdot h) depending on the area of marine vessel operation as specified by requirements of Annex VI MARPOL. Exhaust gas recirculation (EGR) was reviewed as a way to provide for such values. It was proven experimentally that recirculation of exhaust gas in the range of 4.7…18.8 % provides for reduction in concentration of nitrogen oxide (NO\textsubscript{x}) in the exhaust gases respectively down to 13.3…3.3 g NO\textsubscript{x}/(kW\cdot h) depending on the rotation speed and load of diesel engine. Drop of NO\textsubscript{x} concentration in exhaust gases (as compared to NO\textsubscript{x} concentration without any circulation system used) was shown to reach 37.9…53.5%. It is proposed to apply the EGR system as a major technique to reduce NO\textsubscript{x} - emissions and bring the aforesaid parameter in compliance with requirements of international agencies.

KEY WORDS

low-speed marine diesel engine
environmental indicators of diesel engine operation
concentration of nitrogen oxides in exhaust gases
exhaust gas recirculation (EGR) system
brake power
specific fuel oil consumption

1. INTRODUCTION / Uvod

Liquid fuel is the major power source that provides for operation of internal combustion engines used with marine power plants [1]. Power of propulsion units as imparted to the propeller to provide for vessel propulsion can go as high as 56000…81000 kW in the case of products supplied by major diesel engine manufacturers such as Mitsubishi, MAN Diesel, Wartsila-Sulzer, while that of auxiliary engines used to drive marine power generators can reach 2500…4200 kW [2]. Daily fuel consumption by a propulsion engine at average specific fuel oil consumption (SFOC) of 175…188 g/(kW\cdot h) can reach 235…350 t/day, while up to 8…10 t/day will be the consumption figure for an auxiliary engine (the number of which on board of a modern marine vessel can be as high as 4 pcs, with up to 3 pcs of such operated in parallel). In this case, there are some 16…24 t of exhaust gases emitted to the atmosphere per hour of operation, which include toxic components as well.
Exhaust gases from diesel engines inherently represent a very complex mix of vapors, gases, droplets of liquid and solids and contain around 270 substances, some of which are non-toxic. When hydrocarbon fuels of petroleum origin are put to use along with the atmospheric air as an oxidizer, 99.2% of exhaust gases from marine power plant will be made out of non-toxic components - products of incomplete combustion (carbon dioxide CO₂ and water vapor H₂O) and air with low content of oxygen O₂. All toxic components developed in marine diesel engines can be subdivided into two groups. The first group includes incomplete combustion products such as carbon monoxide, hydrocarbons, aldehydes, soot. Toxic components of the second group result from complete oxidation of chemical elements contained in the fuel and air – such as oxides of nitrogen NOₓ and sulfur SOₓ [3].

Amount of nitrogen oxides in exhausts form marine diesel engines is regulated by requirements of MARPOL, Annex VI [4]. Presently there are two levels of environmental requirements in force: Tier II (global requirements) and Tier III (more stringent requirements applicable to ships in Emission Control Areas). Rates of NOₓ – emissions are established for marine diesel engines depending on the maximum rotation of crankshaft (n, rpm), as shown in Table 1 and displayed visually in Fig. 1.

| Tier  | Date  | NOₓ Limit, g/(kW·h) |
|-------|-------|----------------------|
| Tier II | 2011  | 14.4  | 44-9 n⁻²²³ | 7.7 |
| Tier III | 2016 | 3.4  | 9 n⁻²² | 1.96 |

Figure 1 MARPOL Annex VI NOₓ emission limits

Operation of marine diesel engines is associated not only with providing for their power-related indicators (power and torque) but with maintaining the required level of their environmental indicators as well. In this regard both in operation and designing of marine diesel engines there are constant attempts to find effective ways to reduce toxicity of exhaust gases, in the first place of NOₓ-emissions.

Nowadays there are many ways which contribute to reduction of NOₓ -emissions in exhaust gases. In this case there are strictly defined options to match various types of diesel engines (depending on their design and operating conditions), which are optimal for the purpose of minimizing NOₓ -emissions.

For example, Mitsubishi and MAN Diesel advise to apply EGR systems as such a solution for marine engines with power rating above 10000 kW. However, such issues as identifying the optimal extent of gas recirculation and effects of EGR system on main indicators of diesel engine call for further research. All this considered, the present study aimed at determining to what extent the recirculation of exhaust gas from a low-speed marine diesel engine (as a technique used to reduce NOₓ -emissions) affected its environmental, economic and power-related operational parameters.

2. LITERATURE REVIEW / Pregled literature

Nitrogen oxides take the top position among harmful emissions practically in all operating modes of diesel engines irrespective of their type, class, dimensions and design features. Ratio of nitrogen oxides in overall emissions comprises 30…80% by weight and 60…95% by equivalent toxicity. Nitrogen oxides discharged to the atmosphere along with aerosols and chlororganic compounds destroy the ozone layer that stays at 25 km altitude and absorbs 99% of sun rays and ultraviolet rays [5]. Two compounds - NO and NO₂ – are discussed in the context of providing for compliance with environmental requirements in operation of marine power plants [6].

Nitrogen oxides are the only pollutants which cannot be disposed of by substitution of a fuel grade (just as it is possible for the purpose of reducing SOₓ -emissions), since they mostly develop when nitrogen (necessarily as an integral part of liquid fuel) is combined with oxygen (necessarily as an integral part of in-cylinder air).

Among the set of NOx oxides exactly NO represents the substances which prevail inside the cylinder of diesel engine (=90…95 %), while large amounts of NO₂ develop only on contact with low temperatures, i.e. as exhaust gases escape to the atmosphere. NO develops when NO combines with ozone contained in the air. As a result, nitrogen monoxide NO is converted to dioxide NO₂ and oxygen O₂:

\[ \text{NO} + \text{O}_2 \rightarrow \text{NO}_2 + \text{O}_2 \]

Afterwards NO₂ is combined with water vapors H₂O, thus resulting in development of nitrous acid HNO₂ and, next, to formation of nitric acid HNO₃:

\[ \text{NO}_2 + \text{H}_2\text{O} \rightarrow \text{HNO}_2 \rightarrow \text{HNO}_3 + \text{O}_2 \rightarrow \text{HNO}_3 \]

It is exactly this nitric acid that later on becomes condensed in the air and then returns to the ocean surface, island or continental areas of Earth in the form of acid rains, it is the very compound responsible for environmental damage (Fig. 2). To prevent or minimize such phenomenon, there are various design and process solutions which contribute to reduction of nitrogen oxides in exhaust gases.

There are three mechanisms in formation of NOₓ depending on the origin:

1) thermal mechanism, alias the high-temperature Zeldovich mechanism (thermal NOₓ);
2) prompt mechanism, also known as “chemical” (prompt NOₓ);
3) fuel-related mechanism associated with formation of NOₓ from nitrogen-containing components of fuel (fuel-associated NOₓ) [7].

Development of thermal, prompt and fuel-associated compounds of NOₓ depends on the type of fuel. Overall content of NOₓ formed according to thermal, prompt and fuel-
Prompt nitrogen oxides are formed when molecular nitrogen present in the air is combined with hydrocarbon fragments developed in decomposition of fuel at first stages of combustion. Direct measurements taken by C. P. Fenimore in 1971 demonstrated that NO are formed as early as at the beginning of chemical reaction zone. This mechanism is known as "prompt" (prompt NO) or as C. P. Fenimore mechanism [10].

Thermal oxides of nitrogen, which constitute the largest part of all NO\textsubscript{x} types, are formed at high temperatures (T>1500 K) and on condition that there is high concentration of oxygen available during oxidation of air nitrogen in the process of combustion. Thermal oxides are developed in combustion of both gaseous fuel (natural gas and liquefied petroleum gas) and fuel that does not contain substances with included nitrogen [8]. It is believed that increasing the maximum temperature within the combustion zone in excess of 1850 K results in inadmissibly high emissions of NO\textsubscript{x} [9].

Fuel-associated nitrogen oxides are formed in oxidation of nitrogen-containing substances present in the fuel within the flame tongue area. Concentration of fuel-associated oxides can reach impressive values provided the content of nitrogen-containing substances in a fuel exceeds 0.1% by weight. As a rule, this applies only to liquid fuels.

Ratio of prompt NO\textsubscript{x} remains more or less constant while that of fuel-associated NO\textsubscript{x} tends to grow in combustion of fuels with higher molecular weight. When this happens, the ratio of thermal NO\textsubscript{x} decreases [11].

Ways to reduce concentration of NO\textsubscript{x} in exhaust gases are subdivided into primary and secondary techniques. Primary techniques encompass actions taken to optimize air-fuel mixing, delivery and combustion of fuel as well as improvements to the design of fuel system accessories. Secondary techniques (selective or non-selective catalytic reduction) involve purification of a developing exhaust gases prior to their discharge to the atmosphere in supplementary custom devices (reactors) [12].

Below there are given the most widespread primary techniques used to reduce NO\textsubscript{x} emissions:

1) moistening of turbocharged air;
2) use of water/fuel emulsions;
3) direct injection of water in the diesel cylinder;
4) improvement in the design of fuel system accessories;
5) use of exhaust gas recirculation system [13].

The first option entails additional injection of freshwater into the air volume supplied to the cylinder of a diesel engine. A disadvantage of this technique is that it makes necessary to monitor the quality of freshwater delivered to the air receiver, especially as long as such freshwater keeps circulating over the receiver-pump-injector line, when solids can enter the water (collected in the receiver as leaks), thus causing deterioration in operation of injector nozzle later on [14].

The second option provides for creation of a highly consistent water/fuel mixture and delivery of formed emulsion into the cylinder of a diesel engine. However, since the amount of fuel delivered to the cylinder shall remain constant, additional delivery of water (whose amount shall better stay within the range of 15...20%) would result in extended time of water/fuel mix injection as compared with the time for injection of fuel alone. This makes it necessary to increase a fuel injection advance angle, such action may well result in injection of water/fuel emulsion into the air medium whose temperature so far does not provide for reliable self-ignition [15].

The third option provides for direct injection of water in the diesel cylinder and comes to be implemented either through common injection (when both fuel and water are supplied via a common injector) or through separate injection (when both fuel and water are supplied via separate injectors). Such option, however, also contributes to unstable combustion of fuel [16].

The fourth option among primary techniques implicated in reduction of NO\textsubscript{x} emissions is associated with improvements in the design of fuel system accessories (changes to the shape of injector nozzle, increase of fuel injection pressure etc.) and related to the upgrade of the whole HP fuel system [17, 18, 19].

The fifth option, use of EGR system, is under active development presently and has positive practical results from its testing with marine vessels [20]. Studies described in this paper will be related to exactly this technique.

Reduction of NO\textsubscript{x} emissions is also encouraged by the use
of fuel additives [21], such method, however, is applied to a greater extent to intensify the process of fuel combustion. There are also options to reduce concentration of NOx in exhausts due to the use of alternative fuels, this variant, however, applies only to special-purpose vessels [22, 23]. Here belong liquefied gas tankers and oil tankers which can resort to the carried cargo (LNG tankers) or light fractions evaporating off the surface of carried cargo (in case of oil tankers) as fuel for their marine diesel engines.

The most wide-spread method among secondary techniques for reduction of NOx emissions is represented by the selective catalytic reduction (SCR). Such technique involves injection of a chemical agent, usually ammonia or urea, into the stream of exhaust gases so as to make the mixture arrive later to the catalyst [24]. The temperature range in this case remains within 450…900 K, such figure being significantly lower than that in the case of selective non-catalytic reduction (SNCR), which proceeds at 1100…1400 K [25]. Catalysts to be used here are represented by titanium oxide with such additives as vanadium, molybdenum or tungsten, zeolites, ferrous oxides with a thin ferrous phosphate film or granular activated carbon [26, 27].

The SCR technique is considered to be the most effective way to clean exhaust gases from NOx, the oxide separation efficiency in this case can reach 95%. Significant amendments are required here to the design of gas exhaust system of a diesel engine (in particular through installation of an additional gas duct and regulating wastegates), as well as through installation of a SCR-reactor itself (dimensions of which are commensurate with dimensions of a diesel engine). All these considerations along with high costs of a SCR-reactor and an increase in the hazard level (due to the use of urea, and, particularly, ammonia) are responsible for the fact that nowadays SCR systems are applied on marine vessels only in isolated cases.

3. MATERIALS AND METHODS / Materijali i metode

Exhaust gas recirculation systems have been used more and more extensively during the last decade both with stationary power plants [28, 29] and marine power plants [30] to reduce concentration of NOx in exhausts of diesel engines. Such systems are developed for and installed on recently designed marine vessels. So far there is no considerable experience in operation of such systems while recommendations for their application are based mainly on theoretical studies and simulations of involved processes [31].

A peculiar feature in operation of marine vessels lies in their accountability to international classification societies (such as Lloyd’s Register of Shipping – England, Bureau Veritas – France, Det Norske Veritas & Germanischer Lloyd – Germany, American Bureau of Shipping – USA). Moreover, one marine vessel may at the same time be supervised by several classification societies. Relying on rule-of-thumb experience, statistical service and science studies, these societies develop their own procedures for classification of marine vessels and maintain the system of continuous monitoring for compliance with such requirements on classified vessels. This restricts any possible structural changes to the design of marine power plants (heat and mechanical power-driven engines as well as their support systems) without a respective approval from such regulatory authorities. The vessel crew is allowed to retrofit on its own neither the power plant nor its support systems. Therefore both marine engineers and representatives of R&D institutions face the objective of identifying optimal conditions for operation of ship power plant without introducing any improvements or upgrades to its design.

Results described in this paper were received from an experimental study conducted on a low-speed marine diesel engine 7UEC60LS Mitsubishi (equipped with a standard EGR system) which made it possible to determine effects of EGR system on environmental, power-related and economic indicators of engine operation. The said diesel engine was used as a propulsion unit (by imparting its power directly to the propeller, and thus providing for ship propulsion) on a special-purpose marine vessel with deadweight capacity of 50000 tons.

Main specs of the diesel engine:
- type – two-stroke;
- bore size – 600 mm;
- piston stroke – 2400 mm;
- number of cylinders – 7;
- rated power – 12600 kW;
- speed which corresponds to rated power – 82 rpm.

The basic diagram of diesel engine 7UEC60LS Mitsubishi with EGR system is shown in Fig. 4.

Figure 4 Basic diagram of EGR system for low-speed marine diesel engine 7UEC60LS Mitsubishi: 1 – air cooler; 2 – air receiver; 3 – cylinder of diesel engine; 4 – exhaust manifold; 5 – scrubber; 6 – pilot valve of EGR system; 7 – gas turbocharger; 8 – water pump; 9 – water tank; 10 – electrically driven gas blower; T, C – gas turbine and air compressor of gas turbocharger

Exhausts from the engine cylinder 3 arrive to exhaust manifold 4 and, next, to gas turbocharger 7, and later escape to the atmosphere via a gas discharge tube. Gas turbocharger 7 draws the air from the engine compartment, and having compressed it, delivers it via cooler 1 and receiver 2 to scavenging...
ports of diesel engine. The exhaust gas recirculation system consists of pilot valve 6, gas purification scrubber 5, blower 10, water tank 9 and water pump 8. If the EGR system is made use of, the amount of gas is adjusted by valve 6. Exhaust gases are purified and pre-cooled in scrubber 5, and then delivered by an additional charger to be mixed with air (which arrives from gas turbocharger 7) to proceed to cooler 1 and receiver 2 and, next, through scavenging ports into the diesel cylinder 3. Gas blower 10 is represented by a blower fan with the throat area of constant geometry. Such blower type is most popular with EGR systems used on marine vessels, however, there are some experimental studies involving the use of variable geometry blowers with EGR systems [32, 33].

In experimental studies run on board the ship we took measurements of NOx concentration in exhausts, specific fuel oil consumption (SFOC) and brake power Ne for different degrees of exhaust gas recirculation.

It is most practicable to determine and monitor concentration of harmful components in exhausts with the aid of portable gas analyzers [34, 35]. When determining NOx (and O2) concentration in our experimental studies, we made use of Testo350XL gas analyzer (Germany), which allows to determine concentration for such substances as CO, O2, N2, NOx, CH4, SO2, H2S as well as temperature, humidity, velocity and differential pressure of medium to be measured. Testo350XL gas analyzer provides for reading of the said parameters in the temperature range 40...1200°C, thus fully covering the exhaust temperature range for the diesel engine in all its operating modes. By means of Testo350XL analyzer it is possible to determine the content of oxides NOx, oxygen O2, nitrogen N2, NOx, CH4, SO2, H2S as well as temperature, humidity, velocity and differential pressure of medium to be measured. Testo350XL gas analyzer (Germany), which allows to determine concentration of harmful components in exhausts with the aid of exhaust gas recirculation.

Character of changes in concentration of NOx in exhausts of marine diesel engine 7UEC60LS Mitsubishi depending on speed n, rpm and degree of EGR, % is shown in Figs. 5-7.

Results of the study are presented in Tables 2-4 and in Figs. 5-7. Character of changes in concentration of NOx in exhausts of marine diesel engine 7UEC60LS Mitsubishi is presented in Table 2 and in Fig 5. In this case values of NOx were determined for different rotational speeds of diesel crankshaft n and different degrees of EGR. Change in the rotation speed n was affected by increasing or reducing the cyclic delivery of fuel to the engine cylinder, meanwhile the external load value remained constant. Changes to the degree of EGR were effected through assisted changes in settings of pilot valve (pos. 6 in Fig. 4) with cross-checks of this value by means of expression (1).

| Change of crankshaft speed n, rpm | Change in NOx concentration, g/(kW·h) | 0 | 4.7 | 9.8 | 14.6 | 18.8 |
|----------------------------------|----------------------------------------|----|-----|-----|------|------|
| 55                               | 13.3                                   | 10.7| 9.4 | 8.4 | 8.0  |
| 65                               | 10.8                                   | 8.6 | 7.8 | 7.3 | 6.7  |
| 75                               | 8.0                                    | 6.7 | 6.1 | 4.1 | 4.0  |
| 80                               | 7.1                                    | 5.1 | 4.2 | 4.1 | 3.3  |

Figure 5 Change in SFOC, g/(kW·h) of marine diesel engine 7UEC60LS Mitsubishi depending on speed n, rpm and degree of EGR, %

To determine economic indicators of engine from expression $SFOC = \frac{G \cdot \Delta H - \frac{H_{\text{air}}}{\text{EGR}} - \frac{H_{\text{fuel}}}{\text{EGR}}}{N_{\text{work}}}$ calculation was made of specific fuel oil consumption value, where $G$, – hourly fuel consumption (kg/h) determined for each operation mode with the help of ship instruments (flowmeter and timer).

4. RESULTS / Rezultati

Experiments were run for following speed modes in operation of diesel engine: 55, 65, 75 and 80 rpm, which corresponded to values of relative engine power: $N_{\text{work}} = 0.3N_{\text{nom}}$, $N_{\text{work}} = 0.5N_{\text{nom}}$, $N_{\text{work}} = 0.77N_{\text{nom}}$, $N_{\text{work}} = 0.93N_{\text{nom}}$ as measured in kW. $N_{\text{nom}}$ was assumed to be the rated power.
To determine power-related indicators of engine operation, indicator testing was run with the aid of ship diagnostic system “Doctor”, which makes it possible to determine indicated mean pressure $p_i$ and brake power $N_{esct}$ at any operating mode under consideration [36].

As it is evidenced by the completed research, recirculation of exhaust gases contributes to reduction of NOx concentration in exhausts. In this case, however, there is a decrease in power-related indicators of diesel operation such as brake power $N_{esct}$ and degrees of EGR make it possible to identify optimal engine operation modes (as judged from the viewpoint of economic and power-related indicators) during application of exhaust gas recirculation system. Besides, this approach is instrumental in finding an optimal EGR value for different operating modes of diesel engine.

The EGR system provides for forced feed of exhaust gases into the engine cylinder, thus causing a change in the ratios of flammable fuel components (carbon, hydrogen and sulphur) and an oxidizer (oxygen contained in the air). This change in ratios (at constant amount of fuel supplied to the cylinder) has adverse effects on the combustion process, reduces the maximum temperature inside the cylinder and decreases the amount of "thermal" nitrogen oxides, percentage of which is to be prevalent during combustion of liquid fuels. The level of NOx emission is inversely correlated to the degree of recirculation in EGR system. Reduction in the amount of nitrogen oxides contained in the exhausts is also brought about by a more catalytic reduction, selective non-catalytic reduction, water/fuel emulsions, moistening of turbocharged air, direct injection of water in the diesel cylinder) is associated either with high costs or with reduction in reliability of fuel ignition, therefore these methods are used only in isolated cases [37, 38].

Obtained results are in good agreement with data provided in a number of papers devoted to similar research [39, 40]. However, the proposed method for measuring NOx concentration in exhausts and the way to control the degree of EGR make it possible to identify optimal engine operation modes (as judged from the viewpoint of economic and power-related indicators) during application of exhaust gas recirculation system. Besides, this approach is instrumental in finding an optimal EGR value for different operating modes of diesel engine.

5. DISCUSSION / Diskusija

Presently recirculation of exhaust gases is the most suitable technique for reducing the level of NOx emissions from marine diesel engines first of all from the viewpoint of its implementation technology, and, besides, this technique provides for compliance with international regulations for environment protection. Resorting to other strategies in reduction of NOx concentration in exhausts (such as selective catalytic reduction, selective non-catalytic reduction, water/fuel emulsions, moistening of turbocharged air, direct injection of water in the diesel cylinder) is associated either with high costs or with reduction in reliability of fuel ignition, therefore these methods are used only in isolated cases [37, 38].

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The EGR system provides for forced feed of exhaust gases into the engine cylinder, thus causing a change in the ratios of flammable fuel components (carbon, hydrogen and sulphur) and an oxidizer (oxygen contained in the air). This change in ratios (at constant amount of fuel supplied to the cylinder) has adverse effects on the combustion process, reduces the maximum temperature inside the cylinder and decreases the amount of "thermal" nitrogen oxides, percentage of which is to be prevalent during combustion of liquid fuels. The level of NOx emission is inversely correlated to the degree of recirculation in EGR system. Reduction in the amount of nitrogen oxides contained in the exhausts is also brought about by a more catalytic reduction, selective non-catalytic reduction, water/fuel emulsions, moistening of turbocharged air, direct injection of water in the diesel cylinder) is associated either with high costs or with reduction in reliability of fuel ignition, therefore these methods are used only in isolated cases [37, 38].
intensive feed of exhaust gases to the engine cylinder [41].

Providing for environmental indicators in operation of a diesel engine is associated with power-related and economic parameters of engine operation [42]. Beneficial effects of EGR system on NOx emissions is accompanied at the same time by reduction of brake power and increase of SFOC. In our opinion, loss of engine power is related to reduction in the amount of exhausts which reach the gas turbocharger with simultaneous proportional increase of exhausts supplied to the engine cylinder (through the recirculation system). The first thing reduces power of gas turbocharger $N_w$ while the second thing leads to the reduction in the volumetric efficiency of cylinder (condition of being charged with fresh air) $h_1$. In both cases there is a direct dependency relationship between the parameters $N_w$ and $h_1$, something that causes a drop in the brake power in response to the growth in the degree of ERG.

Relative reduction of brake power $\frac{N_{\text{nom}}}{N_{\text{nom}}} 100 \%$ during the use of EGR system at modes close to the rated crankshaft speed $n_{\text{work}} = 0.975n_{\text{nom}}$ (which corresponds to operational load $N_{\text{work}} = 0.93N_{\text{nom}}$) comprises 0.36…1.2% (with a corresponding change in the EGR level of 18.8…4.7%), and - provided the diesel engine is maintained properly – has no significant effects on propulsion characteristics of a marine vessel.

When the diesel engine is operated at high-speed modes $n_{\text{work}} = 0.91n_{\text{nom}}$ (when $N_{\text{work}} = 0.77N_{\text{nom}}$), $n_{\text{work}} = 0.79n_{\text{nom}}$ (when $N_{\text{work}} = 0.5N_{\text{nom}}$), $n_{\text{work}} = 0.67n_{\text{nom}}$ (when $N_{\text{work}} = 0.3N_{\text{nom}}$), decrease of brake power can reach 2.48…3.43%. Such situation, in our opinion, is encouraged by deterioration of gas exchange in the cylinder and more intense withdrawal of heat from the air-and-gas mixture through cylinder walls at reduced revolutions of crankshaft.

Growing amount of exhausts bound to arrive to the engine cylinder in response to the increase in the degree of EGR as well as deterioration of gas exchange inside the cylinder also represent main causes behind the growth of SFOC in cases when the EGR system is put to use. In our opinion, the reason has to do with a change in the stoichiometric ratio and also with increasing heat losses due to incomplete combustion of fuel. The greatest growth in SFOC corresponds to the engine operation modes with minimal rotational speed of crankshaft. Similar results were obtained in the study of effects the EGR system has on the operation of low-power diesel engines [43].

An integrated nomograph that characterizes changes in concentration of NOx in exhausts, a rise in specific fuel oil consumption DSFOC and a drop of brake power DNe in the marine diesel engine 7UEC60LS Mitsubishi at operational load 0.93 Nom depending on the degree of exhaust gas recirculation is shown in Fig. 8. Analysis of the nomograph makes it possible to draw following conclusions.

Use of EGR system improves environmental parameters in operation of a marine diesel engine, in particular, reduces the level of NOx emissions. Thus, it was found experimentally that a change in the degree of EGR across the range 4.7…18.8% would provide for reduction in concentration of NOx in exhausts respectively to 13.3…3.3 gNOx/(kW·h) depending on the speed and load of the engine, the latter values varying throughout the experiment within the ranges $n_{\text{work}} = (0.67…0.975)n_{\text{nom}}$ and $N_{\text{work}} = (0.3…0.93)N_{\text{nom}}$. This expands the envelope of environmentally safe operating modes for a diesel engine (ref. to Fig.1), thus allowing to ensure compliance with environmental requirements within the range of operational loads. Reduction of NOx concentration in exhausts percentage-wise falls within the limits 19.5…48.8 %, where larger values correspond to the load range (0.77…0.93)Nom, i.e. to the operational modes most commonly used with a diesel engine.

Figure 8 Change in concentration of NOx in exhausts, rise in specific fuel oil consumption DSFOC, drop of brake power DNe in the marine diesel engine 7UEC60LS Mitsubishi at operational load 0.93 Nom depending on the degree of exhaust gas recirculation

Application of EGR system is instrumental in lowering power-related and economic indicators in operation of a marine low-speed diesel engine. Thus it was established by experiments that such economic indicator as the specific fuel oil consumption grows proportionally with the increasing degree of EGR, and for various speed modes of engine operation the former would make 0.85…2.01% for cases when EGR=4.7 % and it would be equal 2.16…4.34% for the case when EGR=18.8 %. Increasing the degree of exhaust gas recirculation would reduce the effective (brake) power of a diesel engine. The modes close to the rated loading, for instance $n_{\text{work}}=0.975n_{\text{nom}}$ and $N_{\text{work}}=0.93N_{\text{nom}}$ manifest a drop of brake power by 1.2%, while the modes $n_{\text{work}}=0.67n_{\text{nom}}$ and $N_{\text{work}}=0.3N_{\text{nom}}$ – by 3.43%.

It is also worth mentioning here that, when the used degree of EGR is above 15% (for research conducted in the range 14.6…18.8%), then the value of specific fuel oil consumption would rise by 1.8…2.2% and the engine power would drop by 1.5%, therefore these modes are not advisable for continuous operation of engine.

6. CONCLUSION / Zaključak

The necessity to provide for required environmental parameters in operation of marine diesel engines (among other things, values of NOx emission in exhausts) compels to address additional technological solutions. One of available options...
lies in equipping marine diesel engines with EGR systems which force-feed some part of exhausts from the exhaust system into an engine cylinder. The EGR system cuts down the amount of air intended for fuel combustion, hence the amount of exhaust gases, which return to the engine cylinder, shall support reliable self-ignition and subsequent combustion of fuel. When the EGR system is used, NOx emissions will drop by 37.9…53.5% depending on the engine operating mode and degree of EGR. The optimal degree of EGR would stay in the range ≈5…15%, depend on peculiarities of design and operating modes of a diesel engine, and shall be determined experimentally. Despite deterioration of economic and power-related indicators, applying the EGR technique to marine vessels has excellent prospects, since the use of this method ensures compliance with international requirements for environment protection and contributes to maintenance of environmental safety in ship power plants.

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REFERENCES / Literatura

[1] Demidova, N. P., Marchenko, A. A., Onishenko, O. F. (2016). Evaluating compatibility of marine heavy fuels. Vestnik Kamchatskogo gosudarstvennogo universiteta, 35(15-20). DOI:10.17211/2079-0333-2016-15-15-20. (In Russian).

[2] Sargin, S. V., Solodovnikov, V. G. (2015). Cavitation Treatment of High-Viscosity Marine Fuels for Medium-Speed Diesel Engines. Modern Applied Science, 9(5): 269-278. https://doi.org/10.5539/mas.v9n5p269

[3] Filippov, A. Z. (1980). Toxicity of exhausts from heat engines Kiev: Visha shkola. (In Russian).

[4] International Convention for the Prevention of Pollution from Ships (MARPOL-73/78), Books I and II. St. Petersburg: CNIIMF. 2012. (In Russian).

[5] Dvoynishnikov, V. A., Larkov, A. V., Kofeynikov, A. V., Romanov, E. V., Kleshengovaja, E. A. (2010). A method in developing in-furnace techniques designed to reduce NOx emissions from power boilers. Vestnik MEI, 3: 3-8. (In Russian).

[6] Kozlov, F. V., Terenchenko, A. S. (2010). Analysis of combustion and nitrogen oxide formation in operation of diesel engines operated with diesel and biodiesel fuels. Trudy NAMI, 243: 87-99. (In Russian).

[7] Klimova, E. V. (2011). Development of harmful agents in exhausts of marine diesel engines during combustion of air-and-fuel mixture. Vestnik Astrakhan’skogo GTU: morskaya tehnika i technologiya, 2: 98-104. (In Russian).

[8] Graziano, B., Kremer, F., Pischinger, S., Heuer, K. A., Rohs, H. (2015). On the operation of Medium-Speed Marine Engines. International Journal of Energy Research, 39(1): 269-278. https://doi.org/10.1002/er.3164

[9] Ajayi, O. O., Fenske, G. R., Goldblatt, I. L., Aldajah, S. (2007). Effect of exhaust gas recirculation (EGR) on the temperature of exhaust gases. Applied Energy, 84(3-16): 282–296. https://doi.org/10.1016/j.apenergy.2007.01.011

[10] Methods for reducing emission of NOx and solids from marine diesel engine (proceedings of congress CIMAC 2013). (2014). Dvigatelestroyenie, 3: 34-52. (In Russian).

[11] Zabolotsky, Yu. V., Kuropatynsky, A. A. (2017). Enhancing fuel efficiency and environmental parameters in operation of marine diesel engines through fuel doping. Austria-science, 2: 979-984. (In Russian).

[12] Li, T., Susuki, M., Ogawa, H. (2010). Effect of off-waste stage injection on unburned hydrocarbon and carbon monoxide emissions from ultra-high EGR low temperature diesel combustion. Nippon Kikai Gakkai Ronbunshu, 766(7): 1004-1009.

[13] Belousov, E. V., Ageyev, M. S., Sviridov, V. I. (2010). Exerting influence on operation of medium-speed marine diesel engine by injection of water into the working cylinder. Dvigatel’ny vnutrennego spal’nya, 1: 40-43. (In Russian).

[14] Zheng, M., Asad, U., Reader, G. T., Tan, Y., Wang, M. (2009). Energy efficiency improvement strategies for a diesel engine in low-temperature combustion. International Journal of Energy Research, 33(1): 8-28. https://doi.org/10.1002/er.1164

[15] Advanced fuel injection systems designed to reduce NOx emissions from marine diesel engines (proceedings of congress CIMAC 2013) (2014). Dvigatelestroyenie, 3: 44-56. (In Russian).

[16] Sagin, S. V., Semenov, O. V. (2016). Motor Oil Viscosity Stratification in Friction Units of Marine Diesel Engines. American Journal of Applied Sciences, 13(2): 200-208. https://doi.org/10.3844/ajassp.2016.200.208

[17] Zabolotsky, Yu. V. (2015). Maintaining Boundary and Hydrodynamic Lubrication Modes in Operating High-pressure Fuel Injection Pumps of Marine Diesel Engines. Indian Journal of Science and Technology, 9(20): 208-216. https://doi.org/10.17485/ijst/2016/v9i20/94490

[18] Kuleshov, A., Grekhov, L. (2013). Multidimensional Optimization of DI Combustion Process Using Multi-Zone Fuel Spray Combustion Model and Detailed Chemistry NOx Formation Model. SAE Technical Papers, 2: 1-16. DOI:10.4271/2013-01-0882. https:// doi.org/10.4271/2013-01-0882

[19] Kavtaradze, R. Z., Sergeev, S. S. (2014). New alternative (partially homogeneous) combustion process as a method for reduction of concentrations of nitric oxides and soot in combustion products of diesel. High Temperature, 52(2): 282–296. https://doi.org/10.1134/S0001815114010106

[20] Kotman, P., Bitzer, M., Kugi, A. (2010). Flatness-based feed forward control of a two-stage turbocharged diesel engine with EGR. 2010 IEEE International conference on control application, CCA 2010 Yokohama, 08-10 of September 2010: 979-984. https://doi.org/10.1109/CCA.2010.5611065

[21] Lin, J., Wu, X., Li, X., Li, R. (2010). Flatness-based feed forward control of a two-stage turbocharged diesel engine with EGR. 2010 IEEE International conference on control application, CCA 2010 Yokohama, 08-10 of September 2010: 979-984. https://doi.org/10.1109/CCA.2010.5611065
[34] Yoo, J., Prikhodko, V., Parks, J. E., Partridge, W. P., Perfetto, A., Geckler, S. (2016). High-speed multiplexed spatiotemporally resolved measurements of exhaust gas recirculation dynamics in a multi-cylinder engine using laser absorption spectroscopy. Applied Spectroscopy, 70(4): 572-584. https://doi.org/10.1177/0003702816636802

[35] Hibino, T., Kuwahara, Y., Otsuka, T., Ishida, N., Oshima, T. (1998). NOx detection using the electrolysis of water vapour in a YZL cell - Part I. NOX detection. Solid State Ionics, 107(3-4): 213-216. https://doi.org/10.1016/S0167-2738(97)00538-9

[36] Sagin, S. V., Semenov, O. V. (2016). Marine Slow-Speed Diesel Engine Diagnosis with View to Cylinder Oil Specification. American Journal of Applied Sciences, 13(5): 618-627. https://doi.org/10.3844/ajassp.2016.618.627

[37] Balzani, J. M., Alfoldy, B., Hjorth, J. (2014). Field test of available methods to measure remotely SOx and NOX emissions from ships. Atmospheric Measurement Techniques, 7(8): 2597-2613. https://doi.org/10.5194/amt-7-2597-2014

[38] Likhanov, V. A., Lopatin, O. P. (2015). Effects from the use of natural gas, EGR and methanol- & ethanol/fuel emulsions on the content of toxic components in exhaust gases. Transport na alternativnom toplive, 4(46): 42-47. (In Russian).

[39] Yerokhov, V. I. (2013). EGR systems of modern engines. Transport na alternativnom toplive, 4(34): 36-42. (In Russian).

[40] Ruan, G., Zhang, Z., Wang, Q. (2012). Exhaust gas recirculation control based on artificial neural network. International Journal of Advancements in Computing Technology, 4(19): 131-138. DOI:10.4156/ijact.vol4.issue 19.17.

[41] Lee, K., Kim, T., Cha, H., Song, S., Chun, K. M. (2010). Generating efficiency and NOX emissions of a gas engine generator fueled with a biogas-hydrogen blend and using an exhaust gas recirculation system. International Journal of Hydrogen Energy, 35(11): 5723-5730. https://doi.org/10.1016/j.ijhydene.2010.03.076

[42] Gureev, V. M., Khairullin, A. K., Varlamov, F. A., Gumerov, I. F., Khafizov, R. K. (2016). Influence of exhaust gas recirculation on technical, economic, and environmental performance of high-uprated diesel aircraft engine. Russian Aeronautics, 59(4): 554-558. https://doi.org/10.3103/S1068799816040188

[43] Stein, G. V., Panfilov, A. A. (2016). Conflict: environmental versus fuel-efficiency indicators of a diesel engine. Nauchnoye obozreniye, 18: 66-70. (In Russian).