



ASSESSMENT OF TURBINE ENGINES EXHAUST EMISSIONS FROM VESSELS PROPULSION SYSTEMS

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Abstract

The issue taken in the article concerns vessels using gas turbine engines as part of propulsion systems and is an addition to previously conducted research in the field of vessels impact on the environment. The author's purpose was to determine the impact on the natural environment of the frigate's operation, in the aspect of ecological indicators. As part of research, measurements of harmful compounds concentration in the engine exhaust during frigate's cruise with simultaneous registration of engine operation parameters were carried out. The obtained results from the conducted measurements were the subject of a comparative analysis with the engine load values. The comparison of the obtained data made it possible to assign concentration values of particular harmful exhaust compounds to the appropriate engine load conditions during the cruise. On the basis of the analyzes carried out, emission factors for harmful exhaust emissions were determined. These factors allow determining the mass of harmful compounds emitted to the atmosphere from marine gas turbine engines during the operation of the Oliver Hazard Perry frigate.

Keywords: gasturbine, ship, emission, pollution

OCENA EMISJI ZWIĄZKÓW SZKODLIWYCH W SPALINACH SILNIKÓW TURBINOWYCH UKŁADÓW NAPĘDOWYCH JEDNOSTEK PŁYWAJĄCYCH

Streszczenie

Zagadnienie podjęte w artykule dotyczy oceny wpływu jednostek pływających wykorzystujących w układach napędowych turbinowe silniki spalinowe na środowisko. Celem jest określenie oddziaływania na środowisko naturalne człowieka eksploatacji okrętu klasy fregata, w aspekcie wskaźników ekologicznych. W ramach badań przeprowadzono pomiary stężenia związków szkodliwych zawartych w spalinach silników podczas rejsu okrętu z jednoczesną rejestracją parametrów pracy silników. Uzyskane wyniki z przeprowadzonych pomiarów poddano analizie porównawczej z wartościami obciążenia silników. Wspólne zestawienie uzyskanych danych umożliwiło przypisanie wartości stężenia poszczególnych związków szkodliwych spalin odpowiednim stanom obciążenia silnika w trakcie rejsu. Na podstawie przeprowadzonych analiz wyznaczono wskaźniki emisji związków szkodliwych spalin. Wskaźniki te umożliwiają wyznaczenie masy emitowanych do atmosfery związków szkodliwych zawartych w spalinach okrętowych silników turbinowych podczas eksploatacji okrętu typu Oliver Hazard Perry.

Słowa kluczowe: silnik turbinowy, okręt, emisja, związki szkodliwe

1. INTRODUCTION

The assessment of emissions of harmful compounds in the exhaust of gas turbine engines propulsion systems of vessels is associated with the activity in the field of determining the impact of various types of technical facilities on the human environment. Particular attention is paid to the conditions of exploitation of the objects and the resulting consequences. In the field of means of transport exploitation, power generation of the drive is of great importance in the aspect of the impact on the environment. The combustion engine is responsible for generating energy for the purpose of carrying out the function of destination of the majority of means of transport. It converts chemical energy contained in fuel into mechanical energy

using the combustion process to generate heat required for the energy conversion process. The consequence of this is the formation of exhausts containing harmful compounds in their composition [5, 6, 9, 10, 12].

Turbine marine combustion engines, due to their properties, constitute only a few percent share in the entire population of marine combustion engines. Due to economic reasons (relatively high efficiency, low-quality fuel consumption), propulsive compression-ignition internal combustion engines are used in the majority of propulsion and marine power plants of vessels. For the most part, works related to environmental impact analysis of vessels, as well as development works carried out under various projects refer mainly to civil communication vessels, transport

vessels and compression-ignition engines, which are used to drive them [2, 3, 4, 7, 8, 11]. However, so far only a few research have been taken to assess the emission of pollutants emitted in the exhaust of marine turbine engines with military application, regarding their specific operating conditions [1, 13, 14].

In connection with the above, tests were carried out related to the measurement of carbon dioxide, carbon monoxide, hydrocarbons and nitrogen oxides in the exhaust gas of turbine engines during the cruise of the FFG-7 ship. During the tests, the results of measurements of the concentration of harmful exhaust compounds were recorded while simultaneously recording the values of the operational parameters of the engines and the entire drive system. A comparative analysis of the recorded data was made, which made it possible to assign particular engine performance, propulsion system and ship a proper value of the concentration of harmful exhaust gas compounds. Knowing the concentration values of harmful compounds in relation to particular operational parameters of the objects, an analysis was carried out, from which functional dependences of ecological parameters were obtained in relation to the engine's operational parameters.

2. RESEARCH OBJECT

The research was carried out with the use of two LM 2500 marine turbine engines from FFG-7 frigate propulsion system (Fig. 1). LM 2500 engines are "milled" turbine combustion engines that are widely used on modern warships and civilian vessels (Fig. 2).



Fig. 1. FFG-7 class ship [16]

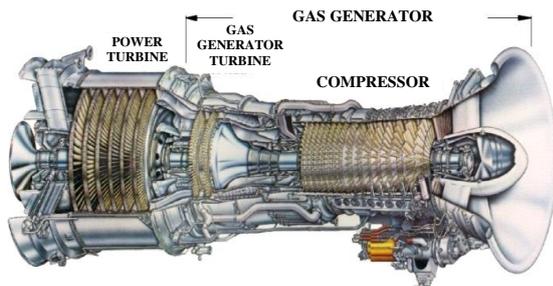


Fig. 2. LM 2500 gas turbine engine [17]

The basic structural elements of the engine are:

- 16-stage axial compressor with maximum pressure ratio of 18,
- an annular combustion chamber equipped with 32 injectors,
- 2-stage gas generator turbine with cooled blades,
- 6-stage power turbine.

An integral part in ship constructions is the intermediate shaft transmitting the torque of the drive turbine to the reduction gear.

Measured engine operation parameters with their measuring range, expressed in units valid in the ship's engine room, are shown in Table 1.

Table 1. Operating parameters LM 2500 engine

Name parameter, designation, unit	Measurement range
Barometric pressure p_o [hPa]	800 – 1040
Ambient temperature t_o [°C]	-40 – +40
The rotational speed of the gas generator shaft n_{GG} [rpm]	0 – 12000
The rotational speed of the power turbine shaft n_{PT} [rpm]	0 – 5000
The inlet air temperature to the engine t_1 [°F]	-40 – +150
The inlet air total pressure to the engine p^*_1 [psig]	0 – 16
Air pressure on the outlet compressor p_2 [psig]	0 – 300
The temperature of the exhaust stream before the power turbine $t_{4.2}$ [°F]	0 – 2000
Total pressure of the exhaust stream before the power turbine $p^*_{4.2}$ [psig]	0 – 75
Temperature exhaust gas T_6 [°F]	0 – 1000
The fuel temperature before engine T_f [°F]	0 – 100
Pressure fuel injectors before p_f [psig]	0 – 1500
Torque (calculated) on the power turbine shaft M_{PT} [LB FT]	0 – 50000
Power on the power turbine shaft P_{TN} [KM]	0 – 25000

The location of the turbine engine in the ship's engine room requires ensuring that its inlet is supplied with a proper stream of air mass and the outlet of gas generated from the exhaust system. For the Oliver Hazard Perry type frigate, equipped with two LM 2500 turbine engines, vertical air intake ducts and vertical exhaust gas channels (Fig. 3) with a length of about 15 m were designed. The air from the inlet channel is mainly directed to the interior of the container engine body in order to ensure air exchange and proper temperature around the running engine. The air flowing around the external elements of the engine, located in the container housing, ultimately is directed to the outlet channel, where it mixes with the exhaust gases generated by the engine. Depending on the need to ensure proper parameters, the air flowing from outside the engine is properly prepared in terms of obtaining the required temperature using

the cooling system and heaters, as well as the required flow speed inside the container housing, controlled with the use of fans. The Semtech-DS exhaust gas analyzer was used for measurements of exhaust components concentration in the exhaust gases, the characteristics of which are presented in Table 2.

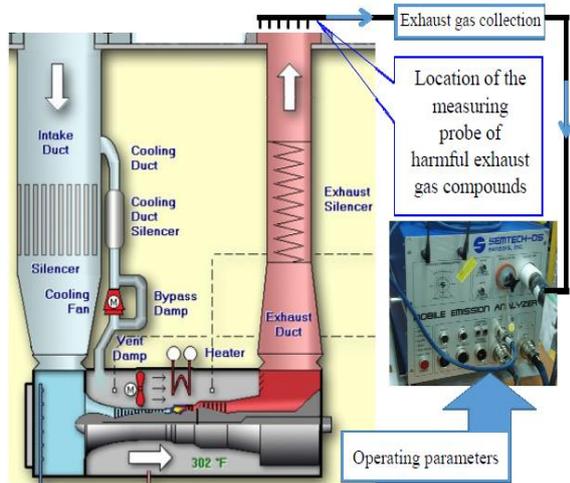


Fig. 3. The air intake system and the exhaust system of the LM 2500 engine installed on the missile frigate with marked sampling point and the Semtech-DS exhaust analyzer

Table 2. Characteristics of the Semtech-DS analyzer

Name parameter, designation, unit	Measurement range
The concentration of oxygen c_{O_2} [%]	0 – 20
The concentration of carbon monoxide c_{CO} [%]	0 – 10
The concentration of hydrocarbons c_{HC} [ppm]	0 – 10 000
The concentration of nitrogen oxides c_{NOx} [ppm]	0 – 3 000
The concentration of carbon dioxide c_{CO_2} [%]	0 – 20

3. EMISSION OF HARMFUL COMPOUNDS FROM LM 2500 ENGINES IN OPERATING CONDITIONS DURING THE CRUISE

Measurements of concentrations of harmful compounds contained in the exhaust gas of the LM 2500 engine were carried out during the ship's departure to the sea. Two engines in the propulsion system of the unit were tested - each engine was tested separately when only one engine in the drive system was running. The measurements were carried out for the range of engine load from idling to load that could be maximally achieved during tests, with the rotor speed of the flue gas generator (n_{GG}) assumed as the parameter setting the measurement points. This parameter was obtained by appropriate changes of the engine fuel supply stream (m_{pal}). The tests were carried out in such a way that in the first step the defined value of the rotational speed n_{GG} was set. After stabilization of

the engine operation parameters, the selected drive system operating parameters (including the engine) were recorded and the parameters of the exhaust gases flowing out of the engine were recorded too. The working time with a predefined fixed engine load was 300 seconds. The measurement time of both the operating parameters of the drive system and exhaust parameters was 20 seconds with a recording frequency of 1 Hz.

Fig. 4 - 7 presents the changes in the parameters of the exhaust gases of the tested LM 2500 1A and 1B engines as a function of the engine load factor expressed by the engine power ratio obtained at the test points to the maximum engine power:

$$W_o = \frac{P}{P_{max}} [-] \quad (1)$$

where:

P – LM 2500 engine power during measurement,

P_{max} – LM 2500 engine maximum power.

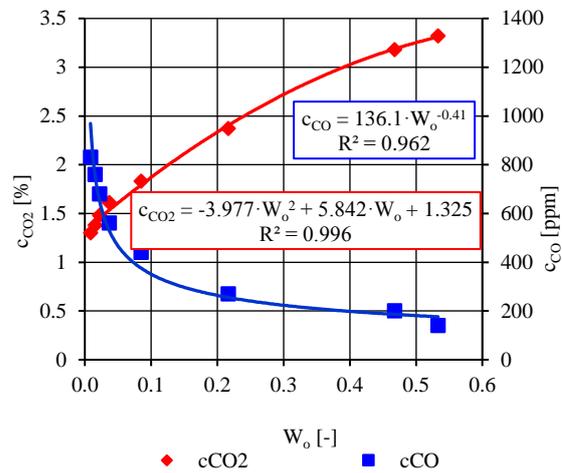


Fig. 4. The concentration of carbon monoxide (c_{CO}) and the concentration of carbon dioxide (c_{CO_2}) in the LM 2500 1A engine exhaust as a function of the engine load factor (W_o)

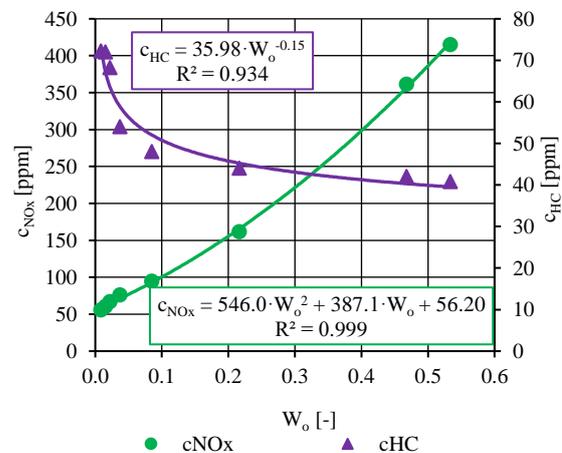


Fig. 5. Concentration of nitrogen oxides (c_{NOx}) and hydrocarbons concentration (c_{HC}) in the LM 2500 1A engine exhaust as a function of the engine load factor (W_o)

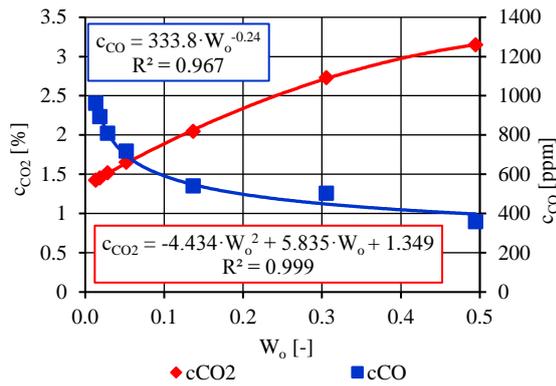


Fig. 6. The concentration of carbon monoxide (c_{CO}) and the concentration of carbon dioxide (c_{CO_2}) in the LM 2500 1B engine exhaust as a function of the engine load factor (W_o)

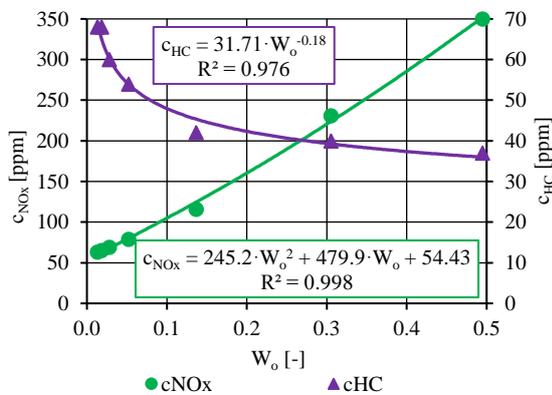


Fig. 7. Concentration of nitrogen oxides (c_{NO_x}) and hydrocarbons concentration (c_{HC}) in the LM 2500 1B engine exhaust as a function of the engine load factor (W_o)

With the increase of the load factor of the LM 2500 1A engine from about 0.01 (engine idle load) to the value achieved during tests of about 0.53 (53% of the maximum engine power), the oxygen concentration in the exhaust gas decreases from about 18.3 % to about 15.3%. The excess air coefficient, which, as a rule, the turbine engine operation is characterized by significant values in comparison to other internal combustion engines, with the increase of the engine load factor in the above range decreases from about 10.5 to about 4.4. As the engine load increases, the concentration of carbon monoxide decreases from about 830 ppm to 140 ppm, while the concentration of carbon dioxide increases from about 1.3% to about 3.3%. The concentration of nitrogen oxides during this time increases from about 56 ppm to about 415 ppm, and the concentration of hydrocarbons decreases from about 72 ppm to about 40 ppm.

A similar character of changes in concentrations of registered exhaust components is found in the exhaust gas of the LM 2500 1B engine. With the increase of the engine load factor 1B from about 0.01 to the value achieved during tests of around 0.5 (50% of the maximum engine power), the oxygen concentration in the exhaust gas decreases from about 17.9% to about 15.6%. The excess air

coefficient decreases from about 9.6 to about 4.6. As the engine load increases, the concentration of carbon monoxide decreases from about 960 ppm to 360 ppm, while the concentration of carbon dioxide increases from about 1.4% to about 3.1%. The concentration of nitrogen oxides during this time increases from about 63 ppm to about 350 ppm, and the concentration of hydrocarbons decreases from about 68 ppm to about 37 ppm. Relatively small values of concentrations of particular compounds in the exhaust gases are associated with a large coefficient of excess air in the combustion chamber, which in the case of turbine engines results in a significant dilution of exhaust gases [15].

Using the functional relationships of changes in the concentration of harmful exhaust gas compounds in relation to the engine load factor (W_o), a functional dependence of the mass emission intensity of a given harmful compound ($\dot{E}_{i,j}$) of the tested engines can be proposed as a function of the engine load factor:

$$\dot{E}_{i,j}(W_o) = \dot{m}_{spal j}(W_o) \cdot g_{i,j}(W_o) \left[\frac{kg}{s} \right] \quad (2)$$

where:

- $\dot{m}_{spal j}(W_o)$ – exhaust mass stream [kg/s] as a function of the engine load factor for the j-th measurement,
- $g_{i,j}(W_o)$ – mass share [-] of the i-th exhaust component as a function of the engine load factor for the j-th measurement.

The values of mass emission intensity of the analyzed harmful compounds are presented in Fig. 8 and 9.

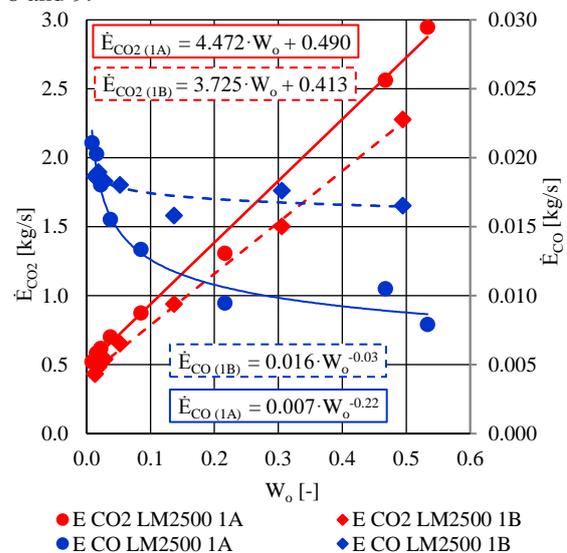


Fig. 8. The mass emission intensity of carbon dioxide (\dot{E}_{CO_2}) and carbon monoxide (\dot{E}_{CO}) in the LM 2500 1A and LM 2500 1B engines exhaust as a function of the engine load factor (W_o)

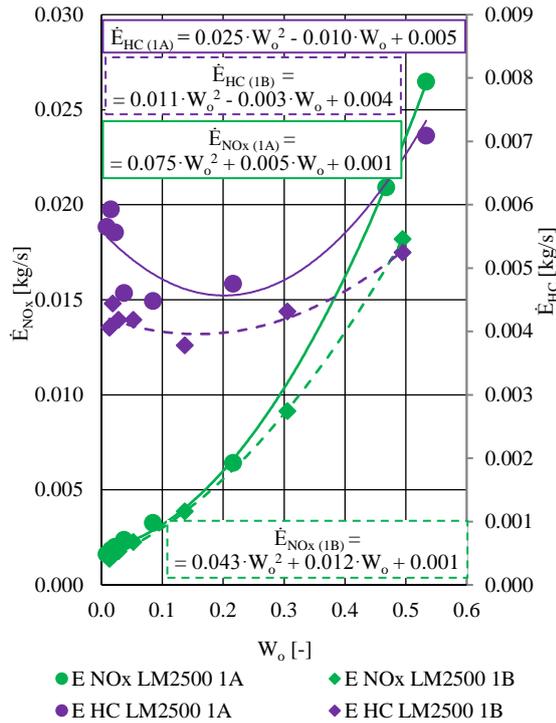


Fig. 9. The mass emission intensity of nitrogen oxides (\dot{E}_{NOx}) and hydrocarbons (\dot{E}_{HC}) in the LM 2500 1A and LM 2500 1B engines exhaust as a function of the engine load factor (W_o)

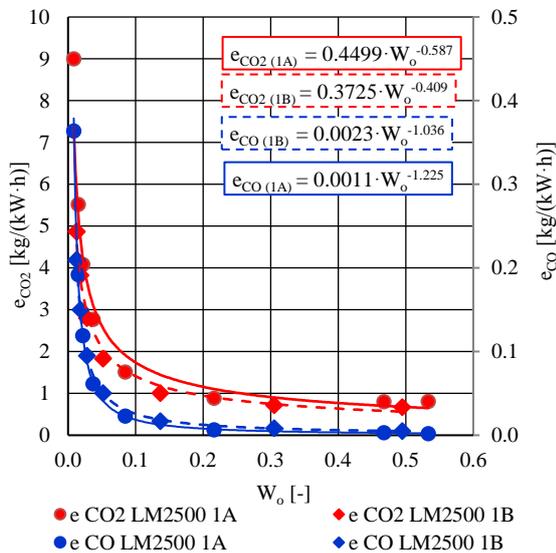


Fig. 10. The unit emission of carbon dioxide (e_{CO2}) and carbon monoxide (e_{CO}) in the LM 2500 1A and LM 2500 1B engines exhaust as a function of the engine load factor (W_o)

The next step in the analysis of emissions of harmful exhaust compounds of LM 2500 engines was to determine the unit emission of individual compounds from the dependence:

$$e_{i,j}(W_o) = \frac{\dot{E}_{i,j}(W_o)}{W_{oj} \cdot P_{max}} \left[\frac{kg}{kW \cdot h} \right] \quad (3)$$

where:

- $\dot{E}_{i,j}(W_o)$ – mass emission intensity [kg/h] of the i-th exhaust component as a function of the engine load factor for the j-th measurement,
- W_{oj} – engine load factor [-] for the j-th measurement.
- P_{max} – the maximum power of the LM 2500 engine (24 608 kW).

The values of determined unit emissions of individual harmful compounds are presented in Fig. 10 and 11.

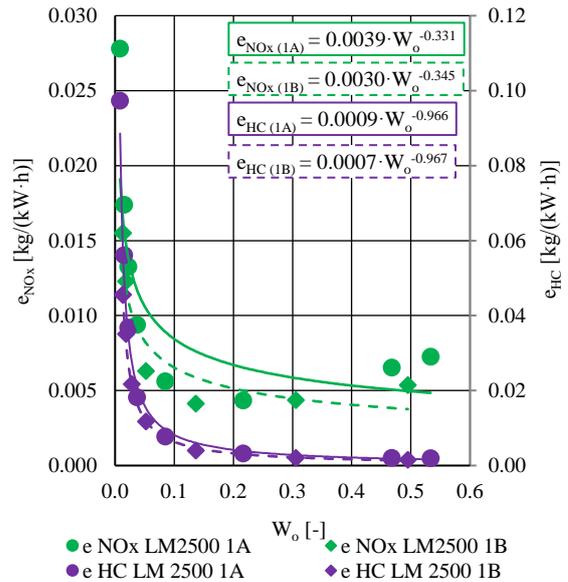


Fig. 11. The unit emission of nitrogen oxides (e_{NOx}) and hydrocarbons (e_{HC}) in the LM 2500 1A and LM 2500 1B engines exhaust as a function of the engine load factor (W_o)

Having the mass emission intensity values of the analyzed exhaust gas compounds LM 2500 1A and LM 2500 1B engines and knowing the duration of each measurement, which during the tests was 300 seconds, it is possible to calculate the mass values of emitted harmful compounds during each measurement. In the next step, we can determine the mass values of emitted harmful compounds during the entire measurement test of each engine.

The mass value of the emitted harmful compound for a given measurement (engine load factor) was determined from the dependence:

$$m_{i,j}(W_o) = \dot{E}_{i,j}(W_o) \cdot \tau_j [kg] \quad (4)$$

where:

- $\dot{E}_{i,j}(W_o)$ – mass emission intensity [kg/s] of the i-th exhaust component as a function of the engine load factor for the j-th measurement,
- τ_j – duration of j-th measurement[s].

The values of the calculated mass of emitted particular harmful compounds during each measurement are presented in Fig. 12 and 13.

The total mass of the emitted harmful compound during the engine measurement test was determined as the sum of the mass of the emitted compound for each measurement:

$$m_i = \sum m_{i,j}(W_o) [kg] \quad (5)$$

where:

$m_{i,j}(W_o)$ – mass [kg] of the i-th emitted exhaust component as a function of the engine load factor for the j-th measurement.

The values of total mass of emitted harmful exhaust gas compounds of both tested engines are presented in Fig. 14.

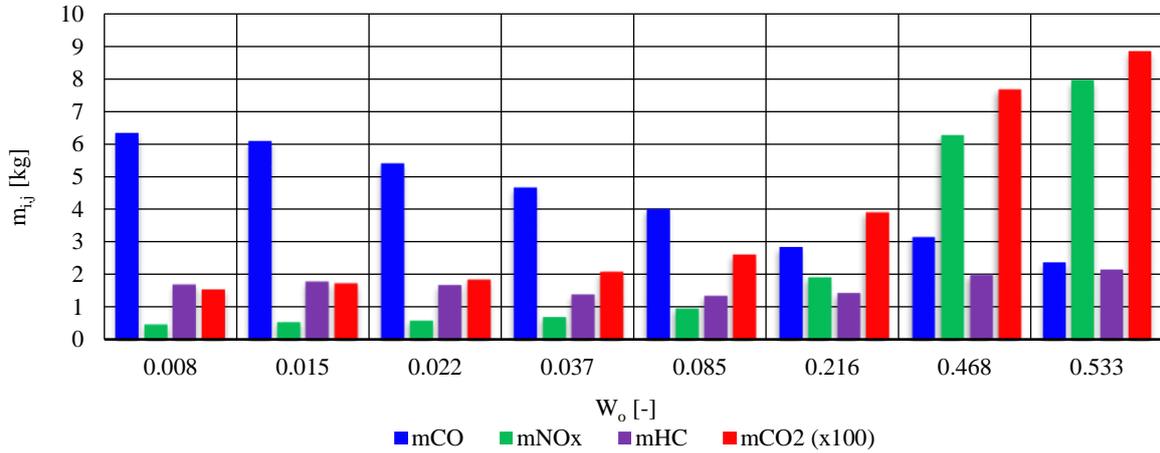


Fig. 12. The mass of emitted carbon dioxide (m_{CO_2}), carbon monoxide (m_{CO}), nitrogen oxides (m_{NO_x}) and hydrocarbons (m_{HC}) in the LM 2500 1A engine exhaust during 300 seconds of measurement duration, as a function of the engine load factor (W_o)

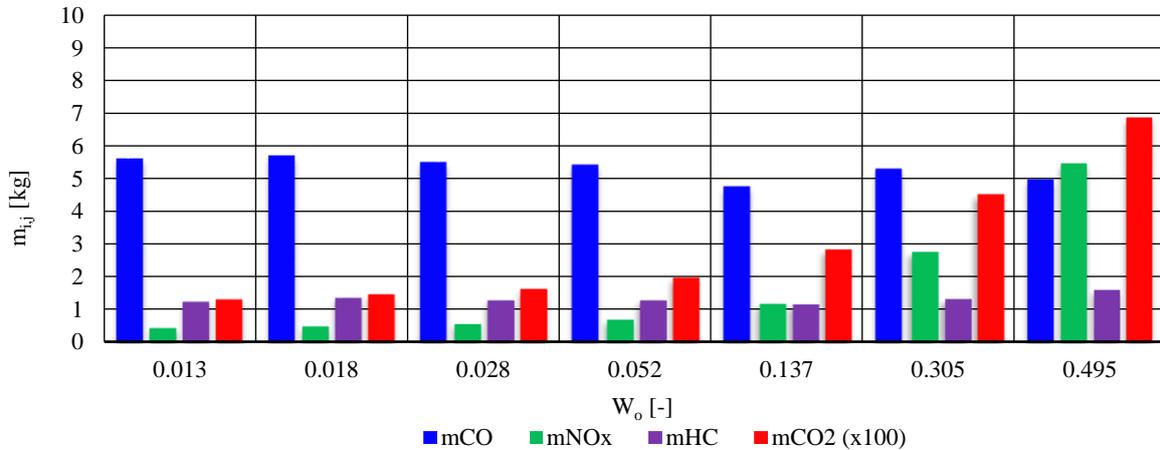


Fig. 13. The mass of emitted carbon dioxide (m_{CO_2}), carbon monoxide (m_{CO}), nitrogen oxides (m_{NO_x}) and hydrocarbons (m_{HC}) in the LM 2500 1B engine exhaust during 300 seconds of measurement duration, as a function of the engine load factor (W_o)

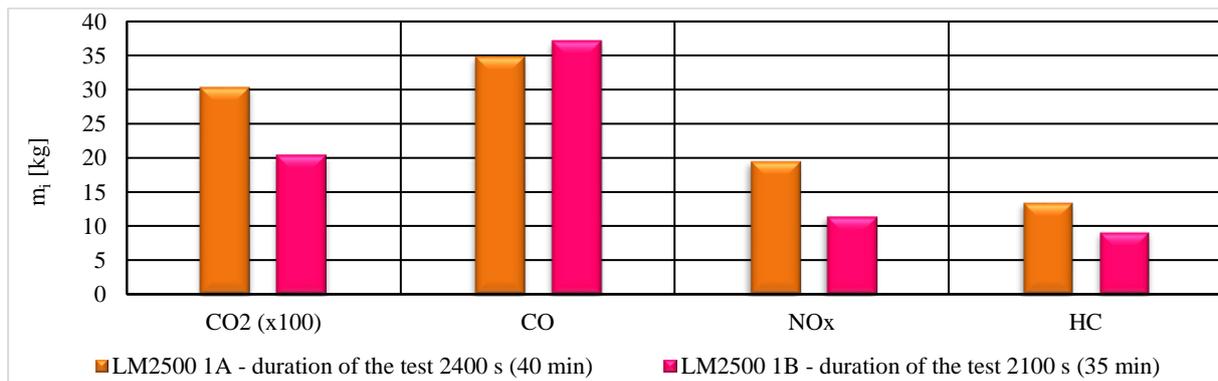


Fig. 14. The total mass of emitted harmful exhaust compounds of LM 2500 1A and LM 2500 1B engines during the tests

4. CONCLUSIONS

On the basis of the conducted research, it can be concluded that the increase in the load on the ship's turbine engine causes a decrease in the concentration of carbon monoxide and an increase in the concentration of carbon dioxide in the exhaust. At the same time, the concentration of nitrogen oxides increases and the concentration of hydrocarbons decreases. The above results from the improvement of the conditions of the combustion process taking place in the combustion chamber of the engine. Additionally, carried out research and the analysis of the actual working conditions of frigate ships indicate the similarity in the form of the time distribution of engine operation in engine load intervals occurring during the ship's tasks during the cruise. In order to determine the level of emission of harmful compounds contained in the exhaust gas generated by the turbine engines of the main propulsion vessel, an analysis of functional dependence of ecological parameters on the operating parameters were carried out.

The conducted analysis showed the possibility of obtaining mathematical functions describing relations between selected parameters. These functions can be used to assess the mass emission intensity and the unit emission of individual harmful compounds emitted while the engine is running at a given load.

Having the mathematical functions describing the mass emission intensity of the analyzed compounds of harmful exhaust gases of LM 2500 engines and knowing the engine operation time with a given load, there is a possibility to determine the mass of emitted harmful compounds during the operation of the engine with this load.

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