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THE USE OF BYPASS EXHAUST GASES TO ENSURE THE ENVIRONMENTAL PERFORMANCE OF MARINE DIESEL ENGINES

The possibility of using bypass exhaust gases to ensure the environmental parameters of the ship diesel engines operation has been considered. It is indicated that the methods currently being developed to reduce the level of nitrogen oxides emissions (as one of the toxic components that is integral part of the exhaust gases of marine diesel engines) are associated with a change in the design of diesel engines and are possible only at the design stage.

At the same time, for diesel engines in operation, the design change of which is either not possible or requires significant investments, the task of reducing the concentration of nitrogen oxides in exhaust gases can be solved by optimizing the modes of their technical operation. The solution of this issue is demonstrated on the example of the exhaust gas system of the ship's 6L20 medium-speed diesel engine manufactured by Wartsila by using bypass exhaust gas in addition to the turbo-compressor directly to the exhaust line.

The degree of bypass exhaust gas during experimental studies varied in the range of 0...9.6 %, the change in the load on the diesel was 55...83 % of the nominal power. The nitrogen oxides concentration determination in the exhaust gases and the specific oil fuel consumption were determined for two options: with a constant position of the bypass valve and different loads on the diesel; with a constant load on the diesel and different positions of the bypass valve.

As a result of research, it has been established that increasing of the degree of exhaust bypass gases in the range of 0...9.6 % contributes to reducing the emission of nitrogen oxides from 8.72 g/(kWh) to 6.53 g/(kWh) and depends on the load on diesel, while the relative reduction of emissions of nitrogen oxides is within 1.15...13.85 %; the highest level of reduction of nitrogen oxides concentration in exhaust gases corresponds to the maximum degree of bypass gases and the maximum load on the diesel; the use of the exhaust bypass system changes the stoichiometric fuel-air ratio, which contributes to an increase in the specific effective fuel consumption (in the experiments performed by 0.26...2.52 % depending on the degree of bypass gases and the load on the diesel).

Despite the increase in specific fuel consumption, the use of the gas bypass system is recommended in special areas of the world's oceans, when the environmental parameters become the prevailing indicator in the operation of ship power plants.

Ключевые слова: судовой дизель, эмиссия оксидов азота, газовыпускная система, турбокомпрессор, система перепуска выпускных газов, удельный эффективный расход топлива

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Keywords: marine diesel, emission of nitrogen oxides, gas exhaust system, turbocharger, exhaust gas bypass system, specific fuel oil consumption

Statement of the problem in general. At present, when operating ship propulsion systems, marine engineers have to solve the tasks not only of ensuring the required speed of the vessel, the maximum possible power of the main propulsion machinery (both main and auxiliary) and minimum specific and daily fuel consumption but also supporting ecological parameters.

Cycling thermodynamic processes ensuring the operation cycle of the ship's internal combustion engines (diesel) are impossible without the release into the atmosphere of exhaust gases. Their composition determines the environmental parameters of sea and river vessels operation, which are governed by the requirements of international conventions and resolutions, particularly the MARPOL convention [1].

Exhaust gases (EG) of diesel includes the following groups:

• NO_X nitrogen oxides, the formation of which is related with the liquid fuel combustion and the presence of nitrogen in it; their content is regulated in accordance with Annex VI of the Convention MARPOL 73/78;

• sulfur oxides SO_X, their formation completely depends on the sulfur content in the fuel; the percentage of sulfur in fuel is regulated in special areas in accordance with Annex VI of MARPOL 73/78 Convention;

• carbon dioxide CO_2, its formation is directly proportional to the amount of burned fuel; currently (according to the Kyoto Protocol) is considered as a global problem due to the fact that carbon dioxide is a “greenhouse gas”, however, the CO_2 content in the EG is not regulated;

• smoke, unburned HC hydrocarbons, carbon monoxide CO, particulate matter, the formation of which is associated with the combustion and gas exchange processes in the engine currently are not regulated by the conventions requirements, in the same time individual types of emissions can be controlled individually at some point.

Providing the required concentration of NO_X in the exhaust gases is an important technical task, which solution allowing fulfill environmental requirements allowing for the operation and in the design of sea vessels and their main propulsion machinery [2].

Analysis of recent researches and publications. The decrease in the concentration of nitrogen oxides in the EG of diesel to the required values and the maintenance of this parameter within the required limits is possible in two principal directions:

— the use of technological solutions aimed at changing the operational properties of fuel, the design of fuel equipment, fuel supply characteristics, the nature of the operation processing performance and preceding the moment of formation of NO_X in the cylinder of a diesel engine;
— direct influence on EG (their cleaning, chemical treatment, recycling) during the time when they are in the exhaust gas system (EGS) of a diesel engine.

The reduction of NO_X emissions by chemical treatment of fuel was investigated in work [3], while its main task was to determine the optimal concentration of reagents added to the fuel in order to intensify the process of its combustion. Ensuring the environmental parameters of the diesel because of the construction modernization and assembly of the fuel system was considered in work [4], but the implementation of the obtained results requires additional equipment, which entails increased energy consumption. The modeling of the formation of nitrogen oxides was carried out in [5], and the work [6] is devoted to the search for the optimal degree of exhaust gas recirculation. At the same time, these studies did not consider such a way to reduce NO_X emissions as bypassing them in addition to a turbocharger (T/C) directly to the exhaust line.

Formulation of the problem. Currently developed methods of reducing NO_X emissions are associated with changes in diesel engine design and are possible only at the design stage. Moreover, for diesel engines in operation, the design change of which is either not possible or requires significant capital investment, the task of reducing the NO_X concentration in exhaust gases can be solved by optimizing the modes of their technical operation. Taking this into account, the task of the study was to determine the optimal (by the criteria of energy and economic efficiency) level of exhaust gas bypass in the EGS exhaust line – and after T/C – exhaust line.

Presentation of the main research material. According to their origin, three mechanisms of NO_X formation are distinguished:

1) thermal mechanism, or Zeldovich high-temperature mechanism (thermal NO_X);

2) fast mechanism, also called a "chemical" (fast NO_X);

3) fuel mechanism related to the formation of NO_X from nitrogen-containing components of the fuel (fuel NO_X) [7].

The formation of thermal, fast and fuel compounds NO_X depends on the type of fuel. The total content of NO_X generated by heat, fast and fuel mechanism is 100%, but their fraction is shifted for fuels of different state of aggregation and fractional composition. The nomogram correlation between NO_X of different types of fuel (under standard combustion conditions) is shown in Fig. 1.

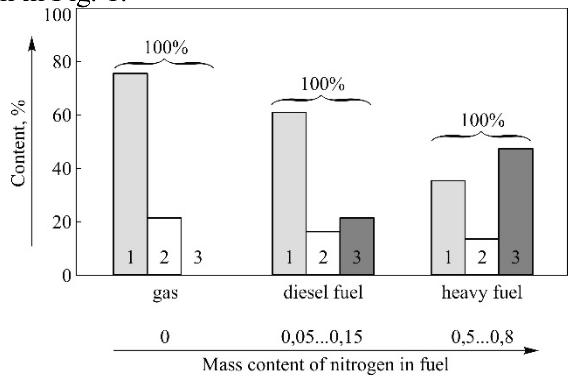


Fig. 1. Nomogram of NO_X type allocation for different fuel type NO_X

1 – thermal; 2 – fast; 3 – fuel

Thermal oxides of nitrogen, which constitute a large part of all types of NO_X, are formed at high temperature (T>1500 K) and at the condition of high oxygen concentration during oxidation of atmospheric nitrogen in the combustion process. It is believed that increasing the maximum temperature in the combustion zone above 1850 K leads to unacceptably high emissions of NO_X.

Rapid nitrogen oxides are formed when molecular nitrogen present in the air is combined with hydrocarbon fragments formed during the decomposition of fuel in the first stages of combustion.

Fuel oxides of nitrogen are formed during the oxidation of nitrogen-containing substances present in the fuel in the zone of the flame. The concentration of fuel oxides can reach significant sizes if the content of nitrogen-containing substances in the fuel exceeds 0.1 % by weight.

Thus, the formation of NO_X occurs during the combustion of any type of fuel, and it is advisable to perform a decrease in their concentration only for the thermal mechanism of their origin, while the main conditions for limiting the amount of nitrogen oxides are to ensure the combustion process with a temperature not exceeding 1500 K. One of the method allowing to assure these conditions, is the bypass of gases, in which a part of the exhaust gases are sent directly to the exhaust line, without using their energy in the T/C.

The exhaust bypass system (Exhaust gas wastegate – EGW) is recommended by some diesel engine builders (for example, Wartsila-Sulzer) to limit the charge air pressure under high loads. At the same time, the EGW system can be used to reduce NO_X emissions. To confirm this, Wartsila's 6L20 medium-speed diesel engine, which performs the functions of a diesel generator as part of the ship power station and equipped by the EGW system, carried out a set of studies aimed at determining the effect of gas bypass in the EGS on its environmental and economic performance. The main characteristics of the diesel 6L20:

cylinders layout – in line;
number of cylinders – 6;
cylinder diameter – 0.2 m;
piston stroke – 0.26 m;
air pressure after turbocharger – 0.38 MPa;
maximum combustion pressure – 16.3 MPa;
rate of ration – 1000 rpm;
nominal output N_{enom}=1200 kW;
specific fuel oil consumption – 0.193 kg/(kW·h).

A principle diagram of the Wartsila EWG ship diesel 6L20 system is shown in Fig. 2. According to the instruction manual of the diesel engine, the EWG system provides gas bypass in the range of 0...10 %.

EG from diesel engine cylinders are delivered to main line 6. They are bypassed through bypass line 5 by valve 4, the repositioning of which is controlled by controller 7 and carried out by pneumatic actuator 8.

The main gas flow after T/C is returned through exhaust line 3. Using mobile flow meter MT100S (allowing to measure parameters in gas streams with temperatures up to 454°C) it is possible to determine the flow rate of gases at various points of the EWG, in particular the total amount of exhaust gases G_Σ and quantities gas entering the bypass G_{wg} in addition to T/C. This makes it possible to calculate the degree of bypass gases

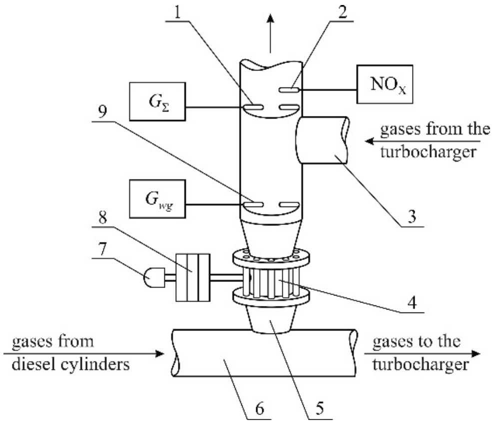


Fig. 2. Principle diagram of EGS of ship's medium-speed diesel 6L20 Wartsila with EWG exhaust bypass system:
1, 9 – control points of main and bypass gas consumption; 2 – control point of NO_X concentration; 3, 6 – main gases' flow exhaust lines; 4 – wastegate; 5 – bypass gases flow exhaust lines; 7 – position controller of bypass valve; 8 – pneumatic air motor of bypass valve

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

The concentration of NO_X in the exhaust gases was determined at point 2 using a Testo350XL gas analyzer. During the experiment, using ship's measuring instruments (a flow meter installed on the main line supplying fuel to high-pressure fuel pumps and a timer) the specific fuel oil consumption (SFOC) has been determined.

The accuracy in measuring the flow rate of gases determined by the flow meter MT100S did not exceed ±0.5 %, the accuracy in measuring NO_X emission in exhaust gases with the Testo350XL gas analyzer was ±3.5 %, the accuracy in determining the SFOC did not exceed ±2.5 %.

The diesel engine on which the experimental studies were performed, provided the power for the constant groups of consumers. At the same time (depending on the studied modes), its power was 660 kW, 805 kW, 890 kW, 1010 kW, which corresponded to $0.55N_{enom}$, $0.67N_{enom}$, $0.74N_{enom}$, $0.83N_{enom}$. The accuracy in the change in power did not exceed ±1.5 %.

The ship power station consisted of three diesel engines of the same type, therefore, in case of a change in the number of energy consumers and their power, the required load was redistributed to diesel engines not involved in the experiment, and the diesel engine on which the studies were conducted was operated at a constant load. In addition, during the experiment on a diesel engine, constant temperature conditions were maintained in the lubrication and cooling systems.

During the experiment, the diesel engine operated for a constant load and a constant position of the bypass valve on each of the experimental modes for 2.5...3 hours. To determine the degree of opening of the bypass valve (position 4 in Fig. 2), initially at point 1, the total gas flow rate G_Σ, coming out of the diesel cylinders and passing through the main gas flow 3 (with valve 4 completely closed), was determined. After that, with the changed position of the bypass valve 4 at point 9, the gas flow rate G_{wg} was determined through the bypass main 5 and the degree of gas bypass was calculated using formula (1). Further measurements were carried out according to two schemes (Fig. 3)

1) at a constant position of the bypass valve, the load on the diesel has been changed, and then NO_X values in exhaust gases were determined and SFOC, for example, at a constant value of δ_{EWG}=9.6 % and different operating values of N_e, corresponding to 55, 67, 74, 83 % from rated power; then the position of the bypass valve has been changed (δ_{EWG}=8.1, 6.0, 3.8 %) and for each value of EWG in the specified range the load on the diesel changed and the measurement of NO_X and SFOC has been repeated;

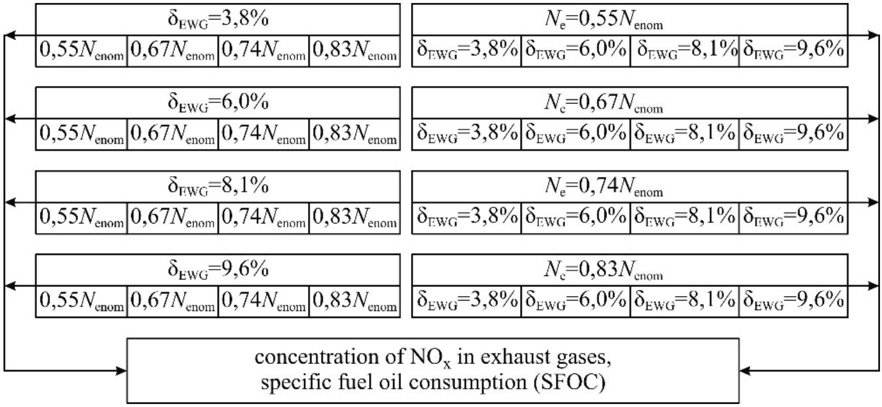


Fig. 3. Experimental researches sequence order

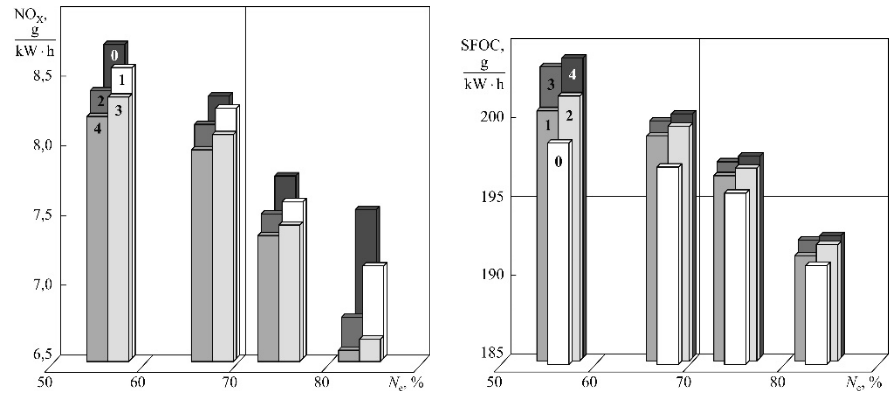
2) with a constant load on the diesel, the position of the bypass valve was changed, and then the NO_X emission values and the diesel engine economy indicator – SFOC, for example, were determined at a constant value N_e=0.83N_{enom} and different values of EWG (δ_{EWG}=9.6, 8,1, 6.0, 3.8 %); further, the load on the diesel engine was changed (0.55N_{enom}, 0.67N_{enom}, 0.74N_{enom}) and for each value in the specified range, the position of the relief valve was changed again and the measurement of NO_X and SFOC has been repeated.

It is allowed to increase the volume of receipt experimental data and to enlarge their information content.

The experimental values thus obtained showed good convergence, which confirmed the correctness of the measurements. The research results are summarized in Table. 1 and presented in Fig. 4.

Table. 1 Experiment results

δ_{EWG}, %	Emission NO_X, g/(kW·h) at engine load				SFOC, g/(kW·h) at engine load			
	55 %	67 %	74 %	83 %	55 %	67 %	74 %	83 %
0	8,72	8,37	7,81	7,58	198,6	196,9	195,5	190,6
3,8	8,58	8,32	7,62	7,18	200,7	198,9	196,3	191,2
6,0	8,42	8,18	7,52	6,83	201,6	199,6	196,8	192,0
8,1	8,38	8,12	7,47	6,63	203,5	199,8	197,3	192,2
9,6	8,24	8,01	7,38	6,53	203,8	200,6	197,5	192,5



a) *b*)

Fig. 4. Contingency of Emission NO_X (*a*) and SFOC (*b*) marine diesel 6L20 Wartsila from load N_e for different opening grade of gas bypass valve EWG: 0 – δ_{EWG}=0; 1 – δ_{EWG}=9,6 %; 2 – δ_{EWG}=8,1 %; 3 – δ_{EWG}=6,0 %; 4 – δ_{EWG}=3,8 %

Conclusions and prospects for further researches. The exhaust gases bypass system (Exhaust gas wastegate – EGW) is recommended and used by some diesel firms (for example, Wartsila) to reduce the charge air pressure at elevated loads of marine diesel engines. The EWG system provides the bypass of exhaust gases in the cylinder in the range of 0...10 % of their total volume directly to the exhaust pipe without using their energy in the T/C. At the same time, it is possible to use the EWG system to ensure the environmental parameters of the internal combustion engine operation (in particular, to reduce NO_X emissions with exhaust gases) in the entire area of diesel operating modes.

For the ship's 6L20 medium-speed diesel engine manufactured by Wartsila operating in the load range N_{ework}=(0,55…0,83)N_{enom} using the EWG system with exhaust gas bypass degree δ_{EWG}=3,8...9.6 % were obtained the following results:

1) an increase in the degree of exhaust bypass in the range of 0...9.6 % account for reducing the emission of nitrogen oxides from 8.72 g/(kW·h) to 6.53 g/(kW·h) and depends on the load on the diesel; while the relative reduction of NO_X emissions is within 1.15...13.85 %;

2) the highest level of reduction of NO_X concentration in exhaust gases corresponds to the maximum degree of gas bypass and the maximum load

on the diesel engine (in the experiments performed, 9.6 % and 0.83N_{enom} respectively);

3) the use of the EWG system changes the stoichiometric fuel-air ratio, which lead an increase of the SFOC;

4) for diesel operation modes approximate to the nominal (in the conducted studies, 74...83 % of the nominal diesel power) using exhaust bypass gases, the increase in the SFOC is 0.8...1.9 g/(kW·h) or in relative values of 0,26...1.05 %; at the same time, taking into account the maximum reduction of NO_X emissions in these operating modes, namely the improvement of the environmental performance of a diesel engine is a prevailing factor for this load range, therefore the use of the EWG system in this case is reasonable and can be recommended as a way to assure environmental requirements for marine diesel engines;

5) on loads (0.55...0.67)N_{enom} increasing of fuel consumption when using the EWG system can reach 1.83...2.52 %; considering that in this variation of loads, the use of EWG provides a reduction in NO_X emissions by 1.15...5.5 %, the use of a bypass gas system for this range is not advisable.

When choosing the most optimal mode of operation of the EWG system, i.e. the amount of gases bypassed to bypass the T/C, it is necessary to carry out a complete assessment of the environmental and economic performance of a diesel engine. Despite the increasing in specific fuel consumption, the use of the EWG system can be recommended in special areas of the world's oceans, when their environmental parameters become the prevailing indicator in the operation of ship power plants.

REFERENCES

1. Голиков В. А. Новые тенденции в экологичности судовых энергетических установок / В. А. Голиков // Судовые энергетические установки : науч.-техн. сб. – 2011. – № 27. – С. 4-9.

2. Голиков В. В. Особенности проектирования многоцелевого судна двойного назначения ледового класса / В. В. Голиков, О. Н. Мазур, О. А. Онищенко // Вісник Нац. техн. ун-ту «ХПІ» : зб. наук. пр. Сер. : Нові рішення в сучасних технологіях. – Харків : НТУ «ХПІ», 2016. – № 42 (1214). – С. 29-37.

3. Zablotsky Yu. V. Enhancing Fuel Efficiency and Environmental Specifications of a Marine Diesel When using Fuel Additives / Zablotsky Yu. V., Sagin S. V. // Indian Journal of Science and Technology. –

2016. – Vol. 9. – Iss. 46. – P. 353-362. DOI: 10.17485/ijst/2016/v9i46/107516.

4. Sagin S. V. Cavitation Treatment of High-Viscosity Marine Fuels for Medium-Speed Diesel Engines / S. V. Sagin, V. G. Solodovnikov // Modern Applied Science. – 2015. – Vol. 9. – № 5. – P. 269-278. DOI:10.5539/mas. v9n5p269.

5. Половинка Э. М. Моделирование процесса образования оксидов азота в цилиндре дизеля / Э. М. Половинка // Судовые энергетические установки : науч.-техн. сб. – 2017. – № 37. – Одесса : НУ «ОМА». – С. 132-140.

6. Sagin S. V. The Use of Exhaust Gas Recirculation for Ensuring the Environmental Performance of Marine Diesel Engines / S. V. Sagin; O. A. Kuropyatnyk // OUR SEA : International Journal of Maritime Science & Technology. – June 2018. – Vol. 65. – № 2. – P. 78-86. doi.org/10.17818/NM/2018/2.3.

7. Куропятник А. А. Снижение концентрации оксидов азота в выпускных газах судовых дизелей / А. А. Куропятник // Universum: Технические науки. – 2018. – Вып. 3(48). – С. 63-66.