Supplying of Marine Diesel Engine Ecological Parameters
Pregled ekoloških parametara brodskih dizel motora

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Abstract

The by-pass system of exhaust gas for the engine 6L20 Wartsila has been observed. The requirements of Annex VI MARPOL towards nitrogen oxide concentration in ship engine exhaust gases have been provided. The purpose of research was the determination of diesel 6L20 Wartsila by-pass exhaust gases optimum volume – at this the nitrogen oxide minimal concentration in exhaust gases is assured, the minimal increase (comparing with operation mode without by-pass) – specific effective fuel consumption, supporting of necessary thermal factor diapason of engine cylinders. The research was performed for the exhaust gas by-pass diapason 0…10 % with engine load diapason 0.55…0.85 % from nominal power. Upon experimental results it has been stated that the exhaust gas by-pass usage favors the ecological parameters of ships engine operation modes – by this at the range of exploitation load 0.55…0.85 % from nominal power the nitrogen oxide concentration in exhaust gas is decreased to 1.32….12.97 %. The exhaust gas by-pass impairs the combustion process and favors the increasing of specific effective fuel consumption and increasing the temperature of exhaust gases. The exhaust gas by-pass system effectiveness assessment should be performed by complex estimation of the following engine operation parameters: the nitrogen oxide concentration in exhaust gas, increasing of specific effective fuel consumption(SFOC), the exhaust gas temperature. As optimal degree of exhaust gas by-pass value when the maximum decrease of nitrogen oxide emission at minimal increase of fuel consumption and simultaneous engine thermal factor handling has to be considered.

Sažetak

U radu je analiziran premosni sustav ispušnih plinova motora 6L20 Wartsila. Navedeni su zahtjevi iz Priloga VI MARPOL konvencije o koncentraciji dušikovog oksida u ispušnim plinovima brodskih motora. Svrha istraživanja bila je određivanje optimalnog volumena premosnice ispušnih plinova dizel motora 6L20 Wartsila – pri tome je osigurana minimalna koncentracija dušikovog oksida u ispušnim plinovima, minimalno povećanje (u usporedbi s režimom rada bez premosnice) – specifična učinkovita potrošnja goriva, podržavanje potrebnog dijapazona toplinskog faktora cilindara motora. Istraživanje je provedeno za raspon premosnice ispušnih plinova 0 – 10 % s rasponom opterećenja motora 0,55 – 0,85 % od nazivne snage. Na temelju eksperimentalnih rezultata utvrđeno je da primjena premosnice ispušnih plinova pogoduje ekološkim parametrima režima rada brodskih motora – time se u rasponu eksploatacijskog opterećenja 0,55 – 0,85 % od nazivne snage smanjuje koncentracija dušikovog oksida u ispušnom plinu na 1,32 – 12,97 %. Premosnica ispušnih plinova otežava proces izgaranja i pogoduje povećanju specifične efektivne potrošnje goriva i povećanju temperature ispušnih plinova. Učinkovitost premosnog sustava ispušnih plinova treba provjeriti kompleksnom procjenom sljedećih parametara rada motora: koncentracija dušikovog oksida u ispušnom plinu, povećanje specifične efektivne potrošnje goriva (SFOC), temperatura ispušnih plinova. Kao optimalni stupanj premosne vrijednosti ispušnih plinova treba uzeti u obzir maksimalno smanjenje emisije dušikovih oksida uz minimalno povećanje potrošnje goriva i simultano upravljanje toplinskim faktorom motora.

1. INTRODUCTION / *Uvod*

Sea transport is an essential part of developed countries all over the world, an exit to the global ocean aquatic area. According to the "United Nations 2019 Maritime Report", the volume of the sea transportation in 2019 has reached 116 billion tons, thus even the after world crisis in 2008-2010 the sustainable growth of the world maritime trade has been confirmed [1].

The active development of the maritime traffic sustains the growth of the ship and engine building [2, 3]. The engine that assures the movement and functionality of the sea and river transport (regardless of their purpose, gross tonnage and region of navigation zone), is the internal combustion engine (diesel) [4]. The engine, fixed at the sea and river vessels, generates

mechanical energy by the fuel air ratio, assuring the permanent heat and mass exchange with the atmosphere during this operation [5]. It takes the air and consumes the fuel, then it is exhaust gas, containing partially the air and the product of fuel oxidation. In this matter of fact the air, coming to the engine cylinder, performs certain thermodynamic cycle, and as a result is transforming into exhaust gas – a complex gas mixture with numerous components.

During the usage of hydrocarbon fuel by diesel oil-derived and atmospheric air as an oxidizing agents the exhaust gases of the ships' power plants consist of 99…99.8 % non-toxic components, namely – the incomplete-combustion products (carbon dioxide CO_2 and water vapor H_2O) and air with the decreased content of oxygen O_2 and nitrogen N_2. The rest (0.1…1.0 % of the volume) are the mechanical impurities, toxic for the environment and the humans [6].

When combustible fuel elements are oxidized by oxygen in the air (carbon C, hydrogen H and sulphur S) as well nitrogen N and further burning of fuel air mixture, the following toxic components appear: carbon dioxide gas CO, carbon oxide and hydrocarbon C_nH_m, soot C, nitrogen oxide NO_x, sulphur oxide SO_x, as well the high-density metals combination, contained in fuel (Fig.1).
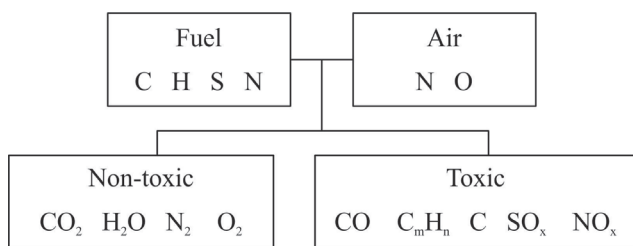

Figure 1 The mechanism of toxic components exhaust gases formation during fuel oxidation and combustion
Slika 1. Mehanizam stvaranja otrovnih komponenti ispušnih plinova tijekom oksidacije i izgaranja goriva

The nitrogen oxide NO_x is one of the most toxic components of exhaust gas [7, 8]. During normal atmospheric conditions the nitrogen is represented in the inert gas. In high pressure and temperature in particular the nitrogen very actively reacts with the oxygen. In the engine exhaust gas more than 90 % of all NO_x quantity is nitrogen oxide NO that in the exhaust system and into atmosphere easily oxidizes into dioxide NO_2 and becomes

an azotic acid HNO_3. After that, the azotic acid condenses into the air, returns to the surface of the world ocean or to the island and inland part of the Earth as an acid rain and infects the environment and the humans [9, 10].

The diesel engines ecological characteristics are specified essentially by the content of nitrogen oxide NO_x in combustion products, which significantly dominates over the other harmful components of exhaust gases as per toxic index. In this respect a range of international organizations (namely International Maritime Organization – IMO) incorporated strict requirements whose implementation assures ecological parameters of ship engine operation [11].

The nitrogen oxide concentration in the ships' power plant exhaust gases are determined by the requirements of the Annex VI MARPOL, depending on the year of ship building and engine revolution per minute. According to the standards Tier-I, Tier-II, Tier-III, (related to the diesel vessels built after 2000, 2011 and 2016) the maximum quantity of NO_x into exhaust gas should not be over the limits determined by the specific formula (Fig. 2) [12].

2. LITERATURE REVIEW / *Pregled literature*

At present, beyond the controlled sea and river transport engine parameters, the high profile is given to such ecological parameters as nitrogen oxide concentration in exhaust gases [13, 14]. This parameter is controlled by the international requirements and is mandatory for ship power plants operation, both in the world ocean aquatic areas and in the territorial waters of seafaring countries [15, 16].

Nitrogen oxide formation during fuel combustion occurres when temperature into engine cylinder increase 1500 K and high oxygen concentration condition during atmospheric nitrogen oxidating is controlled in the burning process. In this respect, all methods that assure decreased NO_x emission are focused on changes of stoichiometric proportion fuel-air, that leads to deterioration of mixing process, of oxidation and burning [17].

The decreased NO_x concentration into exhaust gas is achieved by means of:
- by influence to the operation process into engine cylinder [18-20];
- construction and operation parameters changes of high pressure fuel equipment[21-23];
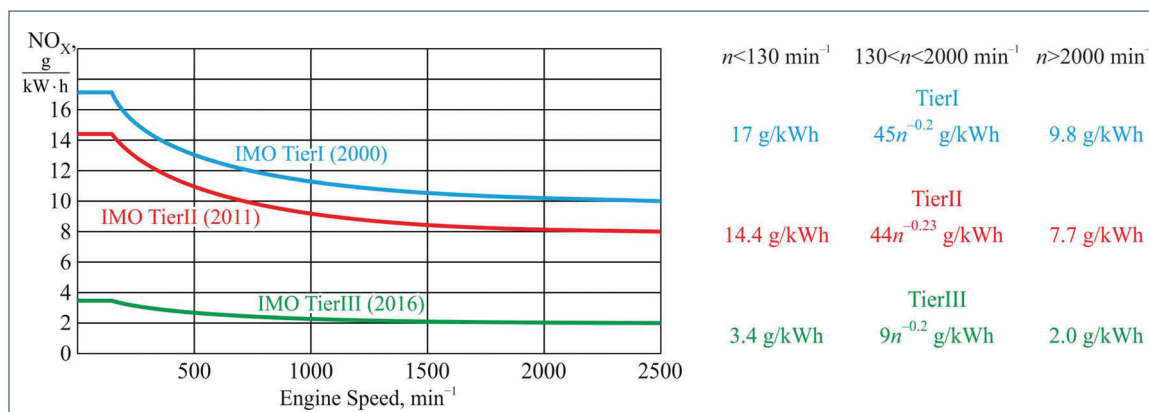- infusion of reagents into exhaust gas during their passing through special reactors [24-26];

Figure 2 Requirements of Annex VI MARPOL to the quantity of NOx into exhaust gas of ship engines
Slika 2. Zahtjevi iz Priloga VI MARPOL-a za količinu NOx u ispušnom plinu brodskih motora

- the usage of exhaust gas system operation assured either their recirculation or (Exhaust gas recirculation – EGR) [27, 28], or their by-pass (Exhaust gas wastegate – EWG) [29].

Exhaust gas recirculation systems (EGR) are used, as a rule, for low speed engine [30, 31]. For the medium speed engine the operation of exhaust gas flow could be performed by their by-pass (EWG) [32, 33]. In this case a part of engine exhaust gas immediately falls into exhaust gas manifold beside exhaust gas turbocharger (TC). At this the rotation rate is decreased as well as pressure and quantity of pressurized air into cylinder. The exhaust gas by-pass is assured by special valve permitting to direct a part of exhaust gas not into TC but specifically into to the exhaust pipe [34]. At present, the EWG system is installed into medium speed engine and assures the functions of main and auxiliary engines [35].

The operation and exploitation characteristics of sea and river ships' engine TC are assured by complex coordination of two components – TC compressor (charges air into engine cylinder) and exhaust gas side of turbine (used exhaust gas energy) [36]. The steady running of engine TC is characterized by the equality of turbo charger power N_T and TC compressor side N_C:

$$N_T = N_C,$$

and the relevant difference of their power δ_{TC}

$$\delta_{TC} = \frac{N_T - N_C}{N_T} 100\%$$

not exceed 0.5 %

The operation process, taking part into the sea and river ships' engines, is in tight connection with the process of charge air and exhaust gas. To adjust the operation process in the combustion chamber and the quantity of air, supplied by the TC compressor side, the following measures of automatic regulation are applied:

- by-pass a part of exhaust gas besides turbine [37];
- the turn of blades of turbine [38];
- the changes of open flow area at turbine entrance [39].

The most practical usage has been provided in the system with automatic regulation with by-pass of exhaust gas beside turbine. It helps to assure the engine with necessary quantity of air at all operation modes and to reduce the maximum turbocharger shaft revolution.

The usage of exhaust gas by-pass beside turbine is possible for the one and two step pressurized system (Fig. 3). In the one step pressurized system (Fig. 3, *a*) after exhaust manifold the exhaust gas flow is going directly to the turbine, and a part of flow (which in the engines of different producers is located between 0…15 %) is redirected to the exhaust pipe. For two step pressurized system (Fig. 3, *b*) the by-pass of a part of exhaust gas (moved from engine cylinders to the exhaust manifold then to the turbine) can be assured either to the TC of low pressure or (as in one stage charger) into the exhaust gas funnel. During the by-pass of exhaust gas flow, it has been throttling to the pressure less than the exhaust gas pressure beside TC [40]. This prevents gas injection and stagnation of gas flow, coming from turbine. Notwithstanding a big cycle of performed research on the engine with two stage TC, there arestill a lot of uncertain moments concerning the thermo-gas dynamic flow [41, 42].

The by-pass exhaust gas "waste-gate" systems are used, as a rule, to decrease the power of turbocharger in case of long work engine used on the maximum load mode or at instant high increase of load. At these terms of operation the turbocharger revolution frequencies could surpass the maximum allowed value, that is why with a help of by-pass the quantity of exhaust gas coming to the turbocharger is decreased. The usage of EWG-system for decreasing NO_x emission for the current moment has no accomplished research with the confirmed results. In some of the previous works [9, 31, 32] the influence of EGR-system on ecological compatibility has been studied.

At the same time, the operation of the exhaust gases recirculation, as a method of assured ship engine ecological parameters, appears almost not to be studied, whose positive results of appliance will differ by scientific novelty, by actuality, and will find a practical use in the maritime transportat.

3. MATERIALS AND METHODS / *Materijali i metode*

The purpose of the research was to determinen the optimum exhaust gas by-pass system of medium speed engine 6L20 Wartsila. As this, from one side, the best ecological parameters

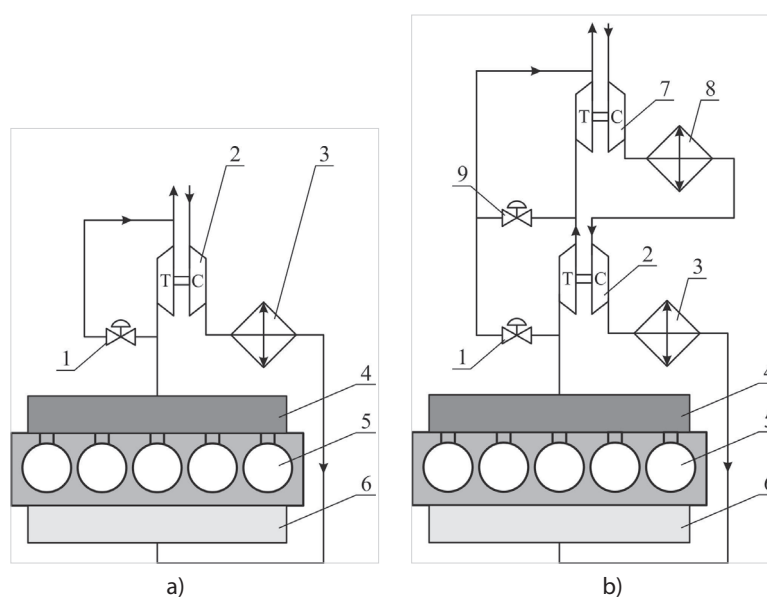a)   b)

Figure 3 Technological scheme of by-pass exhaust gas: 1, 9 – valve EWG; 2, 7 – TC; 3, 8 – air cooler; 4 – exhaust manifold, 5 – engine cylinders; 6 – air receiver; *a* – one stage charger; *b* – two stage charger
Slika 3 Tehnološka shema premosnice ispušnih plinova: 1, 9 – ventil EWG; 2, 7 – TC; 3, 8 – hladnjak zraka; 4 – ispušni razvodnik, 5 – cilindri motora; 6 – prijemnik zraka; a – jednostupanjski punjač; b – dvostupanjski punjač

should be assured for the provided engine operating mode (NO$_x$ concentration in exhaust gas) and from the other side – minimal increase (compared with the engine operating mode without by-pass system) of specific effective fuel consumption at simultaneous maintenance of necessary diesel cylinders thermal factor range.

Main characteristics of the engine 6L20:
- number of cylinders – 6;
- cylinder diameter – 0.2 m;
- piston stroke – 0.26 m;
- maximum combustion pressure – 16.3 MPa;
- engine speed – 1000 min^{-1};
- nominal power – N_{enom}=1200 kW;
- specific effective fuel oil consumption (SFOC) – 193 g/(kWh).

The research has been conducted on three similar types of medium speed engine 6L20 of Wartsila with electronical operating system of fuel supplying phases, air and gas assignment, being part of ship's power plant as diesel generators. The nominal power of Auxiliary engine was N_{enom}=1200 kW at with speed 1000 min^{-1}. The engines have had almost the same running hours and have been used on the equal loads. As operation system of exhaust gas on these engines the system of EWG has been installed. The appliance of this system is recommended by Wartsila firstly to limit the pressure of charge air and to prevent the surging effects of TC at high load and as additional option – to reduce NO$_x$. According to the project documentation the EWG system assures exhaust gas by-pass system in the range 0…10 %. The principal scheme of EWG system of the engine 6L20 Wartsila is shown in Fig. 4.
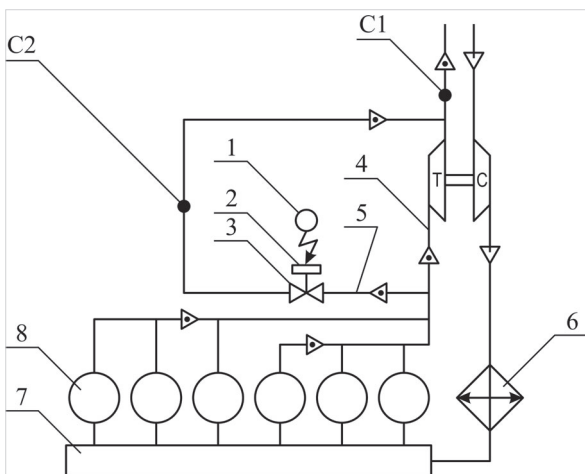

Figure 4 The principal scheme of medium speed engine 6L20 Wartsila with exhaust gas operating system EWG:
1 – controller of by-pass valve position; 2 – pneumatic drive of by-pass valve; 3 – by-pass valve (wastegate); 4,5 – main and by-pass gas flow pipeline; 6 – air cooler; 7 – scavenging air receiver; 8 – engine cylinders; C1, C2 – control points of gas flow; T,C – turbine and compressor of turbocharger

Slika 4. Glavna shema motora srednje brzine 6L20 Wartsila s operativnim sustavom ispušnih plinova EWG:
1 – regulator položaja premosnog ventila; 2 – pneumatski pogon premosnog ventila; 3 – premosni ventil (wastgate); 4,5 – glavni i premosni plinovod; 6 – hladnjak zraka; 7 – prijemnik zraka za usisavanje; 8 – cilindri motora; C1, C2 – kontrolne točke strujanja plina; T,C – turbina i kompresor turbopunjača

The air pressurized by the compressor of TC moves into the air cooler 6 after that going in the engine cylinder 8 through scavenging air receiver 7. In engine (traditionally for medium speed diesel engine Wartsila) the impulse system of TC is realized, at which the exhaust gas from the engine cylinder 8 per separate exhaust gas line going into the turbine of turbocharger. Depending on the by-pass valve position 3 (the transposition is assured by pneumatic actuator 2 and regulated by controller 1) the exhaust gas is going either to the turbine 4, or to the by-pass 5.

The consumption of exhaust gas into lines 4 and 5 is determined in points C1 and C2 by using flowmeter MT100s of "Siemens AG" (Germany). The sensibility of flowmeters MT100 is determined as 0.07…0.2 nm^3/s, the operation temperature is up to 454℃, assuring their functionality at all range of engine operation loads [43]. The flow meters MT100 comply with the requirements of the Environmental Protection Agency (EPA) Continuous Emission Monitoring System.

During the experiment in point C1 by means of gas detector Testo350XL the concentration of NO$_x$ in exhaust gas has been determined [44]. The NO$_x$ concentration control is performed in the exhaust funnel at the distance of 10 m from turbocharger output that corresponds to the NO$_x$ Technical file requirements.

The measuring of exhaust gas flowmeter and NO$_x$ concentration into exhaust gas were held within 10 minutes at 15 second intervals. The obtained results have been averaged.

The operating economy parameter of any engine is fuel consumption. For the ship's engines its value has to be determined not only per unit time but also relevant to the effective power. This allows us to compare the economic effectiveness of diesel engines with different power (the engine value ranges from 100 to 100000 kW). Taking into consideration that in previous research the meaning of all parameters was fixed only at installed modes, the value of fuel consumption has been determined as an average result for all periods of each stage of experiment.

SFOC b_e has been determined by means of ships' measuring tools – the flowmeters, installed on the fuel line of fuel inlet to the high pressure of fuel pumps, and timer and has been analyzed as per formula

$$b_e = \frac{G_h}{N_{ework}^{en}},$$

where G_h – timing consumption of fuel, kg/h, which analyzed as per formula

$$G_h = \frac{V_f \rho_f}{t},$$

where V_f – fuel volume, going through the flow meter, m^3;
r_f – fuel density at corresponding temperature, kg/m^3;
t – time, during that the experiment has been performed on necessary speed mode, hour;
N_{ework}^{en} – engine power on different speed modes, kW, [45, 46].

The specificity of ships' engine power identification at sea and river transport assuring the auxiliary function (the diesel generator engine) is a possibility to identify it as per electric user capacity. There is no necessity to take performance of the engine (that simplifies experiment technology) and a possibility to measure the direct power, for example with watt-meter (that increase the accuracy of experiment). The engine power N_{ework}^{en} is analyzed as per formula

$$N_{ework}^{en} = \frac{N_{ework}^{gen}}{\eta_{gen}},$$

where N_{ework}^{gen} – effective power of generator engine, kW (is determined as per wattmeter in central controlling point);

η_{gen} – electrical generator coefficient of efficiency on relevant exploitation mode (taking into consideration the compliance with the characteristics and instruction manual of electrical generator).

The degree of exhaust gases by pass δ_{EWG} is analyzed as per formula:

$$\delta_{EWG} = \frac{G_{wg}}{G_{\Sigma}} \cdot 100\%, \qquad (1)$$

where G_{wg} – the volume of exhaust gases passing through by pass valve, kg/s (has been measuring in point 9 by means flow meter MT100S);

G_{Σ} – a summary quantity of exhaust gases coming into blowoff pipeline from TC at dully closed by pas valve, kg/s (measured at point 1 by means flow meter MT100S).

The inaccuracy during measurement of gases consumption, determined by flow meter MT100S, did not exceed ±0.5 %, the inaccuracy during measuring of exhaust gases NO_x emission by gas analyzer Testo350XL has been fixed as ±3.5 %, the inaccuracy in checking of specific effective fuel consumption did not exceed ±2.5 %.

4. RESULTS / *Rezultati*

The engine, where all experimental research has been performed, has assured the power for the constant consumer groups. At this (depending on researched modes) its power was 660, 780, 900, 1020 kW, that was in compliance with 55, 65, 75 and 85 % from nominal load – $0.55N_{enom}$, $0.65N_{enom}$, $0.75N_{enom}$, $0.85N_{enom}$. The inaccuracy in power changing did not exceed ±1.5 %.

The ship's power plant contained three single type engines, in this respect in case when the quantity of energy consumer and its power was changing, the required load was redirected to the engine which was not engaged in the experiment, thus the engine engaged in the experiment was used under permanent load. Besides this, during experiment on engine the permanent temperature mode was held in the lubricant and cooling systems. During the experiment, the engine has been under permanent load within 2.5…3 hours with the stable position of by-pass valve on each of the experiment mode. Considering the long period of experiment performance, the exhaust gas consumption checking persistence has been fully neutralized and has no impact on the results.

To identify the degree of wastegate opening, initially, in point C1 the general consumption of gas has been identified G_{Σ}, outgoing from engine cylinder and going through the exhaust gas manifold 4 (at dully closed valve 3). After that, at changed position of wastegate 3 in point C2 the exhaust gas consumption G_{wg} has been identified through by-pass pipeline 5 and the degree of exhaust gas by-passing δ_{EWG}, has been rated per formula (1). The following measurements have been performed as per two schemes (Fig. 5):

1) at constant position of by-pass valve the load to engine has been changed and then the NO_x ratio concentration in exhaust gas and SFOC b_e, have been determined, for example at constant ratio δ_{EWG} =10.0 % and different exploitation meaning N_{ework}^{gen}, corresponding to 55, 65, 75, 85 % from nominal power; further the position of by-pass valve has been changed (δ_{EWG} = 8.0, 6.0, 4.0 %) and for every ratio δ_{EWG} in mentioned diapason the loading to engine has been changed again and the checking of NO_x and b_e has repeated;

2) at constant engine load the by-pass valve position has been changed and then the NO_x emission has been determined and the economic parameter of engine – b_e, for example, at constant ratio $N_{ework}^{en} = 0.85 N_{enom}$ and different meanings δ_{EWG} (δ_{EWG} =10.0, 8.0, 6.0, 4.0 %)); then the engine load meaning has been changed ($0.55N_{enom}$, $0.65N_{enom}$, $0.75N_{enom}$) and for every meaning in the mentioned diapason the position of by-pass valve has been changed again and the measurement of NO_x and b_e was repeated. This helped to get more experimental meanings and to increase their informative content. Thus received experimental meanings have shown good convergence that confirmed corrective way of the performed measurements.

As criteria of engine thermal factor the temperature average value of exhaust gas on engine cylinders have been taken – t_g, measuring of that value has been assured by the ship's diagnostic system Doctor. The temperature value of exhaust gas is recommended by the manufacturer of the engine as well by Scientifics used as the evaluation criteria in te working process and condition of high pressure fuel equipment [48]. The indicator of value t_g has been performed during all time of experiment.

δ_{EWG}=4.0%			
$0.55N_{enom}$	$0.65N_{enom}$	$0.75N_{enom}$	$0.85N_{enom}$

δ_{EWG}=6.0%			
$0.55N_{enom}$	$0.65N_{enom}$	$0.75N_{enom}$	$0.85N_{enom}$

δ_{EWG}=8.0%			
$0.55N_{enom}$	$0.65N_{enom}$	$0.75N_{enom}$	$0.85N_{enom}$

δ_{EWG}=10.0%			
$0.55N_{enom}$	$0.65N_{enom}$	$0.75N_{enom}$	$0.85N_{enom}$

N_e=0.55N_{enom}			
δ_{EWG}=4.0%	δ_{EWG}=6.0%	δ_{EWG}=8.0%	δ_{EWG}=10.0%

N_e=0.65N_{enom}			
δ_{EWG}=4.0%	δ_{EWG}=6.0%	δ_{EWG}=8.0%	δ_{EWG}=10.0%

N_e=0.75N_{enom}			
δ_{EWG}=4.0%	δ_{EWG}=6.0%	δ_{EWG}=8.0%	δ_{EWG}=10.0%

N_e=0.85N_{enom}			
δ_{EWG}=4.0%	δ_{EWG}=6.0%	δ_{EWG}=8.0%	δ_{EWG}=10.0%

concentration of NO_x in exhaust gases, specific fuel oil consumption (SFOC)
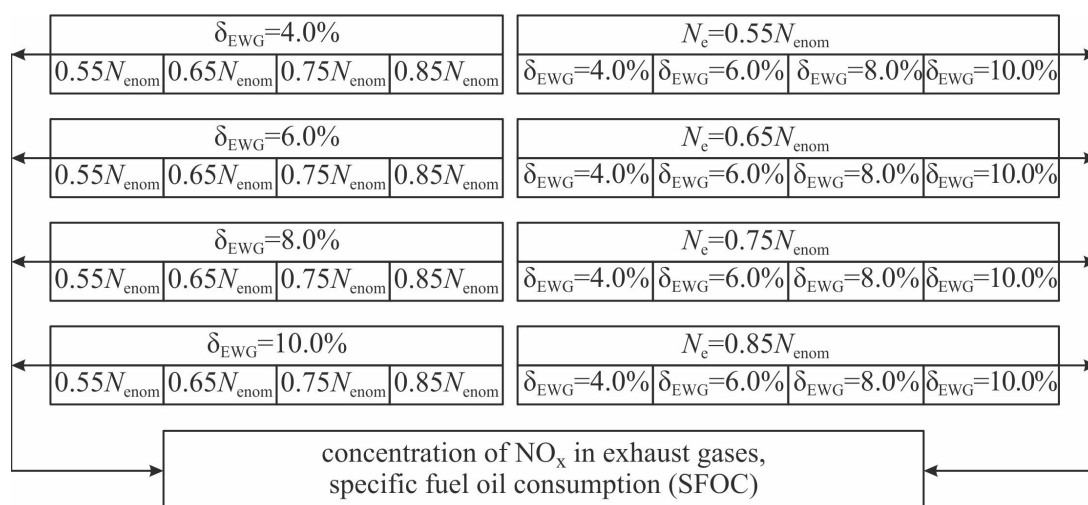
Figure 5 The succession of experimental research performance
Slika 5. Slijed izvedbe eksperimentalnih istraživanja

The research results are generalized in Table 1 and provided in Fig. 6.

Table 1 The parameters changes of ships engine 6L20 Wartsila for different conditions of experiment
Tablica 1. Promjene parametara brodskog motora 6L20 Wartsila za različite uvjete pokusa

Load ratio, %	Bypass degree of exhaust gases, δ_{EWG}, %				
	0	4.0	6.0	8.0	10.0
	emission NO_X, g/(kW×h)				
55	7.58	7.48	7.43	7.33	7.28
65	7.81	7.62	7.52	7.43	7.32
75	8.21	7.82	7.71	7.52	7.34
85	8.48	8.19	7.78	7.64	7.38
	specific effective fuel oil consumption, b_e, g/(kW×h)				
55	198.6	200.7	201.6	203.5	206.8
65	196.9	198.9	199.6	201.3	202.6
75	195.5	196.3	196.8	197.3	198.1
85	191.6	192.5	193.6	195.1	195.7
	exhaust gas temperature t_g, °C				
55	285	294	298	312	318
65	279	285	294	304	308
75	278	283	291	293	297
85	273	281	288	290	293

The relative change in the environmental (Δb_e) and economic (ΔNO_X) performance of a diesel engine in the case of using the EWG system can be determined by the expressions

$$\Delta b_e = \frac{b_e^0 - b_e^{EWG}}{b_e^0} \cdot 100\%, \quad \Delta NO_X = \frac{NO_X^{EWG} - NO_X^0}{NO_X^0} \cdot 100\%,$$

where b_e^0, b_e^{EWG} – specific effective fuel oil consumption without using EWG system and by using EWG system with different degree of by-pass, g/(kW×h);

$NO_X^{EWG} - NO_X^0$ – NO_X emission without using of EWG system and by using EWG system with different degree of by-pass, g/(kW×h).

The meanings b_e^0, b_e^{EWG} and $NO_X^{EWG} - NO_X^0$ are taken from table 1 for relevant load meanings and bypass degree δ_{EWG}. The changes Δb_e and ΔNO_X for different engine loads and different degree of exhaust gas by-pass are shown on the Fig. 7.

5. DISCUSSION / *Rasprava*

The by-pass exhaust gases system (Exhaust gas wastegate – EWG) are recommended and used by certain engine manufactured (for example Wartsila) to reduce the pressure of charged air to reduce the overload engine. The EWG system assures the by-pass of exhaust gas in cylinder in diapason 0…10 % from their general volume directly to the exhaust
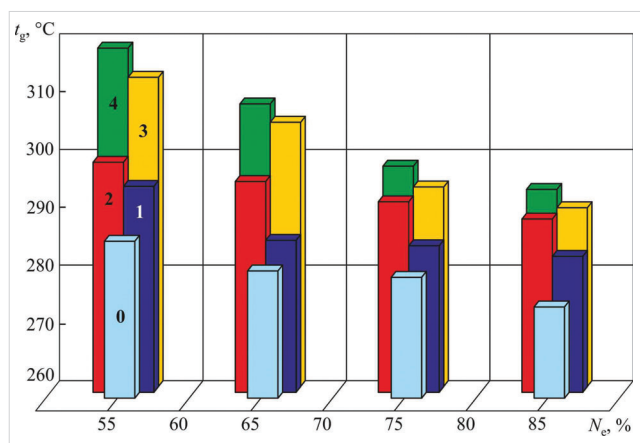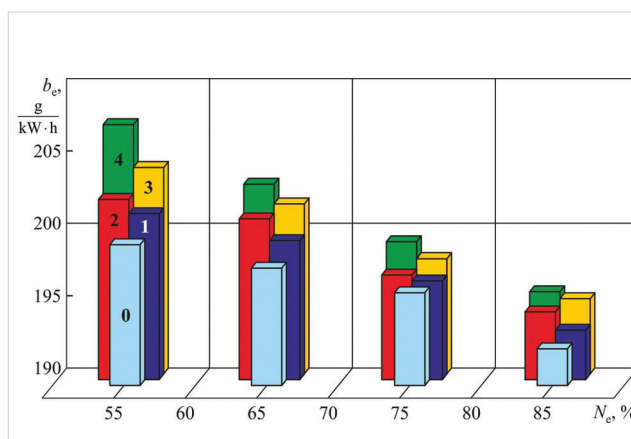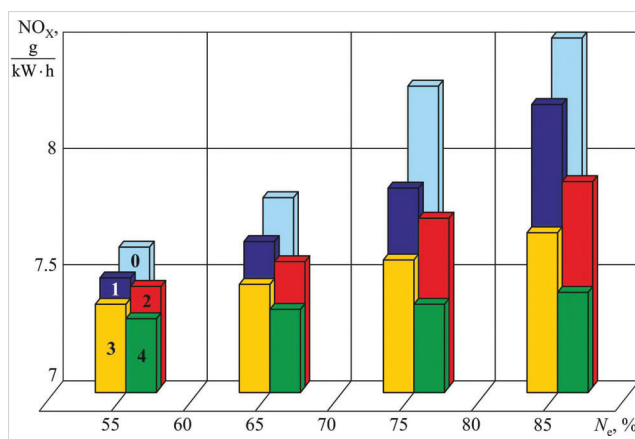

Figure 6 Emissions NO_X, g/(kW×h), exhaust gas temperature t_g, °C, specific fuel oil consumption b_e, g/(kW×h) for different loads N_e, %, of the 6L20 Wartsila marine diesel engine and different degrees of exhaust gas by-pass δ_{EWG}: 0 – without bypass; 1 – 4.0 %; 2 – 6.0 %; 3 – 8.0 %, 4 – 10.0 %

Slika 6. Emisije NOX, g/(kW×h), temperatura ispušnih plinova tg, °S, specifična potrošnja loživog ulja b_e, g/(kW×h) za različita optere-ćenja N_e, %, brodskog dizel motora 6L20 Wartsila i različite stupnjeve premosnice ispušnih plinova δ_{EWG}: 0 – bez premosnice; 1 – 4,0 %; 2 – 6,0 %; 3 – 8,0 %, 4 – 10,0 %

funnel without using their energy into TC. The EWG system can be used for assuring the ecological parameters of engine operation (namely to decrease the NO_x emission with exhaust gas) in all range of engine operation modes.

During experimental research to determine the EWG system influence on sea and river ships' engines exploitation parameters simultaneous with operation modes' process (such as cylinder pressure, power, fuel consumption) the exhaust gas volume flow rate and its temperature on separate engine cylinder have been controlled. The first (the volume flow rate) has assured the control and regulation of EWG system by-pass degree, the second (temperature) has prevented the engine from thermo overheat.

The usage of EWG system assured the degree of NO_x concentration into exhaust gas. Thus, (by poor combustion process) the engine power is decreasing and specific effective fuel consumption is increasing. Besides this, the excessive increasing of exhaust gas quantity leads to the intensive engine thermal factor.

The application of the EWG system has a complex impact on the economic and ecological engine operation parameters. According to the experimental data on every engine loads with increased exhaust gas by-pass degree δ_{EWG}, the meanings Δb_e are

also increasing (relevant to specific effective fuel consumption increasing) as well the ΔNO_x (relevant to nitrogen oxides emission decrease). The Δb_e increasing with growth of by-pass degree δ_{EWG} is connected to the decreasing of turbocharger power, with stoichiometric air-fuel ratio changing, with combustion process degradation and leads to degradation of diesel efficiency operation (decreasing of NO_x quantity in exhaust gas).

The usage of exhaust gas by-pass system favoring the refining of medium-speed engine ecological parameters, namely at this in diapason of operation loads (0.55…0.85) N_{enom} the exhaust gas of NO_x emission degree is decreasing on 1.32…12.97 %. The utmost level of NO_x emission corresponds to 75…85 % load – the most widespread operation modes of medium-speed engine during their appliance as diesel-generators incorporated in the ship's power plant.

The degradation of the charge air supply process during EWG usage favors fuel burning process shifting to the expansion line and provokes the growth of engine thermal factor (that is possible to evaluate as per temperature value of exhaust gas t_g). According to the manual engine operation rules 6L20 Wartsila, to assure the temperature stress the value of temperature exhaust gas t_g should not exceed 300°C. For operation modes, corresponding to (0.55…0.65)N_{enom}, the usage of EWG system
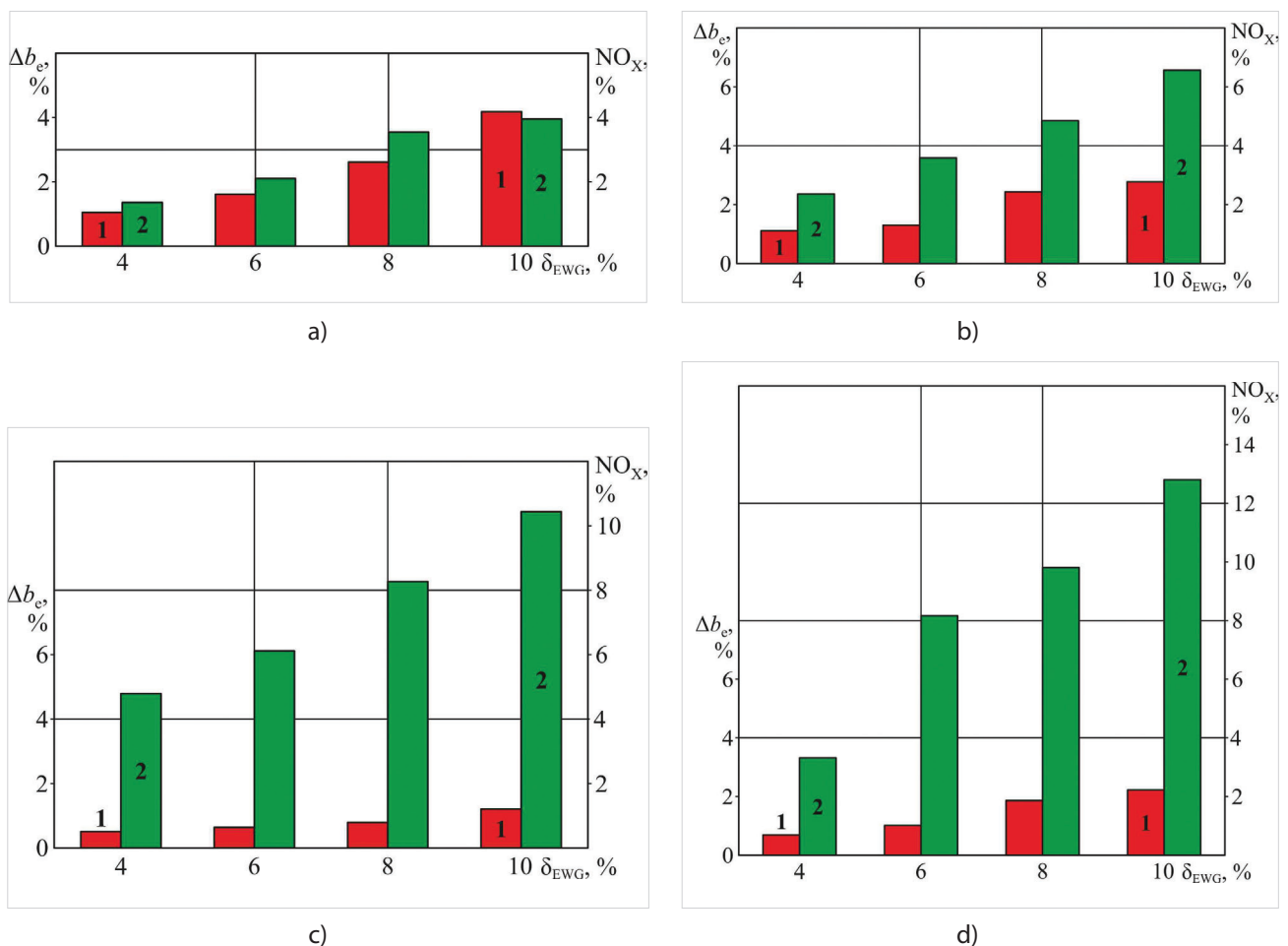

Figure 7 The relevant changes of ecological and economical engine 6L20 Wartsila operation parameters by different degree of exhaust gas by-pass: *a* – 55 %; *b* – 65 %; *c* – 75 %; *d* – 85 %
Slika 7. Relevantne promjene ekoloških i ekonomičnih parametara režima rada motora 6L20 Wartsila na različitom stupnju premosnice ispušnih plinova: a – 55 %; b – 65 %; c – 75 %; d – 85 %

can be possible only in the diapason δ_{EWG}= 0…6 %, because for the majority of values δ_{EWG} the level of exhaust gas temperature t_g increases the recommended limits. For the modes, relevant to the loads diapason $(0.75…0.85)N_{enom}$, in all range of gases by-pass changes δ_{EWG}= 0…10 % occur their temperature growth, but even at level δ_{EWG}= 10 % the value t_g do not exceed maximum accepted limits, that assure the acceptable level of engine thermal factor.

Obtained results are in good agreement with data provided in a number of papers devoted to similar research [49-51].

6. CONCLUSION / *Zaključak*

For ships' medium-speed engine with electronical operation, as a method assured the compliance of Annex VI MARPOL requirements, the exhaust gases by-pass system can be used – namely EWG system, at which a part of combustion products are going to exhaust funnel passing through turbocharger. The electronic engine operations allow to assure this process in smooth mode at range 0…10 % from total exhaust gas volume, going out from the engine cylinder.

The analysis of research results, performed for ships' medium-speed engine 6L20 Wartsila (used at sea and river ships as auxiliary generator engine), allows to conclude the following:

1) the increase of by-pass exhaust gas level at diapason 4….10 % and favor the decreasing of nitrogen oxides emission from 8.48 g/(kW×h) to 7.28 g/(kW×h) and depend on engine load; at this the relevant decreasing of ΔNO_X emission is within the limits 1.32…12.97 %; this proportionally improves the diesel ecological safety capacity works, which is especially important for the auxiliary engines constantly working during ships' location in water area and on the territory of sea ports;

2) the utmost level of nitrogen oxide concentration decreasing in exhaust gas correspond to the maximum level of by-pass exhaust gas and maximum load of engine mode (in performed experiments 10 % and $0.85N_{enom}$ consequently); expressly such modes of auxiliary engines are the most widespread and long termed;

3) the usage of EWG system decreases the exhaust gas emission, going from turbine , that leads to turbocharger capacity, to the decreasing of charge air quantity, going to the engine cylinder, and growth the specific effective fuel consumption; the changing of this parameter is a negative aspect in case if we use the exhaust gas recirculation system;

4) for the operative engine modes close to nominal ones (in performed research $(0.75…0.85)N_{enom}$) by using by-pass exhaust gas system the relevant increase of specific effective fuel consumption is determined as 0.41…2.14 %; at this taking into consideration the maximum (up to 4.74…12.97 %) NO_X emission decrease at current exploitation modes, the improvement of engine ecological operation parameters is a prevalent factor for current charges diapason, that's why the usage of EWG system is effectual and can be recommended as a method to assure the ecological compliance of ships' engine;

5) at load $(0.55…0.65)N_{enom}$ the increase of fuel consumption at use of EWG system can reach 1.06…2.89 %; taking into consideration that in current load option the EWG usage assure the NO_X emission on 1.32…6.27 %, the appliance of by-pass exhaust gas for current diapason is not reasonable;

6) the estimation of EWG system effectivity as one of measure the comply to the Annex VI MARPOL requirements on NO_X emission reducing, should be performed by complex estimation of the following parameters of engine operation: NO_X quantity in exhaust gas, the increasing of specific effective fuel consumption Δb_e, the exhaust gas temperature t_g. As optimal by-pass exhaust gas the values corresponding to maximum NO_X emission decreasing at minimum increase of fuel consumption and simultaneous maintaining of t_g within the limits, not exceeding the thermal factor acceptable level; the additional temperature control of exhaust gas need to be performed during all time of waste gate system usage;

7) for the considered ship engine 6L20 Wartsila (where the research has been performed) the usage of EWG system is reasonable for load increasing the value $0.75N_{enom}$. At this decreasing of nitrogen oxide emission on 8.40…12.47 %, assured the NOx concentration in exhaust gas at level 7.34…8.19 g/(kW×h). The increase of specific effective fuel oil consumption at current modes is within the limits 0.41…2.14 %. For the load $(0.55…0.65)N_{enom}$ the NO_X emission decrease also is relevant (on 1.32…6.27 %), but the specific effective fuel oil consumption is increasing on 2.89…4.13 %, besides this at 8…10 % by-pass of exhaust gas the level of engine thermal factor increase the acceptable limits; in this manner the usage of wastegate system in diapason of diesel loads $(0.55…0.65)N_{enom}$ is non effective from the economic and as well from the exploitation point of view.

The usage of EWG change the stochiometric proportion of fuel-air ration that degradant the combustion process and favor the increasing of specific effective fuel consumption. Notwithstanding the specific increase of fuel consumption, the usage of EWG system could be recommended in specific region of world ocean, when the dominant parameter during ship power plant exploitation became their ecological parameters.

The provided results confirm the usage of EWG system to decrease the NO_X emission level. But the most reasonable usage could be its appliance as additional measure in complex with exhaust gas recirculation system EGR that required additional research.

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