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Kuropyatnyk O.A.[1], Sagin S.V.[2]
National University "Odessa Maritime Academy"

ENSURING EFFICIENCY AND ENVIRONMENTAL OF MARINE DIESEL ENGINES WHICH USING EXHAUST GAS BYPASS SYSTEM

e-mail: kuropyatnyk83@gmail.com[1], saginsergii@gmail.com[2]

Abstract. *The mechanism of formation toxic components in exhaust gases during oxidation and combustion of fuel in marine internal combustion engines is considered. The system of ship engine by-pass exhaust gases 6L20 Wartsila has been observed.* Upon experimental results it has been stated that the by-pass exhaust gases usage favor 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 gases is decreased on 1.32 ... 12.97 %, but the specific effective fuel oil consumption is increasing to 4.13 %.

Анотація. *Розглянуто механізм утворення токсичних компонентів випускних газів під час окислення та згоряння палива в суднових двигунах внутрішнього згоряння. Розглянуто систему перепуску випускних газів суднового дизеля 6L20 Wartsila. Експериментально встановлено, що використання перепуску випускних газів сприяє поліпшенню екологічних показників роботи суднових дизелів – при цьому в діапазоні експлуатаційних навантажень 0,55 ... 0,85% номінальної потужності на 1,32 ... 12,97 % знижується концентрація оксидів азоту в випускних газах, але питома ефективна витрата палива збільшується до 4,13 %.*

Statement of the problem in general. The sea transport is an essential part of the all developed countries all over the world, possessive exit to the global ocean aquatic area. According to "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 (Fig. 1) [1].

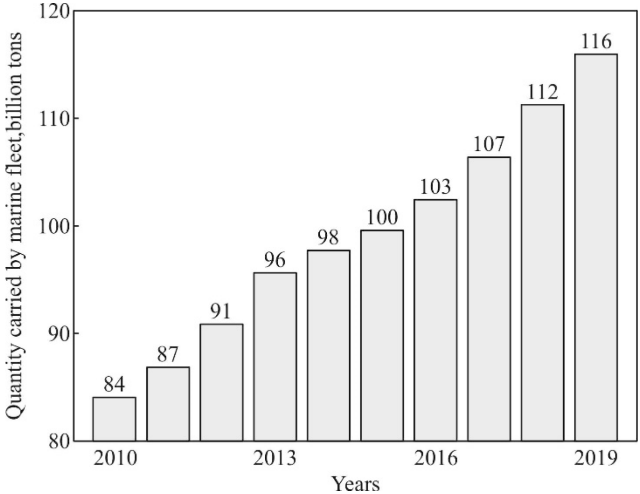

Fig. 1. Quantity carried by marine transport, 2010-2019 years

The diesel, fixed at the sea and river vessels, generate mechanical energy by fuel air ratio, assuring during this operation the permanent heat and mass exchange with the atmosphere [2]. It takes the air and consume the fuel, then exhaust the gases, containing partially the air and the product of fuel oxidation. In this matter of fact the air, incoming to diesel cylinder, performs certain thermodynamic cycle, and as a result is transforming into exhaust gases – a complex gas mixture with numerous components [3].

During combustible fuel elements are oxidized by oxygen in the air (carbon C, hydrogen H and sulphur S) as well a nitrogen N and further burning of fuel air mixture, the next 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, containing into fuel (Fig.2).

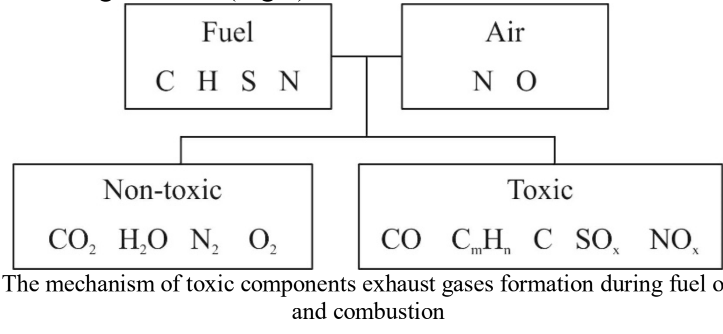

Fig. 2. The mechanism of toxic components exhaust gases formation during fuel oxidation and combustion

The diesel engines ecological characteristics are specified essentially by the containing of nitrogen oxide NO_X into combustion products, that significantly dominate the others harmful components of exhaust gases as per toxic index. In this respect a range of international organizations (namely International Maritime Organization – IMO) incorporate strict requirements, witch implementation assure ecological parameters of ship diesel engine operation [4].

The nitrogen oxide concentration into ships' diesel exhaust gases are determined by the requirements of Annex VI MARPOL depending on ships' building and diesel 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 gases should not be over the limits determined by specific formula (Fig. 3) [5].

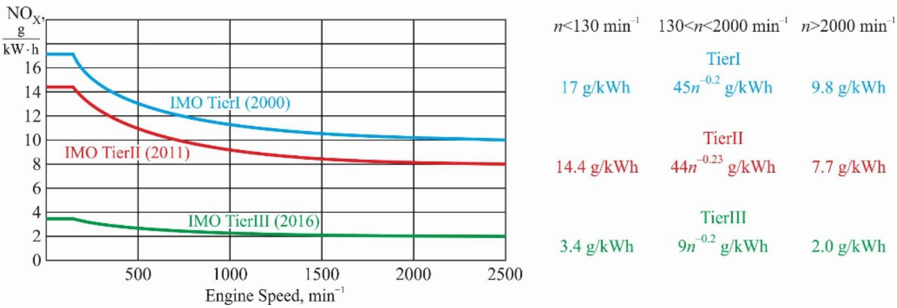

Fig. 3. Requirements of Annex VI MARPOL to the quantity of NO_X into exhaust gases of diesel engines

Analysis of recent researches and publications. At the present time beyond controlled sea and river transport diesel parameters the high profile is given to such ecological parameters as nitrogen oxide concentration in exhaust gases [6]. This parameter is controlled by the international requirements and its supporting into necessary range is mandatory for ship power plants operation, both into world ocean aquatic areas and into territorial waters of seafaring countries [7].

Nitrogen oxide formation during fuel combustion is occurred when temperature into diesel cylinder increase 1500 K and high oxygen concentration condition during atmospheric nitrogen oxidating is controlled at burning process. In this respect all methods, assured decreasing NO_X emission are focused on changes of stoichiometric proportion fuel-air, that leading to deterioration of mixing process, of oxidation and burning [8].

The decreasing NO_X concentration into exhaust gases is achieved by means of:

- by influence to the operation process into engine cylinder [9];
- construction and operation parameters changes of high pressure fuel equipment[10];
- infusion of reagents into exhaust gases during their passing through special reactors [11];
- by usage of exhaust gases system operation assured either their recirculation or (Exhaust gas recirculation – EGR) [12], or their bypassing (Exhaust gas wastegate – EWG) [13].

Exhaust gases recirculation systems (EGR) are used, as a rule, for low speed diesels [14]. For the medium speed diesels the operation of exhaust gases flow could be performed by their bypassing (EWG) [15]. In this case a part of engine exhaust gases immediately fall into exhaust gas manifold besides exhaust gas turbocharger (TC). At this the rotation rate is decreased as well as pressure and quantity of pressurized air into cylinder. The gases bypassing is assured by special valve permitting direct a part of gases not into TC but specifically into to the exhaust pipe [16]. At the present time the EWG systems are installed into medium speed diesels, assured the functions of main and auxiliary engines [17].

Formulation of the problem. The purpose of the research was the determination of optimum exhaust gases by-pass of medium speed engine 6L20 Wartsila. As this, from one side, the best ecological parameters should be assured for provided diesel operating mode (NO_X concentration in exhaust gases) and from the other side – minimal increase (comparing with engine operating mode without by-pass system) of specific effective fuel consumption at simultaneous maintenance of necessary diesel cylinders thermal factor range [18, 19].

Main characteristics of a diesel 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).

Presentation of the main research material. The researches have been performed 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 diesels was N_{enom}=1200 kW at engine speed 1000 min^{-1}. The diesels have had almost the same running hours and have been used on the equal loads [20, 21]. As operation system of exhaust gases on these diesels the system EWG has been installed [22, 23]. The appliance of this system is recommended by Wartsila firstly to limit the pressure of charge air and to prevent surging effects at high load and as additional option – to reduce NO_X. According to project documentation the EWG system assure gases by-pass system in the range 0 … 10 % [24, 25]. The principal scheme of EWG system of diesel 6L20 Wartsila is shown on the Fig.4.

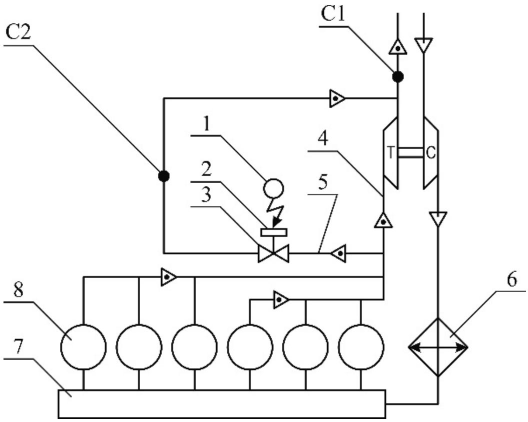

Fig. 4 Principal scheme of medium speed diesel engine 6L20 Wartsile with exhaust gases operating system EWG:

1 – controller of bypass valve position; 2 – pneumatic drive of by-pass valve; 3 – bypass valve (wastegate); 4,5 – main and by-pass gases flow pipeline; 6 – air cooler; 7 – scavenging air receiver;8 – engine cylinders;C1, C2 – control points of gas flow; T,C – gas turbine and air compressor of turbocharger

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

The consumption of exhaust gases into line 4 and 5 are determined in points C1 and C2 by using flowmeter MT100s of "Siemens AG" (Germany). The sensibility of flowmeters MT100 is determine as 0.07 … 0.2 nm^3/s, the operation temperature is up to 454 °C, assuring their functionality at all range of diesel engine operation loads [26, 27]. The flow meters MT100 are in comply to the requirements of the Environmental Protection Agency (EPA) Continuous Emission Monitoring System.

During experiment in point C1 by means of gas detector Testo350XL the concentration of NO_X in exhaust gases has been determined [28].

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 [29, 30].

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

$$\delta_{\text{EWG}} = \frac{G_{\text{wg}}}{G_{\Sigma}} \cdot 100\%, \tag{1}$$

where G_{wg} – the volume of exhaust gases, passing through by pass valve, kg/s (has been measuring in point C2 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 C1 by means flow meter MT100S).

The inaccuracy during measuring 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 % [31].

The engine, where all experimental researches have been performed, has assured the power the constant consumer groups. At this (depending on researched modes) its power was 660, 780, 900, 1020 kW, that was in comply to 55, 65, 75 and 85 % from nominal load – $N_{e\text{work}}=0.55N_{e\text{nom}}$, $N_{e\text{work}}=0.65N_{e\text{nom}}$, $N_{e\text{work}}=0.75N_{e\text{nom}}$, $N_{e\text{work}}=0.85N_{e\text{nom}}$. 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 if the quantity of energy consumers and its power was changing, the required load has been redirected on engine which is not engaged in experiment, thus the engine engaged for the experiment has been used under permanent load. Besides this, during experiment on engine the permanent temperature mode were hold in lubricate and cooling systems. During experiment, engine has been under permanent load within 2.5 … 3 hours and stable position of by-pass valve on each of experiment mode. In consideration to long period of experiment performance the gases consumption checking persistence has been fully neutralized and has no impact to results.

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

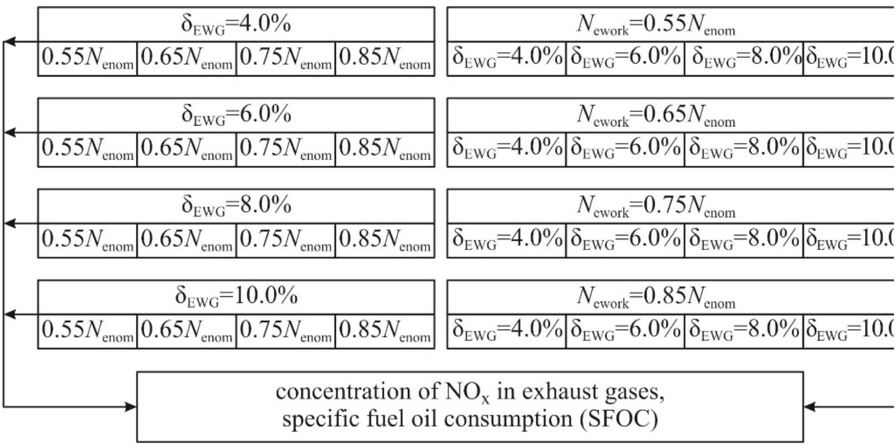

Fig. 5. The succession of experimental researches performance

1) at constant position of by-pass valve the load to engine has been changed and then the NO_X ratio concentration in exhaust gases and SFOC b_e, have been determined, for example at constant ratio δ_{EWG}=10.0 % and different exploitation meaning N_{ework}, 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}=0.85N_{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 mentioned diapason the position of by-pass valve has been changed again and the measurement of NO_X and b_e has repeated. This helped to get more experimental meanings and to increase their informative content. Receipt in that way 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 gases on diesel cylinders have been taken – t_g, measuring of that value has been assured by ships diagnostic system Doctor. The temperature value of exhaust gases are recommended by manufacture of the engine as well by Scientifics used as evaluation criteria of working process and condition of high pressure fuel equipment [32, 33].

The results of researches are generalized in table 1 and provided on Fig. 6.

Table 1 The parameters changes of ships diesel 6L20 Wartsila for different condition of experiment

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 gases 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 economic (Δb_e) and environmental (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 bypassing , 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 bypassing, g/(kW·h) [34].

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 diesel loads and different degree of exhaust gases bypass are shown on the Fig. 7.

Conclusions and prospects for further researches. For marine medium-speed diesels with electronical operation, as a method assured the compliance of Annex VI MARPOL requirements, the exhaust gases bypass system can be used – namely EWG system, at which a part of combustion products are going to exhaust funnel passing by TC. The diesel electronic operating allow to assure this process in smooth mode at range 0 … 10 % from total gases from total gases volume, going out from the engine cylinder.

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

1) the increase of exhaust gases bypassing 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 %;

2) the utmost level of nitrogen oxide concentration decreasing in exhaust gases correspond to maximum level of gases' bypassing and maximum load of engine mode (in performed experiments 10 % and $0.85N_{enom}$ consequently);

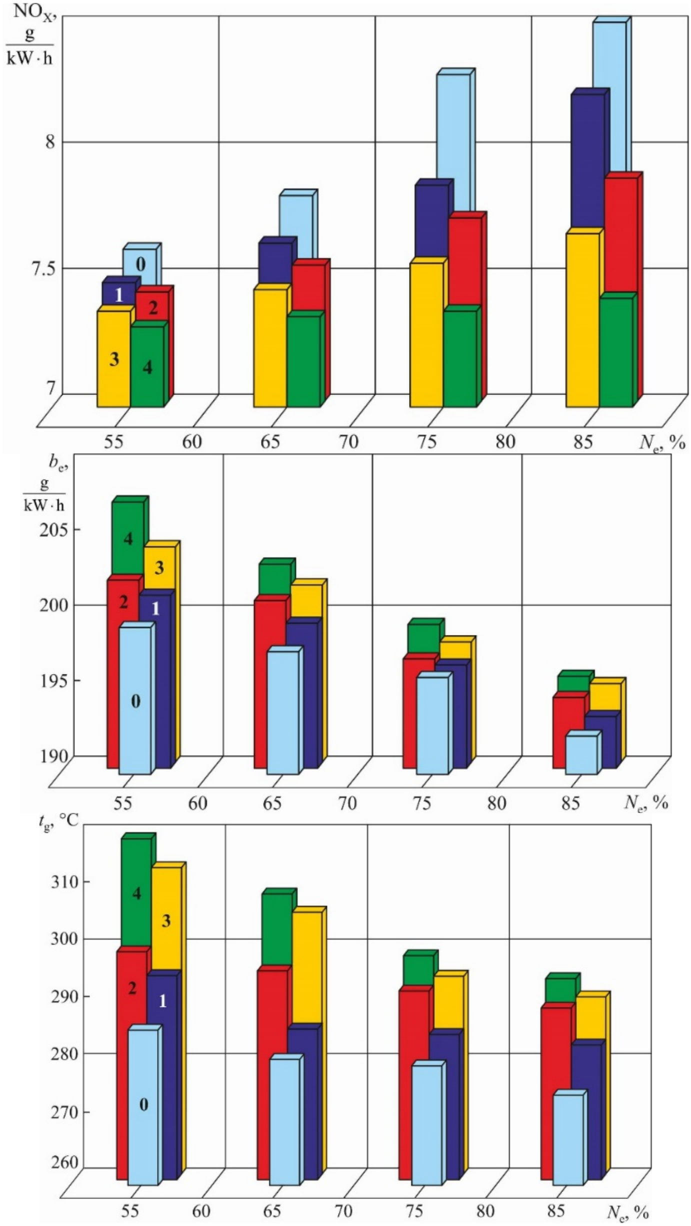

Fig. 6. Emissions NO_X, g/(kW·h), exhaust gas temperature t_g, °C, specific fuel oil consumption b_e, g/(kW·h) for different loads N_e, %, of the 6L20 Wartsila marine diesel engine and different degrees of gas bypass δ_{EWG}:

0 – without bypass; 1 – 4.0 %; 2 – 6.0 %; 3 – 8.0 %, 4 – 10.0 %

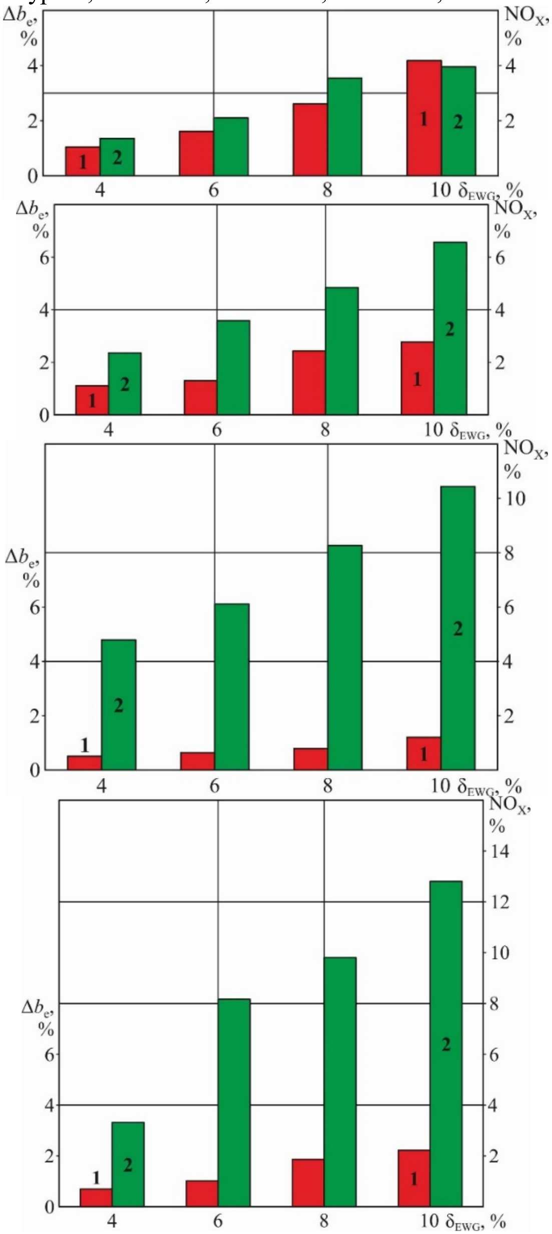

Fig. 7. he relevant changes of ecological and economical engine 6L20 Wartsila operation parameters by different degree of exhaust gases by-pass:

a – 55 %; *b* – 65 %; *c* – 75 %; *d* – 85 %

3) the usage of EWG system decrease the gases emission, going to gas TC, that lead to turbocharging capacity, to the decreasing of air quantity, going to engine cylinder, and growth the specific effective fuel consumption;

4) for the operative diesel modes close to nominal ones (in performed researches $N_{e\text{work}}$=(0.75 … 0.85)$N_{e\text{nom}}$) by using if exhaust gases by-pass 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 diesel 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' diesels.

5) at load $N_{e\text{work}}$=(0.55 … 0.65)$N_{e\text{nom}}$ 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 gases by-pass 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 gases, the increasing of specific effective fuel consumption Δb_e, the exhaust gases temperature t_g. As optimal exhaust gases bypassing 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;

7) for the considered ship diesel 6L20 Wartsila (where the researches have been performed) the usage of EWG system is reasonable for load increasing the value $N_{e\text{work}}$=0.75$N_{e\text{nom}}$. At this decreasing of nitrogen oxide emission on 8.40 … 12.47 %, assured the NO_X concentration in exhaust gases at level 7.34 … 8.19 g/(kW·h). The increase of specific effective fuel oil consumption at current modes are within the limits 0.41 … 2.14 %. For the load $N_{e\text{work}}$=(0.55 … 0.65)$N_{e\text{nom}}$ 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 % bypassing of exhaust gases the level of diesel thermal factor increase the acceptable limits.

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 researches.

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