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Modeling of pollutant emissions from the turbine engine of the main propulsion of a vessel in operating conditions

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Abstract. The intensification of environmental protection measures is being implemented in all economic and industrial activities. The goal of reducing harmful emissions from various types of combustion engines used in different applications is being pursued dynamically. The introduced changes concern the values of harmful emission limits and the methods of measuring or assessing their emissions. There are solutions for propulsion systems, such as turbine engines used on ships, where there is a need for constant monitoring of operational and environmental parameters during the operation of the vessels. Continuous measurement of harmful emission values contained in exhaust gases during the operation of these systems allows for an assessment of their impact on the environment. However, due to the costs of measuring equipment and limitations associated with its use, alternative methods are being sought to evaluate pollution emissions resulting from the operation of turbine engines. One possibility is to assess the emission characteristics of the propulsion system in emission tests under conditions of its actual operation. Based on this, by introducing basic mathematical tools, it is possible to determine the values of emissions of individual pollutants during the propulsion system operation in actual conditions. These actions are presented in this paper.

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1 Introduction

Turbine internal combustion engines (ICE) for marine applications, due to their properties, constitute only a few percent share in the entire population of ICE used in the propulsion of vessels. Therefore, the existing legal regulations regarding the emission of harmful compounds in the exhaust of marine engines apply only to piston engines. One such piece of legislation is the aforementioned MARPOL Convention. In 1997, at a Diplomatic Conference organized by the International Maritime Organisation (IMO), a Protocol amending MARPOL 73/78 was adopted, which added Annex IV containing provisions for the prevention of air pollution from ships. In view of the above-mentioned legal acts concerning the protection of the marine environment, it can be concluded that the evolution of legislation in the last dozen or so years in the field of setting permissible levels of harmful exhaust emissions from marine engines shows how important it is to harmonize regulations in this area. It is sought that they are used by all vessels, regardless of their purpose. Most of the work related to the analysis of the impact of vessels on the environment, as well as development works carried out as part of various projects, concern primarily civil communication units, transport units and reciprocating compression ignition engines, which are used for their propulsion [1-4]. Currently, due to the requirement of using low-sulfur fuels, ship propulsion systems are being designed with hybrid arrangements, equipped with several power generation units using high-speed diesel engines and with additional sets of turbine engines. When designing these propulsion systems, the volume of the engine room and operating costs associated with periodic maintenance are also taken into account, making TEs(TEs) an increasingly attractive option. As a result, their use in ship propulsion systems may increase in the coming years. Therefore, the work presented in this article focuses on finding ways to continuously monitor and assess the impact of TEsused in ships on the environment. To achieve this, work has been carried out to develop a model for evaluating harmful emissions based on operational parameters.

The issue of assessing emissions of pollutants in the exhaust gases of TEs is largely related to the gas flow parameters and the measurement of the concentration of harmful compounds contained in them. TEs are characterized by a large flow rate of the working fluid through the engine during operation. The working fluid is air to which heat generated in the thermodynamic processes during fuel oxidation in the combustion chamber is supplied. The large airflow used to achieve the required engine operating parameters determines the fuel flow rate supplied. Depending on the energy demand generated by the engine, the processes carried out in the combustion chamber also change, contributing to the change in the concentration of harmful compounds in the exhaust gases. To assess emissions of pollutants in the exhaust gases, the mass flow rate of the exiting gases and the concentrations of individual harmful compounds in them are needed [5]. The concentration of harmful compounds in the exhaust gases was measured with a flue gas analyzer of appropriate measurement accuracy. At the same time, a significant problem is the measurement of the mass flow rate of the exiting gases. Another problem in assessing the emissions of pollutants generated by the main TEs during ship operation is the need to measure the concentration of these compounds during operation. Currently, it is not possible to permanently install flue gas analyzers that will continuously measure the concentration of pollutants due to the costs of purchasing and installing the equipment and operational problems arising from measurement accuracy and the need to provide appropriate operating conditions. Therefore, an analysis was carried out to explore alternative methods. The functional relationships between individual ecological and operating parameters were analyzed to achieve this. The obtained relationships made it possible to determine a kind of individual ecological characteristic of the turbine engine. Tests of harmful emissions in exhaust gases of powered craft with turbine engines.

2 Research on the emission of harmful compounds in the exhaust gases of a watercraft powered by turbine engines

2.1 Test methodology

2.1.1 Measurement object and measuring apparatus for measuring harmful compounds in exhaust gases

The work aimed to develop a method for assessing emissions of harmful exhaust compounds from TEs in use as the main propulsion of a vessel. Therefore, it was necessary to carry out operational tests of the selected unit, during which, in addition to recording the values of engine operating parameters, the concentration values of harmful compounds contained in the exhaust gases were continuously recorded. The research object was the FFG-7 frigate-class ship operated in the Polish Navy. ORP "Gen. T. Kosciuszko" (Figure 1). It is powered by two LM 2500 TEs (Figure 2).

Fig. 1. The warship „Gen. T. Kociuszko".

The basic parameters of the drive train, recorded during operational tests at nominal load, reached the following values:

- vessel's speed (displacement 4,000 t, sea state 1, ambient temperature 293 K) – 30 knots;
- propeller shaft rotation speed – 179 rotation/min;
- propeller pitch – 7.16 m;
- torque on the propeller shaft – 1,594,962 N·m;
- propeller shaft power – 29,630 kW;
- fuel consumption – 7,467 kg/h.

The propulsion system's power is approximately 30,000 kW (i.e., 2 x 15,000 kW) at a maximum turbine speed of n_{TN} = 3,600 rpm. The presented COGAG (Combined Gas Turbine and Gas Turbine) propulsion system allows for operation in three basic variants:

- operation with two engines;
- operation with the engine on the left side;
- operation with the engine on the right side.

The first variant allows one to achieve a speed of about 30 knots, while the other variants allow one to achieve a speed of about 25 knots with only one of the engines. For economic reasons, the second or third operation variant is most often used under normal operating conditions.

LM 2500 engines are turbine ICE with a wide range of applications on modern warships and civilian vessels. The basic structural elements of the engine are:

- 16-stage axial compressor with a maximum pressure of 18:1; the first six stages are equipped with adjustable steering paddles,
- annular combustion chamber equipped with 32 injectors,
- 2-stage exhaust generator turbine with cooled vanes, which is the source of compressor drive and auxiliary mechanisms coupled to the engine,
- 6-stage low-pressure turbine, which is structurally the engine drive turbine.

An integral part of marine structures is an intermediate shaft transmitting the torque of the drive turbine to the reduction gear.

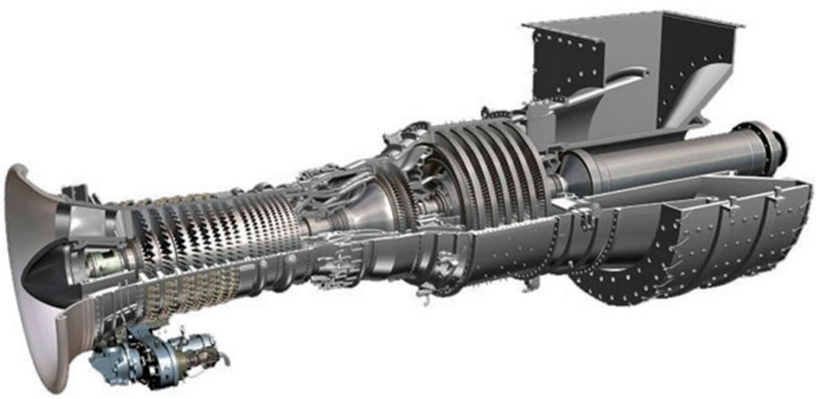

Fig. 2. LM 2500 turbine engine for vessels [6].

Measurements of the energy parameters of the working medium, made in the characteristic control cross-sections of the engine, are an important source of diagnostic information about the state of the structural structure of its flow part. The presented schematic diagram of the LM 2500 engine, with marked control cross-sections of the flow part, makes it possible to illustrate the location of measuring points. The measured and determined engine operating parameters and their measuring range, expressed in units applicable in the ship's engine room, are summarized in Table 1. The concentration of exhaust gas components was measured with the Semtech-DS exhaust gas analyzer (Figure 3) from Sensors (Sensors EMission TECHnology). The characteristics of the Semtech-DS analyzer are presented below (Table 2).

The analyzer allows for the measurement of the concentration of harmful compounds such as carbon monoxide, hydrocarbons, nitrogen oxides, and carbon dioxide. The main advantage of the analyzer is its compact design and small size, which allows for easy movement and positioning in objects being tested under real operating conditions. The analyzer meets the requirements of standard 1065 for measuring exhaust emissions using PEMS systems. It consists of measurement modules:

- FID (Flame Ionization Detector), used to determine the total concentration of hydrocarbons referred to as HC or THC (Total Hydrocarbons) in the exhaust gas,
- NDUV (Non-Dispersive Ultraviolet) type analyzer, non-dispersible to ultraviolet radiation for measuring the concentration of nitric oxide and nitrogen dioxide,

- NDIR (Non-Dispersive Infrared) type analyzer, non-dispersible to infrared radiation for measuring the concentration of carbon monoxide and carbon dioxide,
- ECS (Electrochemical Sensor) analyzer for determining the oxygen concentration in the exhaust gas.

Table 1. LM 2500 engine performance.

Parameter name	Symbol	Unit	Measurement range
Ambient pressure	p_o	[hPa]	800 ÷ 1,040
Ambient temperature	t_o	[°C]	–40 ÷ 40
Rotational speed of the exhaust generator	n_{GG}	[obr/min]	0 ÷ 12,000
Rotational speed of the drive turbine	n_{PT}	[obr/min]	0 ÷ 5,000
Engine inlet air temperature	t_1	[°F]	–40 ÷ 150 (–40 ÷ 65.6°C)
Total air pressure at engine inlet	p^*_1	[psig]	0 ÷ 16 (0 ÷ 1.103 bar)
Air pressure downstream of the compressor	p_2	[psig]	0 ÷ 300 (0 ÷ 20.684 bar)
Exhaust gas temperature in front of the drive turbine	$t_{4.2}$	[°F]	0 ÷ 2,000 (–18 ÷ 1,093°C)
Total exhaust gas pressure upstream of drive turbine	$p^*_{4.2}$	[psig]	0 ÷ 75 (0 ÷ 5.171 bar)
Exhaust gas temperature	t_6	[°F]	0 ÷ 1,000 (–18 ÷ 538°C)
Fuel temperature in front of the engine	t_{fuel}	[°F]	0 ÷ 100 (–18 ÷ 37.8°C)
Fuel pressure before injectors	p_{fuel}	[psig]	0 ÷ 1,500 (0 ÷ 103.421 bar)
Torque on the drive turbine shaft	M_{PT}	[LB·FT]	0 ÷ 50,000 (0 ÷ 67.770 kN·m)
Power on the drive turbine shaft	P_{TN}	[KM]	0 ÷ 25,000 (0 ÷ 18,642 kW)

Fig. 3. Exhaust gas analyzer.

The exhaust gases are introduced into the analyzer using a measurement probe that maintains a temperature of 191°C. In the next step, solid particles are filtered out, and the concentration of hydrocarbons is measured using a flame ionization analyzer. Then, the exhaust gases are cooled to a temperature of 4°C, and the concentration of nitrogen oxides is measured using a non-dispersive method using ultraviolet radiation that allows for simultaneous measurement of nitrogen oxide and nitrogen dioxide concentrations.

Table 2. Characteristics of the Semtech-DS analyzer [101].

Parameter	Method of measurement	Precision
Concentration of compounds in exhaust gases: CO HC NOx = (NO+NO2) CO2 O2	 NDIR, measuring range 0 ÷ 10% FID, range 0 ÷ 10,000 ppm NDUV range 0 ÷ 3,000 ppm NDIR range 0 ÷ 20% Electrochemical analyzer, range 0 ÷ 20%	 ±3% of the measuring range ±2.5% of measuring range ±3% of the measuring range ±3% of the measuring range ±1% of measuring range
Exhaust flow	Mass flow rate flue gas temperature up to 700 oC	±2.5% of measuring range ±1% of measuring range
Warm-up time	900 s	-
Response time	T90 < 1 s	-

The exhaust gases are introduced into the analyzer using a measurement probe that maintains a temperature of 191°C. In the next step, solid particles are filtered out, and the concentration of hydrocarbons is measured using a flame ionization analyzer. Then, the exhaust gases are cooled to a temperature of 4°C, and the concentration of nitrogen oxides is measured using a non-dispersive method using ultraviolet radiation that allows for simultaneous measurement of nitrogen oxide and nitrogen dioxide concentrations. Carbon monoxide, carbon dioxide, and oxygen concentrations are measured using a non-dispersive method using infrared radiation and an electrochemical analyzer, respectively. In addition to measuring exhaust gas components, this analyzer also allows for measuring the mass flow rate of the exhaust gases. Data can be directly transmitted to the analyzer's central unit from the diagnostic system of the tested object, and GPS location signals can also be used.

2.1.2 Method of measurement of harmful compounds in exhaust gases

The research was conducted on a vessel powered by LM 2500 engines under operational conditions. The flue gas analyzer probe was placed in the axis of the final outlet of the exhaust system in the upper part of the ship superstructure (Figure 4). Additionally, the location of the sampling point of the exhaust gas was about 15 meters away from the turbine outlet, ensuring sufficient mixing of the exhaust gas, and therefore the sampling of a representative sample.

Fig. 4. Superstructure on the upper deck with the exhaust system and view of the probe mounted in the exhaust outlet.

The measurements were carried out for the engine load range from idle speed to the maximum load achievable during the tests, with the rotational speed of the exhaust gas generator (n_{GG}) set as the parameter determining the measurement points. This parameter was obtained by appropriate changes in the fuel flow rate supplied to the engine (m_{pal}), which caused the change in the rotational speed of the power turbine (n_{PT}), and the entire propeller shaft (n_{LW}), and finally had an impact on the pitch of the propeller blades. In this way, the resulting ship's speed was achieved. The tests were conducted in such a way that the desired values of n_{GG} were set first. After obtaining the specified engine operating parameters, the selected operating parameters of the propulsion system were recorded and saved. The engine operated at a set load for 300 seconds. The measurement time for both the operating parameters of the propulsion system and the exhaust gas parameters was 20 seconds with a sampling frequency of 1 Hz. The obtained averaged values of the measured operating parameters were used to conduct the necessary analyses to determine the emission characteristics of the turbine engines.

2.2 Emission characteristics

Based on the obtained results, analyses were conducted, resulting in emission characteristics of the TEs of the propulsion system. To make them more efficient, they are presented as a function of the load indicator (Figure 5 and Figure 6).

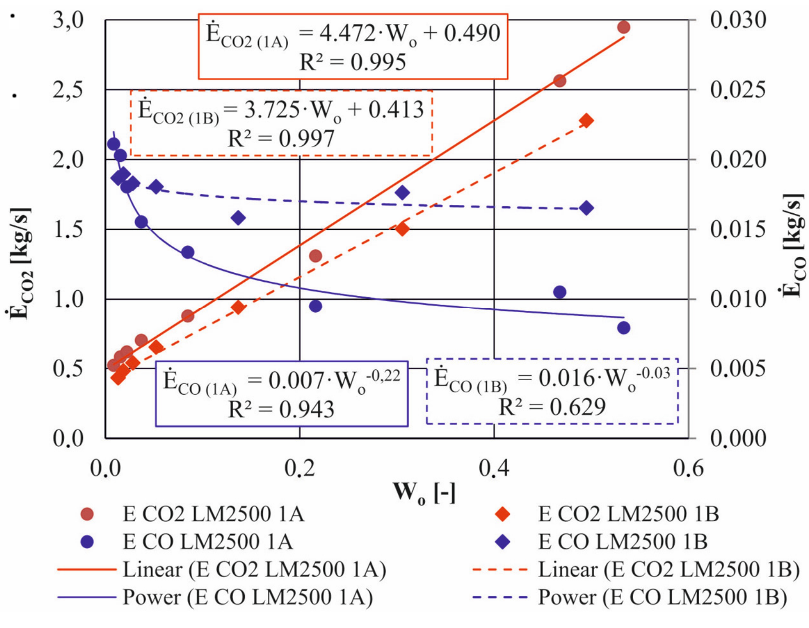

Fig. 5. Carbon dioxide (E_CO2) and carbon monoxide (E_CO) emissions mass load of LM 2500 1A and 1B engines as a function of engine load factor (W_o)

Having the values of the mass emission intensity of the analyzed harmful exhaust compounds of the LM 2500 1A and LM 2500 1B engines and knowing the duration of each measurement, which was 300 seconds, it is possible to calculate the value of the mass of the emitted harmful compounds during each measurement, as well as for the entire measurement test of the engine. The value of the mass of the emitted harmful compound for a given measurement (engine load factor) was determined from the relationship:

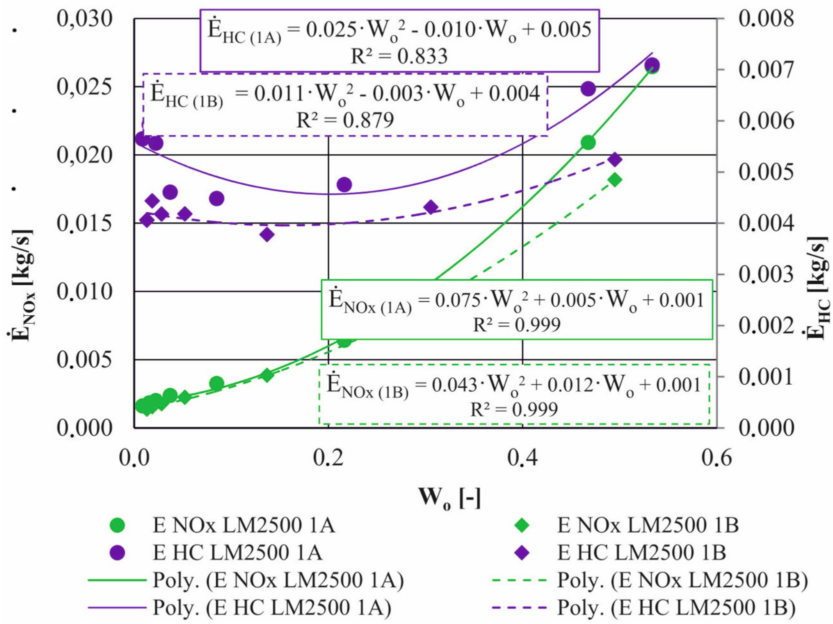

Fig. 6. The mass emission rate of nitrogen oxides (E˙_NOx) and hydrocarbons (E˙_HC) for LM 2500 1A and 1B gas turbines as a function of engine load factor (Wo).

$$m_{i,j}(W_o) = \dot{E}_{i,j}(W_o) \cdot \tau_j [kg], \tag{1}$$

where:

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

τ_j – duration of the j-th measurement [s]

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

$$m_i = \sum m_{i,j}(W_o)\ [kg]. \tag{2}$$

The values of the mass of the emitted harmful compounds can thus be determined continuously during operation or in summary terms from the entire service period, e.g., a cruise.

Therefore, the presented methodology for assessing the ecological indicators of the operation of a warship powered by TEs can be improved by using a numerical algorithm, which can be applied in various programming languages to obtain application tools. For example, an algorithm was prepared to demonstrate the developed emission model.

3 Model of pollutant emissions from the turbine engine of the main propulsion of a vessel in operating conditions

The next step after performing the research on the real object was to create a mathematical model that is its theoretical reflection. This model will allow testing the validity of the assumptions used in testing the object, and, moreover, will allow to check the reliability of the results obtained at a later time. This task was carried out using the SciLab software, and the model is presented in Figure 7 and Figure 8. Thanks to the previously developed emission characteristics of the LM2500 1A engine, in order to obtain information of interest to us from the generated mathematical model, the only data necessary to enter is the power generated by the engine in each second of the considered movement. The measurement results were saved in a file in the .xls format.

The developed mathematical model starts its operation by downloading data from the previously mentioned file, in which information on the power generated by the LM2500 1A motor with a rated power of 24608 kW has been archived. These data are saved in the form of a matrix, which will be later used to calculate the engine load factor (W_0 in SciLab), the momentary emission of individual compounds (M_CO, M_CO2, M_NOX, M_HC in SciLab) and the total mass of emitted harmful compounds (Calk_M_CO , Calk_M_CO2, Calk_M_NOX, Calk_M_HC). At this point, it should be noted that in order to carry out the above-mentioned calculations, it was necessary to use the unit emissions of individual compounds obtained as a result of measurements and to develop emission trend lines for each of them. Calculations of specific emissions depending on the engine load factor are performed in the program in lines from 31 to 34. The results of the calculations are presented in the Figure 9, Figure 10 and Figure 11.

```
1  clear()
2  clc()
3  //Decode file, extract and open Excel stream
4  [fd,SST,Sheetnames,Sheetpos] = xls_open('Motion_record_EN.xls');
5  //Read data sheet
6  [Value,TextInd] = xls_read(fd,Sheetpos(1));
7  //Close the spreadsheet stream
8  mclose(fd);
9
10 // INPUT DATA LM2500 ENGINE
11 //RATED ENGINE POWER [kW]
12 P_max=24608
13
14 //Measurement time [s] - each measurement is performed every 1 second
15 t_pomiaru=1
16
17 //Saving data from the measurement protocol (FROM EXCEL)
18 P_act=Value(2:308,2);
19 t_calk=Value(2:308,1);
20
21 // Determining the size of the matrix/number of elements for the "for loop"
22 number_of_elements= size(P_act,1)
23
24 for x=1:number_of_elements
25
26     //Calculation of engine load value
27     W_0(x,1)=P_act(x,1)/P_max;
28
29     //Emission of harmful compounds [kg/kWh] (characteristics taken
30     //from measurements carried on a real object)
31     e_CO = 0.0011*(W_0^(-1.225));
32     e_CO2 = 0.4498*(W_0^(-0.587));
33     e_NOX = 0.0039*(W_0^(-0.331));
34     e_HC = 0.0009*(W_0^(-0.966));
35
36     //Measurement of momentary emission of harmful compounds
37     M_CO(x,1)=(W_0(x,1)*P_max*t_pomiaru*e_CO(x,1))/3600
38     M_CO2(x,1)=(W_0(x,1)*P_max*t_pomiaru*e_CO2(x,1))/3600
39     M_NOX(x,1)=(W_0(x,1)*P_max*t_pomiaru*e_NOX(x,1))/3600
40     M_HC(x,1)=(W_0(x,1)*P_max*t_pomiaru*e_HC(x,1))/3600
41
```

Fig.7. The program, written in the SciLab environment, is designed to analyze the level of emission of harmful compounds during the examination of the object.

```
    //Measurement of the total emission of
    //harmful compounds during the measurement
    if x==1 then,
        Calk_M_CO(x,1)= M_CO(x,1);
        Calk_M_CO2(x,1)= M_CO2(x,1);
        Calk_M_NOX(x,1)= M_NOX(x,1);
        Calk_M_HC(x,1)= M_HC(x,1);
    else
        Calk_M_CO(x,1)= Calk_M_CO(x-1,1) + M_CO(x,1);
        Calk_M_CO2(x,1)= Calk_M_CO2(x-1,1) + M_CO2(x,1);
        Calk_M_NOX(x,1)= Calk_M_NOX(x-1,1) + M_NOX(x,1);
        Calk_M_HC(x,1)= Calk_M_HC(x-1,1) + M_HC(x,1);
    end
end

//Charts
//Graph of momentary emission of harmful compounds
gda().grid = [1 1]*color("grey70");
title(gda(), "fontsize", 3, "color", "lightseagreen", "fontname", "helvetica bold");
scf(1); clf


subplot(2,2,1), plot(t_calk, M_CO)
title("Momentary CO emission as a function of time");
xlabel "Time [s]"
ylabel "CO [kg/s]"

subplot(2,2,2), plot(t_calk, M_CO2)
title("Momentary CO2 emission as a function of time"); gca().sub_ticks(1) = 8;
xlabel "Time [s]"
ylabel "CO2 [kg/s]"

subplot(2,2,3), plot(t_calk, M_NOX)
title("Momentary NOx emission as a function of time"); gca().sub_ticks(2) = 8;
xlabel "Time [s]"
ylabel "NOx [kg/s]"

subplot(2,2,4), plot(t_calk, M_HC)
title("Momentary HC emission as a function of time"); gca().sub_ticks = [8 8];
xlabel "Time [s]"
ylabel "HC [kg/s]"
sda();

//Graph of the total emission of harmful compounds during the measurement
gda().grid = [1 1]*color("grey70");
title(gda(), "fontsize", 3, "color", "lightseagreen", "fontname", "helvetica bold");
scf(2); clf

subplot(2,2,1), plot(t_calk, Calk_M_CO),
title("Total CO emissions at the time of measurement");
xlabel "Time [s]"
ylabel "CO [kg]"

subplot(2,2,2), plot(t_calk, Calk_M_CO2),
title("Total CO2 emissions at the time of measurement"); gca().sub_ticks(1) = 8;
xlabel "Time [s]"
ylabel "CO2 [kg]"

subplot(2,2,3), plot(t_calk, Calk_M_NOX),
title("Total NOx emissions at the time of measurement"); gca().sub_ticks(2) = 8;
xlabel "Time [s]"
ylabel "NOx [kg]"

subplot(2,2,4), plot(t_calk, Calk_M_HC),
title("Total HC emissions at the time of measurement"); gca().sub_ticks = [8 8];
xlabel "Time [s]"
ylabel "HC [kg]"

//Graph of the emission of harmful compounds in the aspect of engine load value
gda().grid = [1 1]*color("grey70");
title(gda(), "fontsize", 3, "color", "lightseagreen", "fontname", "helvetica bold");
scf(3); clf

subplot(2,2,1), plot(W_0, M_CO),
title("Total CO emissions at the time of measurement");
xlabel "Engine load [-]"
ylabel "CO [kg/s]"

subplot(2,2,2), plot(W_0, M_CO2),
title("Total CO2 emissions at the time of measurement"); gca().sub_ticks(1) = 8;
```

Fig.8. Further part of the program, written in the SciLab environment, is designed to analyze the level of emission of harmful compounds during the examination of the object.

Figure 9 shows the momentary emissions of individual compounds emitted during the operation of the LM2500 1A combustion engine. The engine in the simulation presented in Figure 9, Figure 10 and Figure 11 worked as follows - from the level of 1,000 kW of generated power, it increased it by 100 kW every second until reaching the maximum power of 24,608 kW. This power was maintained for 13 seconds, after which it began to drop by 500 kW every second. The whole considered movement lasted 307 seconds, the increase of power took place for 238 seconds, and after 13 seconds of stability, it decreased for the next 56 seconds. The presented graphs show that with the increase of the power generated by the engine, and thus the load, the CO_2, NO_x and HC emissions increase, while the CO emission decreases significantly.

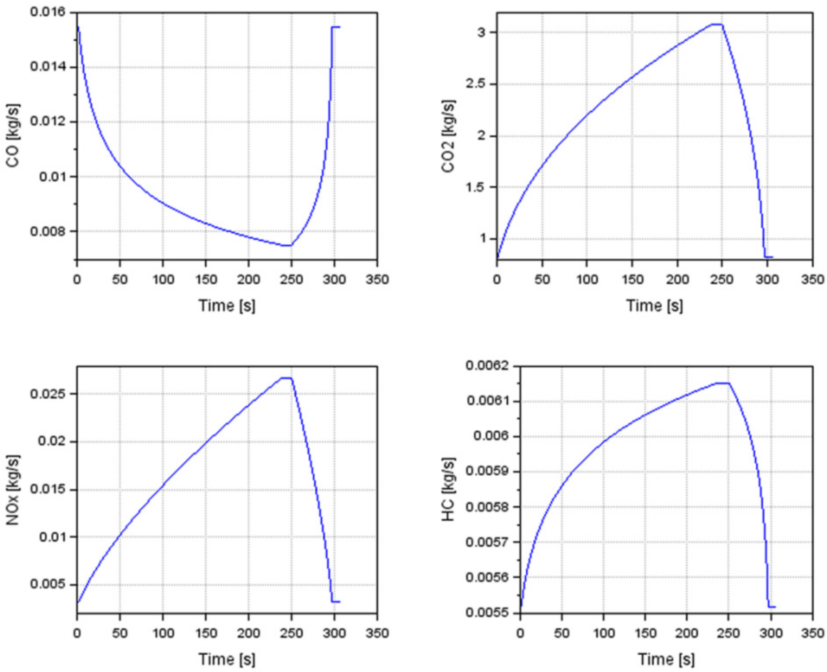

Fig. 9. Momentary emission of harmful compounds depending on the duration of operation of the considered object.

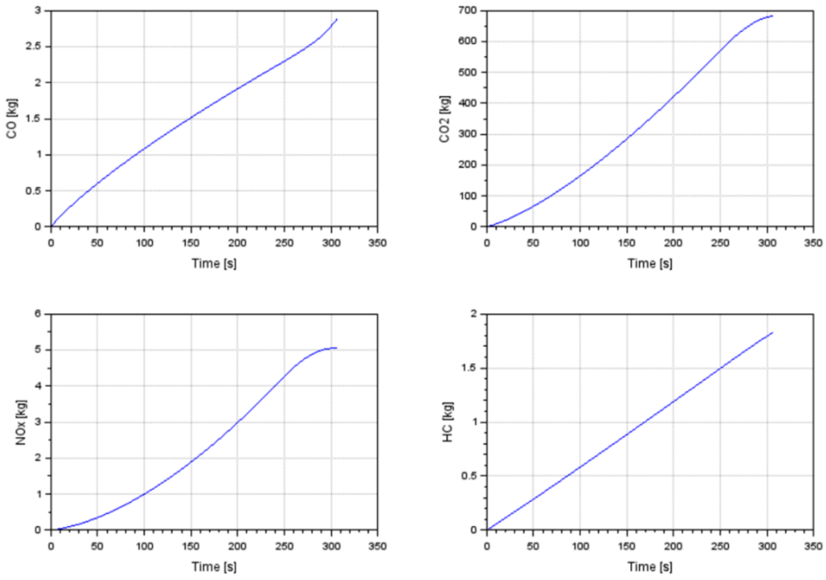

Fig. 10. Total emission of harmful compounds depending on the duration of operation of the considered object.

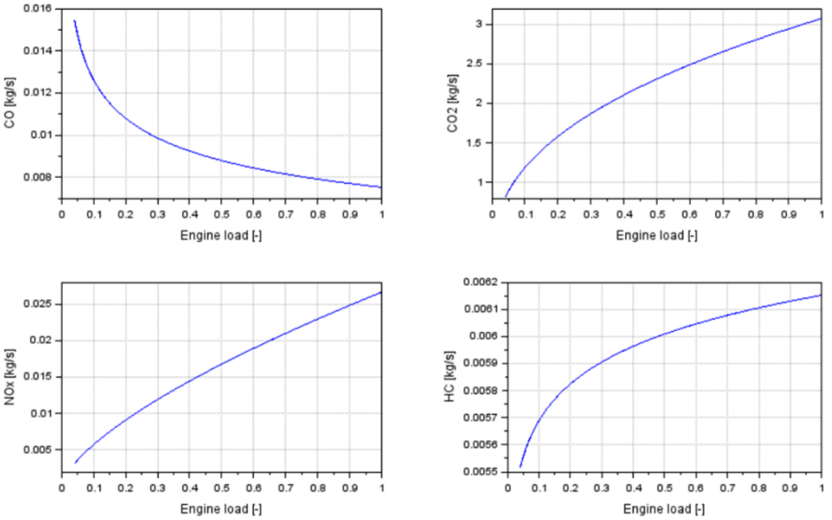

Fig. 11. Momentary emission of harmful compounds depending on the engine load factor of the considered object.

4 Conclusions

The developed method of assessing the ecological parameters of the propulsion system of warships is conditioned by the characteristics of the emission parameters of such vessels. These characteristics must be determined first, as they, together with all components of the propulsion systems, constitute the ecological assessment of the warship as an exploited object. Continuous measurement of several basic operating parameters, along with their relation to the emission characteristics of the particular vessel, allows for a quick determination of the current emissions of pollutants. Additionally, the use of algorithms implemented in numerical tools enables a quick assessment of the impact of the warship on the environment. The proposed tool allows for a continuous evaluation of emissions, which, combined with constant monitoring of operating parameters, can be used to optimize the usage conditions of warships and consequently contribute to reducing CO_2 emissions into the atmosphere. However, it should be mentioned, that the numerical model was developed on the basis of designated trend lines, which describe the phenomenon to which they refer with some approximation. The measure of the credibility of the trend line is the R^2 coefficient. The closer its value is to 1, the better the trend line is suited to the described phenomenon. For this reason, the mathematical model is only an approximation of the real object.

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