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INFLUENCE OF THE MARINE 4-STROKE DIESEL ENGINE MALFUNCTIONS ON THE NITRIC OXIDES EMISSION

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Abstract

The article presents the results of the laboratory study on nitric oxides (NO_x) emission level from marine four-stroke diesel engine. The object of the study was laboratory piston engine, operating at constant speed. Measured engine parameters were necessary to determine the NO_x emission in accordance of the requirements of the Annex VI to MARPOL 73/78 Convention. The study consisted of tests during the engine operation without malfunctions and engine operation with simulated malfunctions. Malfunctions of the charge gas exchange in the form of throttling of the air intake duct and the throttling of the exhaust gas duct were taken into account in the simulations. Measurements during the engine operation with simulated malfunctions of the fuel pump on one of the cylinders were also carried out. Mentioned malfunctions were delay of the fuel injection by 5° of the crankshaft angle position and the leakage of the fuel pump of the second engine cylinder. The simulated malfunctions decrease the total weighted NO_x emission in all considered the engine loads. All simulated malfunctions resulted in an increase of the NO_x emissions during engine operation at low the engine loads and a decrease of the mentioned emission at maximum the engine loads operation. The calculations of the weighted specific fuel consumption present a little change in engine efficiency which are within the range of measuring error of the used method.

Keywords: *emission, malfunction, piston engine, marine engine, nitric oxides*

1. Introduction

In 2005 Annex VI to the Convention for the Prevention of Air Pollution from Ships MARPOL [1, 2] was ratified. According to the mentioned regulation all marine engines with nominal power above 130 kW and installed on ships after 2000 year should meet the standards for nitric oxides emission (NO_x). Annex VI to the MARPOL Convention is the only international law in force concerning the limitation of emissions of toxic compounds into the atmosphere.

Standard construction of the engine room has installed on couple of piston engines with nominal power above 130 kW. The one or more of diesel engines are used for propulsion. Typically there are low-speed, two-stroke diesel engines running with fixed pitch propeller [3], or medium speed, four-stroke engines, operating at a constant speed with variable pitch propeller. Moreover, there are 2 or more power generators and one emergency power generator on the ship engine room. Engine generators typically consist medium speed, four-stroke diesel engines operating at a constant speed. Other design solutions are encountered, e.g. based on a gas or steam turbine or electric motor with power generators. It should be noted that there are rarely used technical solutions due to lower efficiency of such solutions. Marine piston engines typically are the turbocharged diesel engines with direct fuel injection into the cylinder, fuelled with diesel oil or heavy fuels. The fuel system of this type of engine is based on a Bosch type, mechanically controlled by camshaft injection pumps and multi-hole injectors [4]. The first 4-stroke diesel engine with Common Rail system has been installed on the ship in 2001. It should also be remembered that in 2011 over 50% of the world fleet was older than 15 years (more than 42.5 thousand vessels above 100 gross tonnage) [5].

The marine engines operation causes changes in their technical structural components. Results of this are changes in the toxic compounds emissions. It should be remembered that average main propulsion engine (nominal power equal 10 MW) emits into the atmosphere more than 3 tons of NO_x per day, even if it meet the standards of the MARPOL Convention. Change of the technical state of the engine, caused by deterioration of its components, cause changes in the fuel injection process [6] and changes in the process of the fuel evaporation and the fuel combustion. Result of this is the increase of fuel consumption and the increase of both carbon monoxide (CO) and carbon dioxide (CO_2) emissions. The increase of fuel consumption (carbon content in fuel equals 0.35 in a molar [4]) by 1% (1.9 g/kWh) causes the increase of CO_2 emission from mentioned 10MW power output engine by 7 tons per 24 hours. It should be noted, that presented change in the fuel consumption is often unnoticeable during ship operation. The reason for this is the methodology of fuel consumption measuring on board, which consists of periodically checking the amount of fuel in ship tanks. Relatively small changes in the efficiency of marine engines are not being detected by the ship automation systems also. The effect of this approach is the situation where marine engines are being operated for a long period of time with reduced performance, resulting in a significant increase of nitric oxides emission. For this reason, it is necessary to investigate the effect of ship engine malfunction on emissions of toxic compounds.

In 2004, Lindgren et al. [7] present characteristics of toxic compound emission from two-stroke engine, with nominal power similar to the marine engines, operated with transient conditions. Sarvi et al. [8–10] present an extensive work about the emission characteristics of large-size, medium speed diesel engine with technical parameters similar to marine engines. Petzold et al. [11] present composition of the exhaust gas from the ship engine, operating in the transient load conditions. Cooper [12] and Agrawal et al. [13, 14] represent the emission characteristics from the selected marine vessels.

2. Laboratory test

The object of study is 3-cylinder, four-stroke diesel engine with the direct fuel injection, installed in Internal Combustion Engines Laboratory at the Gdynia Maritime University. The engine is turbocharged by VTR 160 Brown-Boveri turbine with the air intercooler and it is fueled by diesel oil. The engine is loaded by the electric generator, electrically connected to the water resistance. The test stand can measure all the parameters necessary to determine the NO_x emission from the engine in accordance with ISO 8178 [15] standard regulation.

The composition of exhaust gas was recorded by electrochemical gas analyzer with infrared carbon dioxide sensor. The diagram of a measuring test stand is presented in Fig. 1 and the parameters of the engine work in Tab. 1.

Tab. 1. Parameters of the Al25/30 engine [16]

Parameter	Value	Unit
Max. electric power	250	kW
Rotational speed	750	rpm
Cylinder number	3	–
Cylinder diameter	250	mm
Stroke	300	mm
Compression ratio	12.7	–

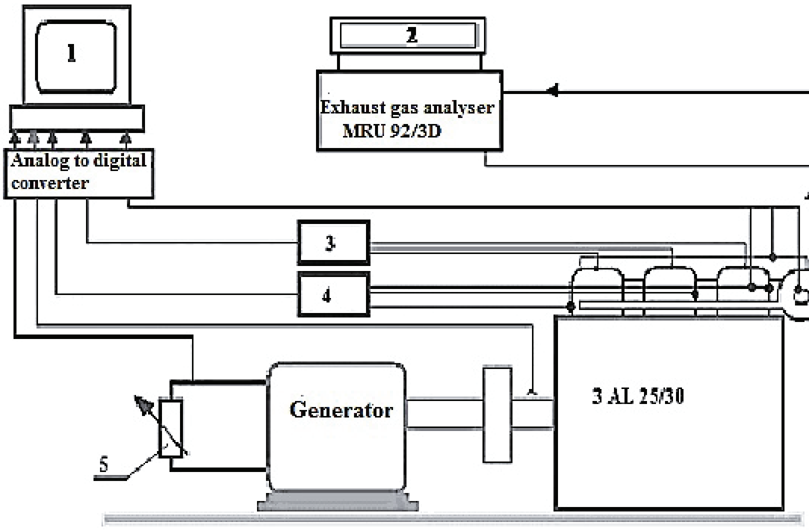

Fig. 1. The laboratory stand diagram: 1 – computer-recorder, 2 – exhaust gas analyser, 3 – combustion pressure indicator, 4 – injection pressure indicator, 5 – water resistance , 6 – exhaust duct

The purpose of the study was to measure the impact of simulated malfunctions of the engine on the NO_x emission. Laboratory studies were carried out according to E2 test cycle [2, 15]. Mentioned cycle is intended for main propulsion engines, operating with pitch propeller. Load and engine speed, the order of the measurements and weight factors for this cycle are presented in Tab. 2.

Tab. 2. E2 cycle engine adapted to the laboratory engine according to [1, 15]

Number of measurement	1	2	3	4
Electric power [kW]	240	180	120	60
Rotational speed [rpm]	750	750	750	750
Weight factor W_i	0.2	0.5	0.15	0.15

Laboratory study consisted of 5 observations:

- the engine assumed as operated without malfunctions,
- the throttling the exhaust gas duct by rotation barrier about $\varphi = 56°$ (see Fig. 2),
- the delay of the fuel injection by 5° of crankshaft angle in the second engine cylinder,
- the leakage of the fuel pump on the second engine cylinder,
- the throttling of the air intake duct by reducing the cross section area by 60%.

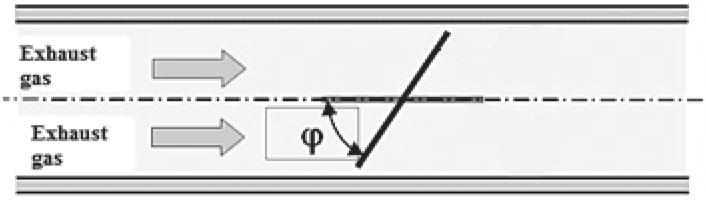

Fig. 2. The scheme of the exhaust gas duct throttling

Rotational barrier, presented in Fig. 2 throttle the exhaust gas duct. Chosen angular position of the barrier is 56 degrees in relation to exhaust gas duct axis.

3. Results and discussion

Figure 3 presents the results of the calculation of the NO_x emission for all considered observations and all points of the engine operation.

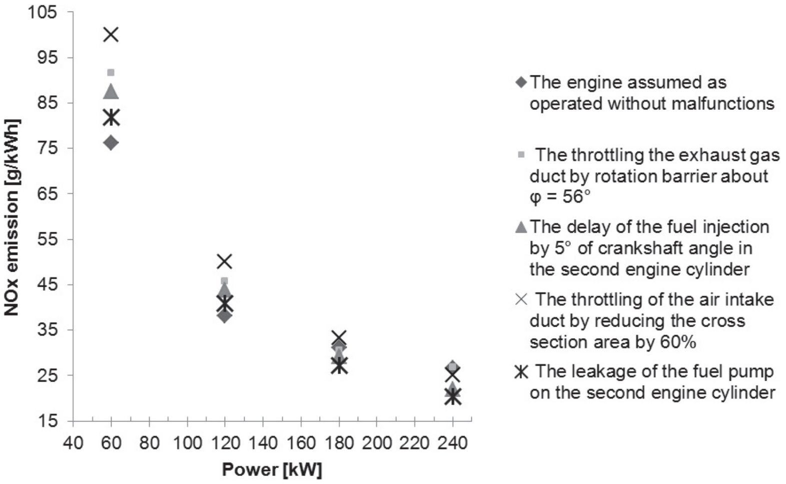

Fig. 3. The NO_x emission for all considered loads and observations

According to the presented results, the NO_x emission decreases with increasing of the engine load for all observations. It means, that the engine operated at maximum loads emits the smallest the NO_x gas stream in comparison to generated energy. All simulated malfunctions cause an increase of the NO_x emission during the operation of the engine at 60 kW and 120 kW loads. The highest the NO_x emission increase was observed for the throttling of the air intake duct by reducing the cross section area by 60%. The engine operation with this simulated malfunction caused an increase the NO_x emission by 31% during the engine operation at 60 kW load. Only the engine operation at 240 kW load, the NO_x emission decreases about 4% in relation to the engine operation without malfunctions. The leakage of the fuel pump on the second engine cylinder resulted relatively minimal changes of the NO_x emission. The engine operation with such simulated malfunction at the load up to 60 kW results the 8% increase of the NO_x emission. The NO_x increase during the engine operation at 120 kW load was also noticed. A further the load increasing resulted of the NO_x emission reduction up to 24% in comparison to the engine assumed as operated without malfunctions.

Figure 4 presents the calculated values of the weighted total NO_x emissions in [g/kWh] in accordance to the following formula:

$$E_{NOx} = \frac{\sum_{i=n}^{i=1} M_i \cdot W_i}{\sum_{i=n}^{i=1} P_i \cdot W_i}, \tag{1}$$

where:

E_{NOx} – the total weighted NO_x emission in [g/kWh],
M_i – the NO_x emission for the *i*-th phase of the measurement cycle in [g/h],
W_i – the weight factor for the *i*-th phase of the measurement cycle,
P_i – the engine power for the *i*-th phase of the measurement cycle in [kW].

Figure 4 presents the percentage change of the total weighted NO_x emission compared to the NO_x emission from the engine assumed as operated without malfunctions. According to the presented results, all simulated malfunctions reduced the amount of the weighted NO_x emissions compared to the emission from the engine assumed as operated without malfunctions. The largest decrease of the NO_x emission is observed for malfunctions of the fuel pump of the second cylinder. The delay of the fuel injection by 5° of crankshaft angle position caused the decrease of the NO_x emission by 18%. The leakage in the fuel pump of the second engine cylinder caused the greatest decrease of the total weighted NO_x emission compared to the emission from the engine assumed as operated without malfunctions. The simulated malfunctions of the engine gas exchange system reduced the total weighted NO_x emission by 2 and 7%.

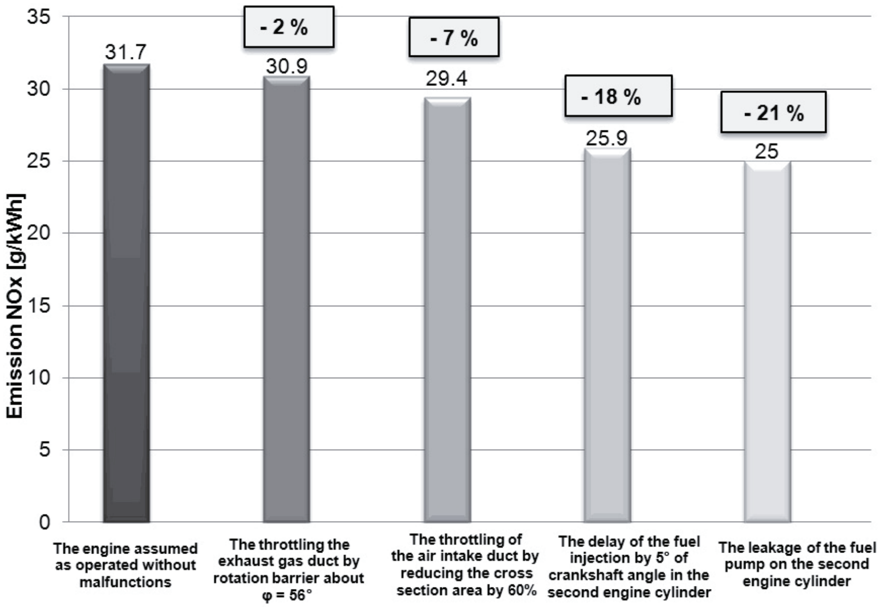

Fig. 4. The values of the total weighted NO_x emissions

Simulated malfunctions of the laboratory engine causes changes of the organization of the combustion process in the cylinders. This results in changes in the fuel consumption. In order to check how the simulated malfunctions of the engine influence on the fuel consumption the analysis of obtained results were made. Tab. 3 presents the values of the specific fuel consumption obtained during the measurements. The analysis of the results from Tab. 3 confirms assumption that the tested engine has the highest efficiency at the load equal 240 kW. It means that this engine is designed to operate at load close to 240 kW. Applied E2 measurement cycle is designed for main propulsion engines, operated at a constant rotational speed. According to the cycle's assumptions engine should work with a load equal to 75% of maximum load for 50% of the operation time (Tab. 2). According to the results presented in Tab. 3 all simulated malfunctions caused the improvement of efficiency in relation to the engine assumed as operated without malfunctions at 60 kW load. The simulation of leakage in the fuel pump's of cylinder number 2 and the throttling both, the air intake and the exhaust gas duct reduces specific fuel consumption by 12-15%. The increase of load results in a significant decrease of the engine efficiency. For 120 kW and 180 kW loads, the specific fuel consumption during engine operation with simulated malfunctions is almost unchangeable compared to the engine assumed as operated without malfunctions. The observed differences are about 1–2%. Applied method of the fuel consumption measurement consisted in measure of the combustion time of a fuel volume. Size of the measuring volume and combustion time allowed for the estimation accuracy of about 1.6%. This means that the observed differences are within the measuring error. The engine operating at 240 kW load with a simulated leakage in the fuel pump of the second cylinder and throttling of the exhaust gas duct as well caused an increase of the fuel consumption by 3%. It should be noted that the injection delay for the second cylinder did not result in significant changes of the specific fuel consumption for all mentioned engine loads.

Weighted mean of the specific fuel consumption for all considered engine loads was also calculated, according to E2 measurement cycle. The results of calculations are presented in the last row of Tab. 3. Acquired differences in fuel consumption are within the limits of measuring error. For this reason it can be concluded that the simulated malfunctions did not cause significant changes in the mean specific fuel consumption.

According to the acquired results, the injection delay of one of the cylinders causes a significant reduction in NOx emission without reducing engine efficiency. The injection delay in the cylinder causes the displacement of the combustion process to the expansion stroke. As a consequence combustion process temperature decreases. Note, that the temperature decrease of the combustion

Tab. 3. The specific fuel consumption in [g/kWh]

	Power, *P* [kW]				The weighted average of E2 test cycle
	240	180	120	60	
The engine assumed as operated without malfunctions	277	285	315	476	316
The delay of the fuel injection by 5° of crankshaft angle in the second engine cylinder	277	283	315	475	315
The throttling of the air intake duct by reducing the cross section area by 60%	285	292	317	418	313
The throttling the exhaust gas duct by rotation barrier about $\varphi = 56°$	279	288	311	413	309
The leakage of the fuel pump on the second engine cylinder	285	288	330	403	311

causes, besides reduced quantity of produced NO_x, extension of combustion process and the deterioration of efficiency. For this reason, the remaining cylinders have to compensate the loss of energy of the second cylinder. The increase in load of the other cylinders causes decrease of specific fuel consumption for cylinders without simulated malfunctions and increase in specific fuel consumption in a cylinder with simulated malfunctions. Throttling the air inlet and exhaust gas duct causes changes in the organization of the combustion process on all cylinders. It must be remembered that the increase in engine load causes an increase in fuel consumption and amount of air needed for combustion. Cross section of the throttling in the inlet and exhaust duct was constant for the all mentioned the engine loads. For this reason, both of the simulated malfunctions resulted in visible changes of the emission and the specific fuel consumption during the engine operating at low loads. Fuel leakage in one of the engine cylinder's fuel pump causes extension of the fuel injection process into the cylinder. It results in extension of combustion process in time. In case of the engine operation at high loads the extension of combustion process causes lowered temperature of the process and deterioration of cylinder's efficiency. The result is a reduction in NO_x emission.

4. Conclusions

The article presents the results of laboratory research of the four-stroke marine diesel engine. Emission of nitric oxides and fuel consumption were measured according to the requirements of Annex VI to the MARPOL Convention. E2 measurement cycle was used. Measurements for simulated malfunctions of both the fuel system and the engine exchange system were made. The obtained results allow to formulate the following conclusions:

– all simulated malfunctions caused a reduction of the weighted emission of nitric oxides. The largest reduction was observed during the engine's operation with simulated fuel system malfunctions on the cylinder number 2,
– the calculations of the weighted specific fuel consumption present a little change in engine efficiency which are within the range of measuring error of the used method,
– it should be noted that the engine's operation with small loads caused an increase in NO_x emission compared to engine assumed as operated without malfunctions. The increase the load to maximum caused an increase in NO_x emission compared to engine assumed as operated without malfunctions,
– all considered malfunctions caused an increase in the efficiency of the engine during operation at low loads. The increase of load caused deterioration of engine's efficiency compared to the engine assumed as operated without malfunction. Only the injection delay in second cylinder did not result in significant changes in the fuel consumption for all considered loads of the engine.

Acknowledgments

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