Initial tests of emissions of harmful compounds in the exhaust of a marine gas turbine engine in operating conditions

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Abstract. The paper presents the plan and results of tests of emission of harmful compounds in the exhaust of a gas turbine engine. The aim of the research is to determine the relationship between the engine operation parameters and the emission level of harmful exhaust gas compounds. An analysis was also made of the possibility of measuring concentrations of harmful compounds in the exhaust of a marine gas turbine engine of a propulsion system in conditions of its operation on a vessel. The results of preliminary tests of emissions of harmful exhaust gases from the laboratory gas turbine engine were presented. Test results of harmful compounds emission from a marine gas turbine engine will allow to determine the specific emission of individual compounds. Thus, it will be possible to deduce further steps to reduce the amount of emissions of harmful exhaust gases to the environment of this type and the use of an internal combustion engine.

1. Introduction

Energy requirements of maritime transport arising from their operational needs related to the function of the movement of the vessel and their existential functions has long been carried out by using mainly combustion-ignition piston engines.

In the case of gas turbine engines, depending on the destination of the vessel and energy needs, power units and marine power plant with steam turbines are used in cases where nuclear power plants and systems with the so-called gas turbines in the form of gas turbine engines are used.

As a result of smaller energy efficiency and the resulting higher fuel consumption, gas turbine engines for marine use are being replaced by piston engines and represent only a few percent share in the total population of marine combustion-ignition engines. However, gas turbine engines have one significant advantage - they are characterized by a high concentration of power expressed as a ratio obtained under the terms of the weight of the engine. In comparison, the vessels power must take into account not only the weight but the mass of the entire engine propulsion unit, since the use of the gas turbine engine requires the use of additional reduction of gear rotational speed of the motor drive shaft to the desired speed of the vessel propulsion. The list compares power, economic and technical parameters conducted for piston and gas turbine engines used for main propulsion and the validity of the use of gas turbine engines for propulsion of warships is achieved.
In connection with a significant quantitative predominance of marine combustion-ignition piston engines of the vessel's gas turbine engines, legal regulations concerning the emission of harmful exhaust gases of marine engines are mainly with regard to piston engines (table 1). One of these acts is the International Convention for the Prevention of Pollution from Ships of 1973, Signed in London on 2 November 1973 as amended by the Protocol compiled in London on 17 February 1978 (Journal of Laws of 1987 No 17, item 101) and by the Protocol done at London on 26 September 1997 (Journal of Laws of 2000 No 202, item 1679), hereinafter known as the „MARPOL Convention”.

All engines used on warships are exempt from compliance with standards of emission of harmful exhaust gases. It should be noted that the percentage of the population of gas turbine engines installed on warships is several times higher in comparison to the civil fleet. However, governments with warship fleets seek to implement the provisions relating to the protection of the marine environment (e.g. MARPOL) on warships as far as it is possible.

| Emission level | Year of validity | NO\(_x\) emission limits \([\text{g} (\text{kW} \cdot \text{h})^{-1}]\) depending on the nominal engine speed \(n\) [rpm] |
|----------------|------------------|------------------------------------------------------------------------------------------------------------------|
|                |                  | Low Speed Engine \(n < 130\) | Medium Speed Engine \(n \leq 130 < 2000\) | High Speed Engine \(n \geq 2000\) |
| I              | 2000             | 17.0 \(a\)                     | 45.0 \(n^{0.2} \) \(a\)                     | 9.8 \(a\)                        |
| II             | 2011             | 14.4 \(b\)                     | 44.0 \(n^{0.23} \) \(b\)                     | 7.7 \(b\)                        |
| III            | 2016             | 3.4 \(c\)                      | 9.0 \(n^{0.2} \) \(c\)                      | 2.0 \(c\)                        |
|                |                  | \(a\) these values apply to vessels built or those that have undergone modernization after 1 January, 2000 and before 1 January, 2011, |
|                |                  | \(b\) these values apply to any vessel built after 1 January, 2011, |
|                |                  | \(c\) these values apply to any vessel built after 1 January, 2016 and sailing in the North American Emission Control Area or Area in the Caribbean Sea of the United States. |

Ever increasing emission of exhaust gases from marine engines implemented have necessitated the development of new construction concepts of marine power plant of civilian ships and warships. Increasingly, it contemplates the use of gas turbine engines in marine power plant focused on the production of electricity used by electric motors vessel propulsions. In the case of gas turbine engines, the disadvantage is lower efficiency of electricity generation, as evidenced by the high value of the specific fuel consumption (figure 1), but the important advantage is the high concentration of generated energy in the unit occupied by the combustion power system volume. The advantage of using gas turbine systems is the ability to supply these motors with so-called light fuels with low sulphur compounds, alternate fuels such as vegetable oil esters, methanol, ethanol, methane and gaseous fuels such as natural gas and propane-butane.

![Figure 1. a) specific fuel consumption (SFC) and b) NO\(_x\) emission - as a function of the power used for the propulsion types of compression-ignition and gas turbine engines [15]](image-url)
The concepts of using gas turbine engines are associated with the necessity of accepting higher specific fuel consumption resulting from lower engine efficiency, but also to contribute to obtaining the improvement of ecological indicators in the form of lower emission of harmful exhaust gases. Assessment of the real benefits of using gas turbine engines for marine propulsion, obtained under the operating and environmental parameters requires a number of studies and analyses, some of which are presented in this article.

2. Emission of harmful compounds in the exhaust of gas turbine engines
The emission of harmful compounds in the engine's exhaust is related to the combustion process, the conditions of engine operation and the fuel it is supplied with [9,10,11].

The gas turbine engine is characterized by a high power to weight ratio and is therefore widely used as a propulsion for an aircraft. This advantage also lead engineers to use these engines to propel boats - mainly on warships. The number of marine vessels powered by gas turbine engines is small in relation to the number of aircraft. The reason for this is the estimation of the importance of the criterion of engine mass to the achieved operating parameters, i.e. engine power, fuel consumption, fuel quality, general efficiency, complexity of operating systems, the need for reduction gearing due to the engine speed achieved in comparison to marine piston engines. Currently, an additional criterion for assessing the applicability of given propulsion systems is the emission of pollutants into the atmosphere, which has certain advantages in using a gas turbine engine [2]. These benefits result from a different process of fuel combustion in the engine, another type of fuel used to drive the engine and the energy demand of the vessel.

2.1. Initial tests of emissions of harmful compounds in the exhaust of a gas turbine engine
Initial tests of emission of harmful compounds in the exhaust gases were carried out on a laboratory station of a GTD-350 type turbine engine (figure 2) at the Institute of Ship Construction and Operation of Polish Naval Academy. It is a two-rotor engine with a separate drive turbine, with an unusual design solution consisting in placing the combustion chamber behind the turbines located immediately after the compressor. The effect of such a solution is to shorten the rotor shafts and allow them to achieve high rotational speeds, thus reducing the engine mass. In this way, the unit mass of the engine is reduced and the economy of its work is increased [3]. Diagram of the station is shown in figure 3.

Figure 2. View of the laboratory station with GTD-350 engine
The measurements were carried out for the engine load range from 10 to 80 kW, whereas the rotating speed of the rotors of the gas generator ($n_{WS}$) and the power turbine ($n_{TN}$) was assumed as the parameters determining the measurement points. These parameters were obtained by appropriate changes in the fuel stream supplying the engine ($m_{\text{fuel}}$) and changes in the brake load, i.e. the force ($F$) generated on it, which is a function of the water stream supplied to the brake. The tests were carried out in such a way that first the desired speed values were set, and after obtaining the determined operating parameters, the recording of the engine operation parameters and the parameters of the exhaust took place. The measurement time was 60 seconds with the frequency of 10 Hz recording for the engine operating parameters and 1 Hz for the exhaust parameters. The obtained values of the measured parameters were analysed.

During the tests carried out for the assumed values of rotational speeds of the engine's rotors, and hence the specific engine load, measurements were made, among others hourly fuel consumption ($G_e$), stream of air mass ($m_{\text{air}}$) flowing into the engine and oxygen concentration ($c_{O2}$) in the exhaust gases, on the basis of which the value of the excess air coefficient ($\lambda$), resulting from the conditions of the combustion process, was determined. The concentrations of harmful compounds in the exhaust gases, were also measured, the values of which depend strictly on the course of the combustion process carried out in the combustion chamber of the engine. These concentrations are also related to the engine load. For the obtained distributions of concentration values, the equations of the trend line in the form of the second degree polynomial equation were determined, which in most cases describe with high correspondence the occurring relationships between values of oxygen and harmful compounds concentration and GDT-350 engine power. The changes of concentrations of harmful compounds are presented in figure 4.

### 2.2. Analysis of the dependence of selected exhaust parameters

The determined concentration characteristics of individual harmful compounds as functions of the engine power, supplemented with the value of fuel consumption and the excess air coefficient were used to determine the instantaneous emission values of pollutants contained in the exhaust of the gas turbine engine.

In the case of using exhaust gas analysers that do not have the option of directly measuring the excess air coefficient, this coefficient is determined on the basis of the concentration of oxygen, nitrogen and carbon monoxide in the exhaust gas. Determining the value of the excess air coefficient is necessary to determine the exhaust mass flow. The functional dependence of the excess air coefficient and hourly
fuel consumption on the engine load and the known theoretical air demand, the exhaust mass flow is obtained as a function of the engine power

\[ m_{ex\lambda}(P) = G_e(P) \cdot [1 + \lambda(P) \cdot 14.95] \quad [kg \cdot h^{-1}] \quad (1) \]

where:
- \( G_e \) – hourly fuel consumption [kg\cdot h^{-1}],
- \( \lambda \) – excess air coefficient [-], directly measured or designated on the basis of the exhaust gas composition,
- \( P \) – engine power [kW].

Using the functional relationships of changes in the concentration of harmful exhaust gases relative to the load, a functional dependence of the mass emission intensity of a particular harmful compound can be proposed as a function of the engine load

\[ \dot{E}_i(P) = m_{ex\lambda}(P) \cdot g_i(P) \quad [kg \cdot h^{-1}] \quad (2) \]

where:
- \( m_{ex\lambda}(P) \) – exhaust mass flow as a function of engine load [kg\cdot h^{-1}],
- \( g_i(P) \) – mass share of the i-th exhaust component as a function of engine power [-].
Knowledge of the mass emission intensity value of harmful exhaust gas compounds for a determined engine load allows determining the specific emission of individual compounds depending on the engine power

\[ e_i(P) = \frac{\dot{e}(P)}{P_e} \left[ kg \cdot (kW \cdot h)^{-1} \right] \]  

(3)

where:

- \( P_e \) – useful power of the engine [kW].

**Figure 5.** Change in the specific of harmful emission of a GTD-350 engine as a function of engine power

One of the most harmful compounds found in the exhaust gases are nitrogen oxides (NO\(_x\)). With increasing demand for engine power, the combustion temperature increases, which also increases the concentration of NO\(_x\) in the exhaust gases.

Carbon monoxide (CO) is another harmful exhaust component. As the engine power increases, the CO concentration decreases. Carbon monoxide (CO) is an incomplete combustion product, and thus, when there is a shortage of air for fuel combustion, its formation takes place. Therefore, with the increase in the engine power carbon monoxide (CO) will be reduced. At higher temperatures, carbon monoxide (CO) will already be oxidized to carbon dioxide (CO\(_2\)).

3. **Preparation for testing the emissions of harmful compounds exhaust gases from marine gas turbine engines**

The authors therefore undertake to try to determine the emission of harmful exhaust gases, in marine gas turbine engine, used in the drive system of guided missile frigate class of warship (figure 6). The propulsion system unit consists of a power unit equipped with two gas turbine engines from General Electric LM 2500 (figure 7), a cumulative drive reduction gear ratio of 1/20, one line shaft and adjusting screw. The power of the drive is about 30 000 kW at a maximum turbine propulsion speed of 3600 rpm.

Gas turbine engines used in the propulsion system of frigates consist of two rotor units. The basis of engine design is the exhaust gas generator in which the sixteen-stage axial compressor is driven by a two-stage high-pressure turbine. The first six stages of the compressor are equipped with an adjustable steering blades operating in the range of the –30\(^\circ\) to +30\(^\circ\) angular position with an accuracy of 10\(^\circ\). Setting the steering is dependent on the pressure of fuel supplied to the injectors, the rotor speed of the gas
generator and the air temperature in the inlet section of the engine. This solution enables the extension of the stable operation of the compressor, especially in transition processes. The continuous combustion process takes place in an annular combustion chamber supplied with fuel through the thirty-two injectors. Six level separate turbine propulsion co-operates with the exhaust gas generator which constitutes a source of mechanical energy for the vessel propulsion system. The engine is entirely located in a casing isolating it from the rest of the power system. This solution was adopted for reasons of fire safety and for reducing noise propagation inside the power system. The exhaust system has a length of a several meter vertical channel with a diameter of two meters, ending in narrowing to a diameter of about a meter.

Figure 6. Oliver Hazard Perry class missile frigate

Figure 7. LM 2500 marine gas turbine engine

Measurements of thermal gas-dynamic parameters of the working medium made in specific sections of the engine control are an important source of diagnostic information about the state of the structure of construction part of the flow. The schematic diagram of the LM 2500 engine (figure 8) presented with marked control flow sections enables visualization of the distribution points. The measured values and calculation of individual parameters of the engine and the measurement range expressed in units of force in the power system of vessels is summarized in table 2.

Figure 8. Block diagram of LM 2500 gas turbine engine,

- S compressor
- KS combustor
- TWS gas generator turbine
- TN power turbine
- PR reduction gear
- SN propeller
- PSK space between S and KS
- PTT space between TWS and TN

The location of the turbine engine in the engine room requires the assurance of supply to the inlet of the corresponding mass flow of air and exhaust mass derivation generated from the engine exhaust. Vertical air intake channels and exhaust gas outlet channels (figure 9) of about 15 meters have been designed for Oliver Hazard Perry class missile frigate equipped with two LM 2500 turbine engines. The air from the manifold is directed mostly to the inlet of the engine. A small portion of air from the intake side channel is collected and is fed to the interior of the container assembly for the engine in order to
ensure a proper temperature around the running engine. Air flowing from the outer parts of the engine in the container housing is ultimately directed into the exhaust duct to be mixed with the gases generated by the turbine engine. Depending on the need to ensure the appropriate parameters, air flowing from the outside of the engine is suitably prepared by an appropriate temperature using the cooling system and the heaters and the flow rate of the respective container inside the housing, controlled by using a fan.

| 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 $t_i$ [°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 idea of operating an internal combustion engine is directed in order to achieve the operational performance which translates into propulsion operation. The flow of the exhaust stream generating torque of the power turbine is important for the turbine shaft which eventually results in the drive shaft
receiving power from the engine. Parameters values of exhaust gas generated by the so-called generator exhaust - part of the turbine engine - are responsible for the operating parameters obtained from the power turbine shaft. These parameters include mass flow of exhaust gases and the energy described by the temperature and the flow rate at various stages of the turbine. The resulting thermodynamic parameters of the exhaust gas as a working medium are directly dependent on the conditions in the combustion chamber, which are closely related to the operating parameters resulting from the energy requirements. Therefore, there is a relationship between the operating parameters and the conditions of the combustion process occurring in the combustion chamber and the emission of pollutants in the exhaust gas which was generated in order to obtain the required mechanical energy on the drive shaft of the motor.

According to these interdependencies, the emissions contaminants contained in the generated exhaust gases can be evaluated depending on engine load energy. For this purpose, it is necessary to specify the mass flow of generated exhaust gases as a function of engine load and concentrations of harmful compounds contained in them. It is necessary to obtain emission characteristics of the engine as a function of load. The issue is familiar and is presented in many more studies [6,8]; however, studies of high power turbine engines require an individual approach so that the issue of the assessment of gas emission from turbine engines is carried out under static conditions at a few selected points of the study and for certification purposes of the engine. In contrast, the evaluation of pollutant emissions, carried out by the authors, in the exhaust gases of the turbine engine shaft used at sea is focused on the evaluation of the operating conditions of the vessel during the voyage being undertaken.

In order to determine the characteristics of the LM 2500 engine emission, it is necessary to estimate the generated mass flow of exhaust gases. The mass flow of exhaust gases is the total flow of air and fuel supplied to the engine. Therefore, it is necessary to designate the mass flow of air and the mass flow of fuel. When available, the possible measured values of engine operating parameters LM 2500 can be troublesome. Therefore, the calculation of one of these values and measuring the excess air ratio for the engine carried out in the combustion process using a broadband oxygen sensor is a necessary condition. By knowing the ratio of the air-fuel consumption, the air or engine fuel according to which the value is obtained from the measurement can be established. Establishing the exhaust gas mass can be linked to the value of concentrations of harmful compounds, thus obtaining the emission of pollutants in the exhaust gases. In carrying out the emission characteristics of the engine as a function of load, it is necessary to obtain the dependent equation that can be used in the algorithm for determining the instantaneous emission from engine operating conditions. Examples of the emission characteristics have been developed by the authors on the basis of the GTD-350 gas turbine engine [2] and the resulting equations describe the changes of the concentration of the individual compounds as a function of load (figure 4). The distribution of received values and dependencies should be considered as an example of a distribution of received values of described equations, are a feature of its own motor. Therefore, it is necessary to determine the emission for the engine, for which assessment of emission standards in operating conditions shall be undertaken in the subsequent stage. It is necessary to relate the obtained dependencies on the operating parameters of the engine in order to make such evaluation, i.e. the engine-generated power, the speed of rotation of the shaft gas generator, the rotational speed of the power turbine shaft, rotational speed and screw settings of the ship propeller, the sailing speed of the vessel and the parameters of the course as a further step.

Summary
The analysis of the monitored operating parameters in the engine room of Oliver Hazard Perry guided missile frigate class, which is in the service of the Polish Navy, important the need for additional equipment and mathematical algorithms to determine the level of performance necessary to assess pollutant exhaust gas generated by the turbine engine shaft of the main drive. This evaluation requires earlier studies related to obtaining emission characteristics of the engine for all of its operations. However, the supplemented characteristics of the algorithm determine the mass flow of exhaust gases and allow it to derive the emission of harmful compounds in the operating conditions of the vessel.
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