Exhaust Gas Recirculation as a Major Technique Designed to Reduce NO_x Emissions from Marine Diesel Engines

Ponovno strujanje plina kao glavna tehnika kojoj je svrha smanjiti NO_x emisije iz dizelskih brodskih motora

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DOI 10.17818/NM/2019/1.1
UDK 621.436
621.5.02:502
Original scientific paper / *Izvorni znanstveni rad*
Paper accepted / *Rukopis primljen:* 6. 11. 2018.

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·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_x) in the exhaust gases respectively down to 13.3…3.3 g NO_x/(kW·h) depending on the rotation speed and load of diesel engine. Drop of NO_x concentration in exhaust gases (as compared to NO_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_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

Sažetak

Cilj studije je identificirati: "Do koje mjere ponovno strujanje ispušnoga plina iz sporohodnog dizelskog stroja, utječe na okolišne, ekonomske i energetske parametre pri radu stroja?" Koncentracija nitrogen oksida pri ispušnim plinovima, smatra se energetskim parametrom stroja, a specifična potrošnja goriva, kao ekonomski parametar, dok je učinkovita (konjska) snaga energetski parametar. Sadržaj nitrogen oksida pri ispušnim plinovima koje ispušta sporohodni brodski dizelski stroj, ostat će unutar dometa od 3.4…14.4g/(kW·h) ovisno o području djelovanja broda na moru, kako je specificirano zahtjevima Annexa MARPOL Konvencije Ponovno strujanje plina (EGR) odabrano je za dokazivanje tih vrijednosti. Eksperimentalno je dokazano da ponovno strujanje ispušnoga plina u dometu od 4.7…18.8% osigurava smanjenje koncentracije nitrogen oksida (NO_x) pri ispušnim plinovima, prema redosljedu navođenja sve do 13.3…3.3 g NO_x/kW·h ovisno o rotacionoj brzini i opterećenju dizelskoga stroja. Pad koncentracije pri ispušnim plinovima (u usporedbi s NO_x) koncentracijom bez ikakva sustava cirkulacije dostigao je 37.9…53.5%. Predlaže se da se primijeni EGR sustav kao glavna tehnika smanjenja NO_x emisija i da se dovede spomenuti parametar u skladu sa zahtjevima međunarodnih agencija.

KLJUČNE RIJEČI
sporohodni dizelski motor
okolišni pokazatelji djelovanja dizelskoga stroja
koncentracija nitrogen oksida pri ispušnim plinovima
sustav ponovnoga strujanja plina
konjska snaga
specifična potrošnja goriva

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·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 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% content of exhaust gases from marine power plant will be made out of non-toxic components - products of incomplete combustion (carbon dioxide CO_2 and water vapor H_2O) and air with low content of oxygen O_2. 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 NO_x and sulfur SO_x [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 NO_x – 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.

Table 1 MARPOL Annex VI NO_x emission limits
Tablica 1. MARPOL Annex VI NO_x limiti emisija

Tier	Date	NO_x Limit, g/(kW·h)		
		$n<130$	$130 \le n < 2000$	$n \ge 2000$
Tier II	2011	14.4	$44 \cdot n^{-0.23}$	7.7
Tier III	2016	3.4	$9\ n^{-0.2}$	1.96

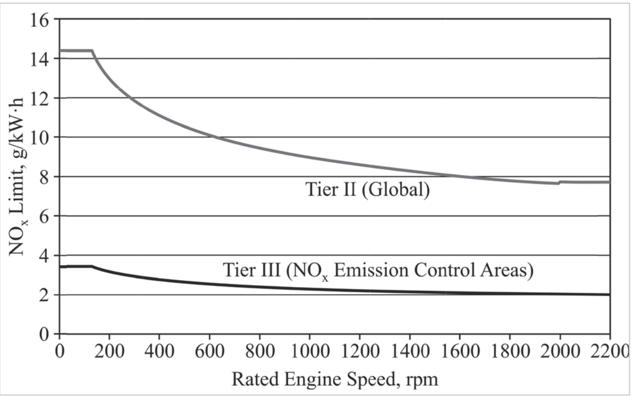

Figure 1 MARPOL Annex VI NO_x emission limits
Slika 1. MARPOL Annex VI NO_x limiti emisija

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 NO_x-emissions.

Nowadays there are many ways which contribute to reduction of NO_x -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 NO_x -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 NO_x -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 NO_2 – 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 SO_x –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 NO_2 develop only on contact with low temperatures, i.e. as exhaust gases escape to the atmosphere. NO_2 develops when NO combines with ozone contained in the air. As a result, nitrogen monoxide NO is converted to dioxide NO_2 and oxygen O_2:

$$NO + O_3 \rightarrow NO_2 + O_2.$$

Afterwards NO_2 is combined with water vapors H_2O, thus resulting in development of nitrous acid HNO_2 and, next, to formation of nitric acid HNO_3:

$$NO_2 + H_2O \rightarrow HNO_2 \rightarrow HNO_2 + O_2 \rightarrow HNO_3.$$

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 NO_x depending on the origin:

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

Development of thermal, prompt and fuel-associated compounds of NO_x depends on the type of fuel. Overall content of NO_x formed according to thermal, prompt and fuel-

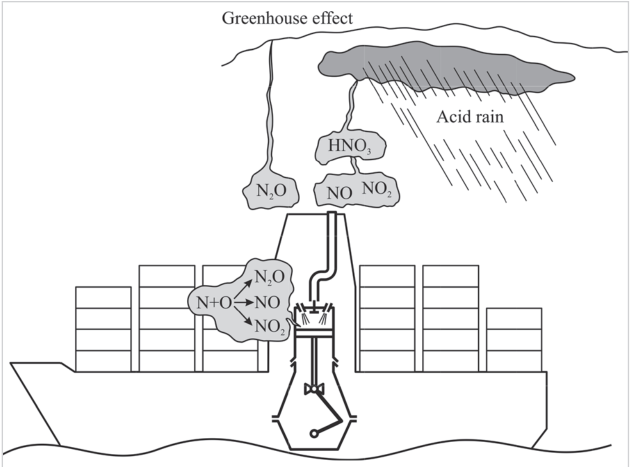

Figure 2 Effects of nitric acid on environment in operation of heat engines

Slika 2. Učinci dušične kiseline pri djelovanju zagrijanih motora

associated mechanisms comprises 100%, their ratios, however, are offset for fuels with different aggregative states and fractional breakdown. The nomograph for correlation of NO_x in various types of fuel (at standard combustion conditions) is given in Fig. 3.

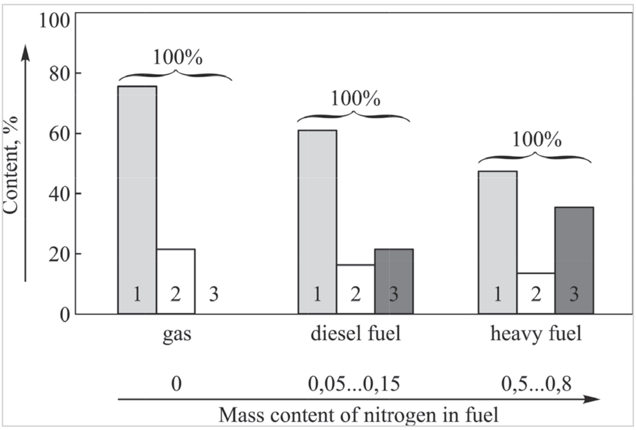

Figure 3 Nomograph for distribution of NO_x types in various types of fuel

1 - thermal; 2 - prompt; 3 - fuel-associated

Slika 3. Graf rasporeda NOx tipova pri različitim vrstama goriva

1 - termalno; 2 - promptno; 3 - povezano s gorivom

Thermal oxides of nitrogen, which constitute the largest part of all NO_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_x [9].

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].

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_x remains more or less constant while that of fuel-associated NO_x tends to grow in combustion of fuels with higher molecular weight. When this happens, the ratio of thermal NO_x decreases [11].

Ways to reduce concentration of NO_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 developed exhaust gases prior to their discharge to the atmosphere in supplementary custom devices (reactors) [12].

Below there are given the most wide-spread primary techniques used to reduce NO_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 supply 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 against 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_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_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 NO_x 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 NO_x–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 NO_x, 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 NO_x 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.

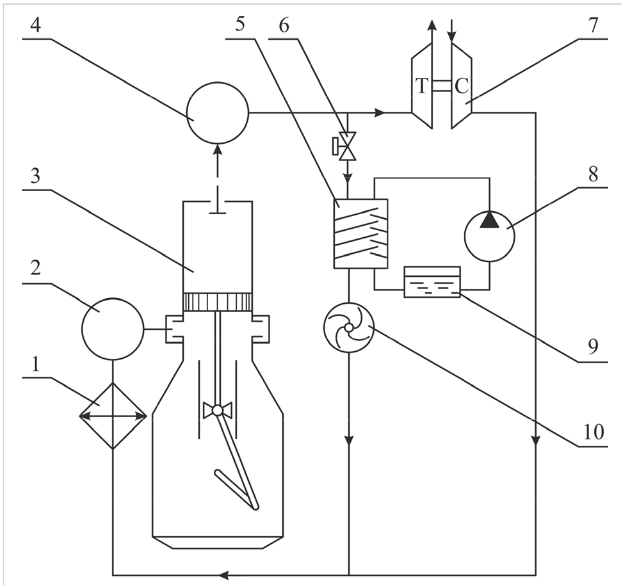

Figure 4 Basic diagram of EGR system for low-speed marine diesel engine 7UEC60LS Mitsubishi: 1 – air cooler; 2 – air receiver; 3 – cylinder of diesel engine; 4 –exhaust manifold; 5 –scrubber; 6 – pilot valve of EGR system; 7 – gas turbocharger; 8 – water pump; 9 – water tank; 10 – electrically driven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

Slika 4. Osnovni dijagram EGR sustava za sporohodni brodski dizelski motor 7UEC60LS Mitsubishi: 1 – hladnjak zraka; 2 – prijemnik zraka; 3 – cilindar dizelskoga stroja; 4 – ispušna manica; 5 – četka; 6 – pilotski ventil EGR sustava; 7 – turbopuhalo plina; 8 – pumpa vode; 9 – vodenti tank; 10 – raspršivač plina na električni pogon; T, C – plinska turbina i zračni kompresor ili turbopuhalo plina

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 NO_x concentration in exhausts, specific fuel oil consumption (SFOC) and brake power N_e 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 NO_x (and O_2) concentration in our experimental studies, we made use of Testo350XL gas analyzer (Germany), which allows to determine concentration for such substances as CO, O_2, N_2, NO_x, CH_4, SO_2, H_2S 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 NO_x, oxygen $O_{2,Gas}$, and nitrogen $N_{2,Gas}$ in exhausts with the instrument range 0…3000 mln^{-1} with accuracy up to 1 mln^{-1}.

Degree of exhaust gas recirculation was measured during the experiments with following values: EGR=4.7 %, EGR=9.8 %, EGR=14.6 %, EGR=18.8 % and calculated from the expression

$$\mathrm{EGR} = \frac{\alpha_{\mathrm{EGR}}}{\alpha}, \qquad (1)$$

where α – excess-air factor with no EGR system in use;

α_{EGR} – excess-air factor with an EGR system used.

To determine the degree of EGR, the excess-air factors α and α_{EGR} were determined with allowance for volume concentration of oxygen and nitrogen in exhaust gases during engine operation without EGR system – $O_{2,Gas}$, $N_{2,Gas}$ and with ERG system – $O^{EGR}_{2,\,Gas}$, $N^{EGR}_{2,\,Gas}$.

$$\alpha = \frac{1}{1 - 3{,}76\dfrac{O_{2,\,Gas}}{N_{2,\,Gas}}}, \qquad \alpha_{EGR} = \frac{1}{1 - 3{,}76\dfrac{O^{EGR}_{2,\,Gas}}{N^{EGR}_{2,\,Gas}}}.$$

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_{ework}=0.3N_{enom}, N_{ework}=0.5N_{enom}, N_{ework}=0.77N_{enom} и N_{ework}=0.93N_{enom} as measured in kW. N_{enom} was assumed to be the rated power.

Results of the study are presented in Tables 2-4 and in Figs. 5-7.

Character of changes in concentration of NO_X in exhausts of marine diesel engine 7UEC60LS Mitsubishi is presented in Table 2 and in Fig 5. In this case values of NO_X were determined for different rotational speeds of diesel crankshaft *n* and different degrees of EGR. Change in the rotation speed *n* was effected 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).

Table 2 Changes in concentration of nitrogen oxides NO_x, g/(kW·h) in exhausts of marine diesel engine 7UEC60LS Mitsubishi depending on speed *n*, rpm and degree of EGR, %

Tablica 2. Izmjene u koncentraciji dušičnog oksida NO_x g/(kW·h) pri ispusima brodskoga dizelskog motora 7UEC60LS Mitsubishi ovisno o brzini n, rpm i stupnju EGR, %

		Changes in degree of EGR, %				
		0	4.7	9.8	14.6	18.8
Change of crankshaft speed *n*, rpm	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

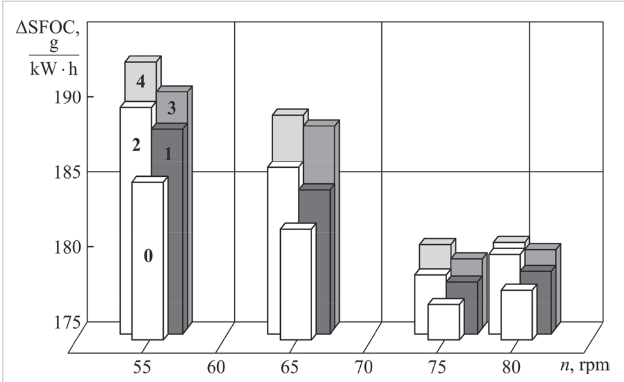

Figure 5 Change in SFOC, g/(kW·h) of marine diesel engine 7UEC60LS Mitsubishi depending on speed *n*, rpm and degree of EGR, %: 0 – operation without recirculation (EGR=0%;) 1 – EGR=4.7%; 2 – EGR=9.8%; 3 – EGR=14.6%; 4 – EGR=18.8%

Slika 5. Izmjena pri SFOC, g/(kW·h) brodskog dizelskog stroja 7UEC60LS Mitsubishi ovisno o brzini n, rpm i stupnju EGR, %.: 0 – djelovanje bez ponovne cirkulacije (EGR=0%) 1 – EGR=4.7%; 2 – EGR=9.8%; 3 – EGR=14,6%; 4 – EGR=18.8%

To determine economic indicators of engine from expression $\mathrm{SFOC} = \frac{G_h}{N_{ework}}$ calculation was made of specific fuel oil consumption value, where G_h – hourly fuel consumption (kg/h) determined for each operation mode with the help of ship instruments (flowmeter and timer).

Nature of changes in SFOC of marine diesel engine 7UEC60LS Mitsubishi is displayed in Table 3 and in Fig. 6.

Table 3 Changes in SFOC, g/(kW·h) of marine diesel engine 7UEC60LS Mitsubishi depending on speed п, rpm and degree of EGR, %

Tablica 3. Izmjene pri SFOC, g(kW·h) brodskoga dizelskog stroja 7UEC60LS Mitsubishi ovisno o brzini n, rpm i stupnju EGR, %

		Changes in degree of EGR, %				
		0	4.7	9.8	14.6	18.8
Change of crankshaft speed *n*, rpm	55	184.3	188.0	189.2	190.5	192.3
	65	181.0	184.1	185.3	188.0	188.8
	75	176.2	177.0	178.2	179.1	180.2
	80	177.1	178.5	179.5	180.0	180.3

Table 4 Relative power loss $\frac{N_{eEGR}}{N_e}\cdot 100, \%$ in marine diesel engine 7UEC60LS Mitsubishi depending on speed *n*, rpm and degree of EGR, %

Tablica 4. Relativan gubitak energije $\frac{N_{eEGR}}{N_e}\cdot 100, \%$ *pri brodskom motoru 7UEC60LS Mitsubishi ovisno o brzini n, rpm i stupnju EGR, %*

		Changes in degree of EGR, %			
		4.7	9.8	14.6	18.8
Changes of crankshft speed *n*, rpm	55	3.43	2.48	1.71	1.52
	65	2.95	1.97	1.33	1.17
	75	2.06	1.56	1.11	0.76
	80	1.26	0.82	0.54	0.36

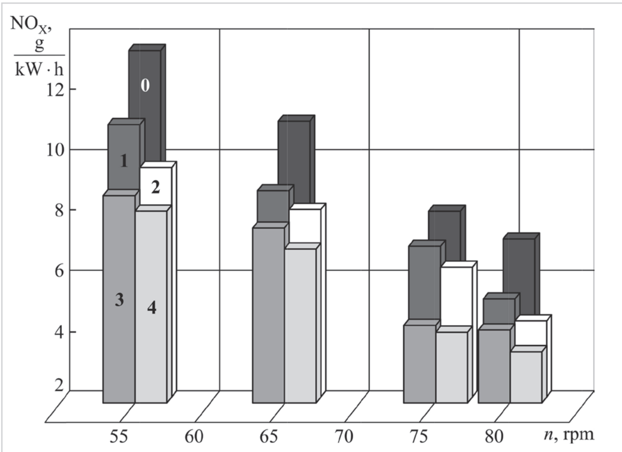

Figure 6 Change in concentration of NOX, g/(kW·h) in exhausts of marine diesel engine 7UEC60LS Mitsubishi depending on speed п, rpm and degree of EGR, %: 0 – operation without recirculation (EGR=0%;) 1 – EGR=4.7%; 2 – EGR=9.8%; 3 – EGR=14.6%; 4 – EGR=18.8%

Slika 6. Izmjena u koncentraciji NOx,g/(kW·h) pri ispusima brodskoga dizelskog motora 7UEC60LS Mitsubishi ovisno o brzini n, rpm i stupnju EGR, %. 0 – djelovanje bez ponovne cirkulacije (EGR=0%) 1 – EGR=4.7 %; 2 – EGR=9.8%; 3 – EGR=14.6%, 4 – EGR=18.8%

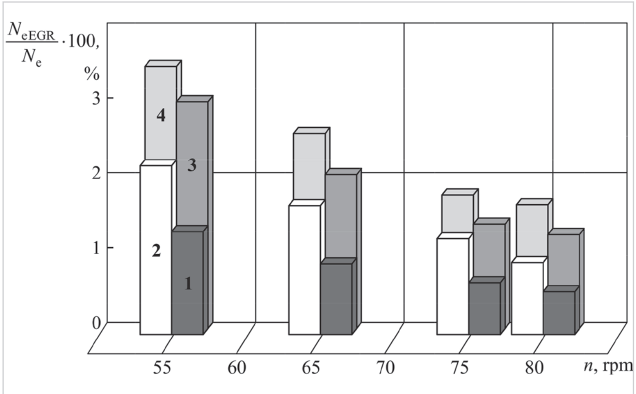

Figure 7 Relative drop of brake power $\frac{N_{eEGR}}{N_e}\cdot 100, \%$, in marine diesel engine 7UEC60LS Mitsubishi depending on crankshaft speed *n*, rpm and degree of EGR: 1 – 4.7%; 2 – 9.8%; 3 – 14.6%; 4 –18.8%

Slika 7. Relativan pad konjske snage $\frac{N_{eEGR}}{N_e}\cdot 100, \%$*, kod brodskog dizelskog stroja 7UEC60LS Mitsubishi ovisno o brzini koljeničaste osovine n, rpm i stupnju EGR; 1 – 4.7%; 2 – 9.8%; 3 – 14.6%; 4 –18.8%*

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_{ework} at any operating mode under consideration [36].

As it is evidenced by the completed research, recirculation of exhaust gases contributes to reduction of NO_x concentration in exhausts. In this case, however, there is a decrease in power-related indicators of diesel operation such as brake power N_{eEGR} in the modes which correspond to different levels of EGR (due to reduction of excess-air factor). Assessment of brake power reduction level can be made from expression $\frac{N_{eEGR}}{N_e}$.

Nature of changes in this value for different crankshaft speeds and degrees of EGR is provided in Table 4 and in Fig.7.

5. DISCUSSION / *Diskusija*

Presently recirculation of exhaust gases is the most suitable technique for reducing the level of NO_x 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 NO_x 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].

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 NO_x 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.

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 NO_x 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 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 NO_x 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_T, while the second thing leads to the reduction in the volumetric efficiency of cylinder (condition of being charged with fresh air) h_v. In both cases there is a direct dependency relationship between the parameters N_T~G_T and N_e~h_v, something that causes a drop in the brake power in response to the growth in the degree of ERG.

Relative reduction of brake power $\frac{N_{e\,EGR}}{N_e}\cdot 100\,\%$ during the use of EGR system at modes close to the rated crankshaft speed n_{work}=0.975n_{nom} (which corresponds to operational load N_{ework}=0.93N_{enom}) 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_{work}=0.91n_{nom} (when N_{ework}=0.77N_{enom}), n_{work}=0.79n_{nom} (when N_{ework}=0.5N_{enom}), n_{work}=0.67n_{nom} (when N_{ework}=0.3N_{enom}), 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 NO_x in exhausts, a rise in specific fuel oil consumption DSFOC and a drop of brake power DN_e with a marine diesel engine 7UEC60LS Mitsubishi operated at load 0,93N_{enom} 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 NO_x–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 NO_x in exhausts respectively to 13.3…3.3 gNO_x/(kW×h) depending on the speed and load of the engine, the latter values varying throughout the experiment within the ranges n_{work}=(0.67…0.975)n_{nom} and N_{ework}=(0.3…0.93)N_{enom}. 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 NO_x 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)N_{enom}, i.e. to the operational modes most commonly used with a diesel engine.

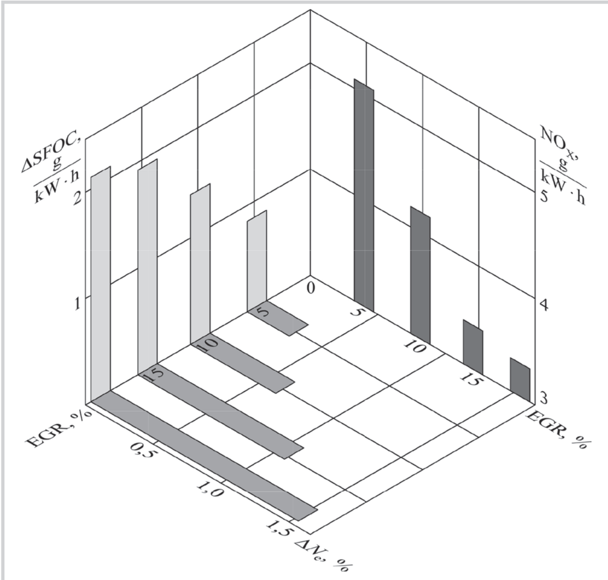

Figure 8 Change in concentration of NOx in exhausts, rise in specific fuel oil consumption DSFOC, drop of brake power DNe in the marine diesel engine 7UEC60LS Mitsubishi at operational load 0.93 Nenom depending on the degree of exhaust gas recirculation

Slika 8. Promjena u koncentraciji NOx ispuha, rast u specifičnoj potrošnji nafte DSFOC, pad konjske snage kod broskog dizelskog motora 7UEC60LS Mitsubishi pri radnom opterećenju 0.93 Nenom ovisno o stupnju recirkulacije plina

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_{work}=0.975n_{nom} and N_{ework}=0.93N_{enom} manifest a drop of brake power by 1.2%, while the modes n_{work}=0.67n_{nom} and N_{ework}=0.3N_{enom} – 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 NO_x 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, NO_x 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.

ACKNOWLEDGMENTS / *Zahvale*

Presented studies were conducted in accordance with the Research plan of National University "Odessa Maritime Academy", Project "Improvement of efficiency and environmental indicators of ship power plants on the basis of modern engineering and IT processes".

The authors express their gratitude to Prof. Vladimir Antonovich Golikov, Doctor of Engineering, Vice-principal for Research at National University "Odessa Maritime Academy", for his assistance provided in developing the research plan and procedures and for his advice in management of experimental study techniques and presentation of study results.

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