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EVALUATION OF RELATIONS OPERATING AND ECOLOGICAL PARAMETERS OF TURBINE ENGINES

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Abstract

The article concerns the evaluation of exhaust emissions from turbine engines. The results of the work are associated with development of analytical methods useful in estimating the emissions of harmful exhaust gases during turbine engine operating conditions. The results of studies and the interdependence between emission indicators and operating parameters were pointed out. The analysis of these interdependence shows a strong similarity in the nature of changes of particular relationship in relation to the engines tested, but also shows their individuality. The article shows the direction of further work to develop methods of assessment the emissions from turbine engines during their operation. The methods developed for the analysis of ecological parameters during operation of turbine engines may be useful to implement in models of assessing pollutant emissions from maritime transport and to analyze and evaluate the impact of transport on the environment. This assessment may be important to consider, with regards to meeting the newly introduced emission standards, in accordance with the MARPOL directive, which has been in force since January of 2015.

Keywords: exhaust emissions, engine turbine, ecological parameters, operating parameters

1. Introduction

A turbine engine is characterized by its high power to weight coefficient, and is therefore widely used as a propulsion for aircraft. This advantage also lead engineers to use such engines for marine propulsion – mainly in warships. The number of sea vessels powered by turbine engines is small compared to the number of aircrafts. The reason for this is the calculation of criterion validity of engine weight to achieved operating parameters: power output, fuel consumption, fuel quality, general efficiency, and the complexity of operating systems, transmission, and engine speeds compared to marine diesel piston engines. At the moment an additional criterion for assessing the applicability of drive systems is the emission of pollutants into the atmosphere, which shows some benefits in using a turbine engine [3, 4, 5, 6]. These benefits arise from a different process of fuel combustion in the engine, other type of fuel used to power the engine, and the type of energy and the energy demand of the watercraft.

Operation of most water vessels is characterized by established work parameters of the drive system and the motor. Development of time density characteristics of operating parameters and determining of the environmental performance characteristics in the engine operating range will allow for the assessment of the ecology of the drive system in that operating range. The correlation of operating parameters of the drive with the concentration content of harmful substances in the exhaust gases is important for work in this field. Of particular importance in this work is the methodology of measuring pollutant emissions. The problem with implementation of the measurement of the concentration of harmful substances in the exhaust gases for turbine engines lies with the exhaust gas sampling methods [7]. The exhaust gas discharged from the engine is characterized by a high flow velocity and a large mass of flowing exhaust gas. Therefore, it becomes necessary to use methods of analytical assessment for the emission measurement, with the use of selected operating and ecological parameters. The knowledge of mutual correlation of selected parameters is useful when using this method.

2. Measurement methodology of environmental parameters

2.1. Research of GTM 120 turbine jet engine

The methodology of measuring emissions from gas turbine engines involves measuring the concentration of impurities contained in the sample retrieved from the stream of exhaust gases flowing through a special probe. The provisions of ICAO – Annex 16 [8] does not define the physical parameters of the probe, but does define the general guidelines. The probe in contact with the sample exhaust gas must be made of stainless steel or other non-reacting material. If a multi-hole probe is used, all holes must be of the same diameter. The probe design must be such that at least 80% of the pressure acting on the probe was drawn in through the holes. The number of fume sampling sites cannot be less than 12. The plane of sampling must be located as close to the plane of the engine exhaust, as allowed by the engine performance but in any case it must be at a distance of less than 0.5 of the nozzle diameter. The legislation includes the requirement to prove to the certifying authorities that the proposed design of the probe and its placement helps ensure obtaining a representative sample for each specific engine thrust settings.

Using a multi-hole probe for measuring the engine exhaust emissions results in obtaining an average exhaust sample. Averaging the collected gas sample is related to the fact that with increasing distance from the axis of the gas stream leaving the exhaust the concentration of exhaust gas components is reduced. This effect depends on the type of construction of the engine, including the method for cooling and separation of engine components from the hot gas as well as the associated turbulence in the stream of exhaust gases. The exhaust gas sampled by the probe's several holes with different concentrations of impurities is mixed together, which in turn leads to the averaged value of the concentration of pollutants in the exhaust gas [1, 2]. Therefore, it is desirable to measure the concentration of pollutants in the exhaust gas in an area where the gases are not mixed with the air cooling engine parts, or the air captured by the swirling stream leaving the exhaust gas. Using such a measurement the actual composition of the exhaust gases can be estimated, and using additional information – the mass of flowing exhaust and hourly emissions of pollutants contained in it can be determined.

The concept of the internal combustion engine operation is aimed at obtaining operating parameters that translate into propulsion. For turbine jet engines the flow of the exhaust stream is essential to generating thrust. According to the basic equation defining thrust, the mass and velocity of the exhaust gas flow is important. These indicators relate to operating parameters such as air intake and fuel consumption, which translate into the total mass of the exhaust gas generated by the engine (Fig. 1). Knowing the instantaneous value of the fuel consumption and measuring the chemical composition of the exhaust gases, to enable determination of the instantaneous value of the air-fuel ratio λ, the air mass fed to the engine in time can be estimated.

The sum of fuel consumption and air intake corresponds to the flow of exhaust gas generated:

$$\dot{m}_{air} + \dot{m}_{f} = \dot{m}_{exh}\,, \tag{1}$$

where:

$\dot{m}_{air}$ – air mass flow,

$\dot{m}_{f}$ – fuel mass flow,

$\dot{m}_{exh}$ – exhaust gas mass flow.

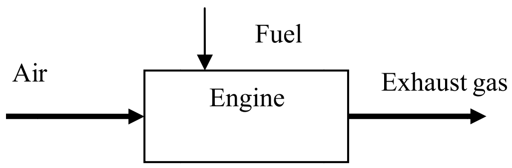

Fig. 1. Diagram of the input and output of a turbine jet engine

Assuming that it is possible to measure two of these three values, the third value can be calculated. Therefore, a study was conducted with the aim of measuring the fuel consumption and the size of the stream of exhaust emitted and simultaneously measuring the concentrations of harmful exhaust compounds and air-fuel ratio λ. The study was conducted on a prepared workbench (Fig. 2), which included a small turbine engine, turbojet GTM 120.

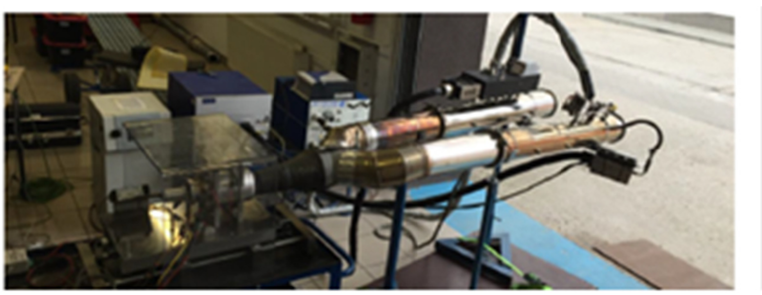

Fig. 2. Workbench equipped with the GTM 120 jet engine

The engine was supplied with fuel from the integrated power module comprising of an ATMX 2040 measurement device. Exhaust flow measurements were carried out using a system consisting of two exhaust gas flow meters having a flow diameter of 125 mm. The use of two exhaust gas flow meters was justified by the need to separate the flue gas stream and reduce the flow rate adjusting it to the flow measuring range of the device. Reducing the flow rate of the exhaust gas streams is achieved through an increase in flow cross-sectional area. Measurements of the gas flow rate, the concentration of harmful exhaust components, and the values of air-fuel ratio λ, were made using Semtech exhaust gas analyzer of Sensors Inc. Measurements were carried out for specified engine thrust values of 10 N to 120 N with increments of 10 N. The tests were performed in such a manner that the setting of the thrust value was done first, during this time the exhaust gas separation system with the exhaust gas flowmeters was moved away from the outlet nozzle of the engine. After the appropriate value of thrust was reached the flue gas separation system together with the measuring system was moved closer to the discharge nozzle. The time of the exhaust flow measurement and measurement of concentrations of pollutants for a single thrust value was dependent on stabilization of the temperature of the measurement system and ranged from a dozen to several dozen seconds. The resulting values of the measured parameters were analyzed.

2.2. Research of GTD 350 turboshaft engine

A similar methodology was adopted during the tests of the GTD 350 engine. This is a turboshaft engine, which is mounted on the workbench (Fig. 3) and connected with a drive shaft to the brake, which loads the engine. The measurements of operating parameters of the engine such as: the fuel consumption, the rotational speed of exhaust gas generator shaft and the rotational speed of the turbine shaft of the drive, at the load setting of 600 N·m, which was in line with the operational capabilities of the brake.

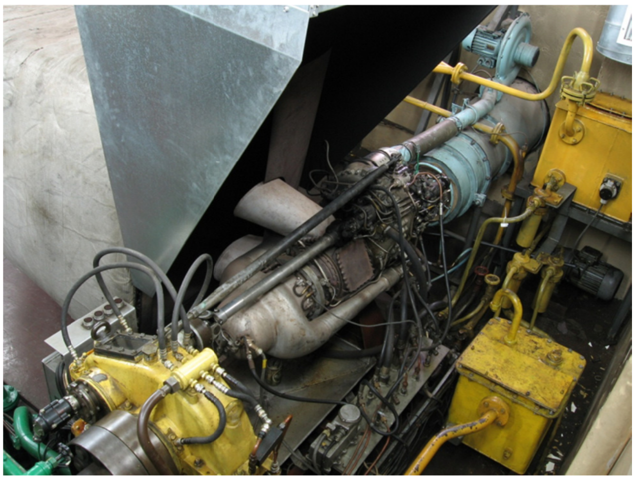

Fig. 3. Workbench equipped with the GTD 350 engine

In the conditions of set operating parameters, corresponding to the individual measurement points, the exhaust concentration measurements were done for O_2, as well as the concentration of harmful substances: CO, NO_x and CO_2. Exhaust emission measurements were performed using the TESTO 350 analyzer.

3. Measurement results for environmental parameters

3.1. Test results for GTM 120 engine

During tests performed for set values of thrust F, values of engine operating parameters were obtained. The hourly fuel consumption $\dot{m}_f$, the air-fuel ratio λ resulting from the combustion conditions, and flue gas mass streams flowing through the flowmeters $\dot{m}_{exh}$ 1 and 2 were measured. The total exhaust mass flow was also determined as the sum of the two exhaust gas streams as registered by the two flowmeters.

In accordance with the target set in the article, attempts to estimate the value of the exhaust stream were carried out based on the measured values of hourly fuel consumption (Fig. 4), and the air-fuel ratio (Fig. 5) during combustion, as determined based on the composition of the exhaust gases. Given that total and complete burning of one kilogram of fuel requires around 14.2 kg of air, the following relationship can be established:

$$\dot{m}_{exh} = \dot{m}_f \cdot (1 + \lambda \cdot 14.2) \quad \left[\frac{\text{kg}}{\text{h}}\right], \tag{2}$$

Using this dependence the exhaust gas mass flow values were obtained. The results derived on the basis of calculations were compared to the values of exhaust gas mass flow obtained during measurements (Fig. 6). The comparison was made by calculating the percentage difference in the value relative to the measurement results for each value of thrust. A comparison of the exhaust gas mass flow values obtained during the performed tests with the values derived on the basis of calculations, indicates that the calculated values of exhaust gas streams are similar to values obtained from measurements. A characteristic feature of the tested engine is an almost linear relation of the exhaust mass flow as a function of thrust, which is closely related to the values of fuel consumption.

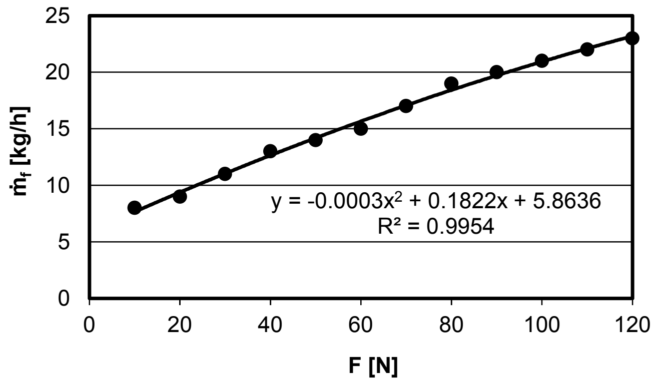

Fig. 4. The values of hourly fuel consumption as a function of engine thrust for GTM 120

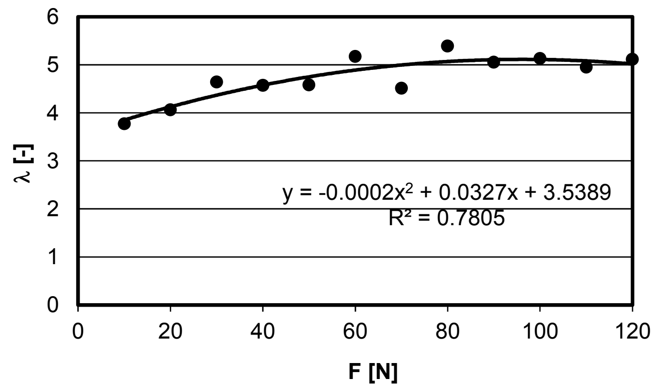

Fig. 5. The values of the air-fuel ratio in the exhaust gas as a function of engine thrust for GTM 120

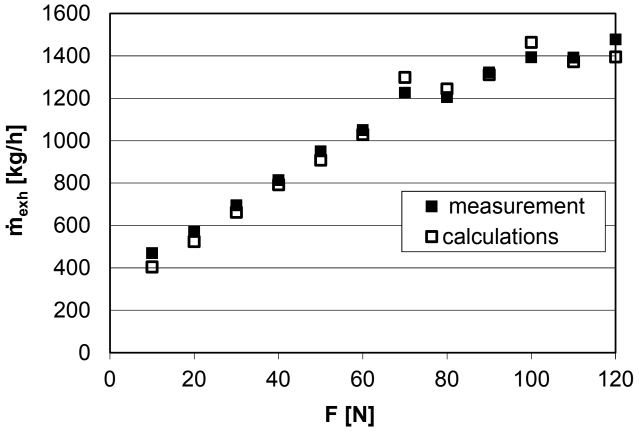

Fig. 6. Comparison of the measured and calculated engine exhaust mass flow for GTM 120

The levels of toxic compounds in the exhaust gases (Fig. 7–10) were measured during the study. The concentration of toxic compounds in the exhaust gases is highly dependent on the combustion process in the combustion chamber of the turbine engine, which depends on the engine load or the need for a specific thrust. For the obtained emission results the trend lines in the form of second degree polynomial equations have been drawn, which accurately describe the relation between the values of concentrations of harmful compounds and the GTM 120 engine thrust.

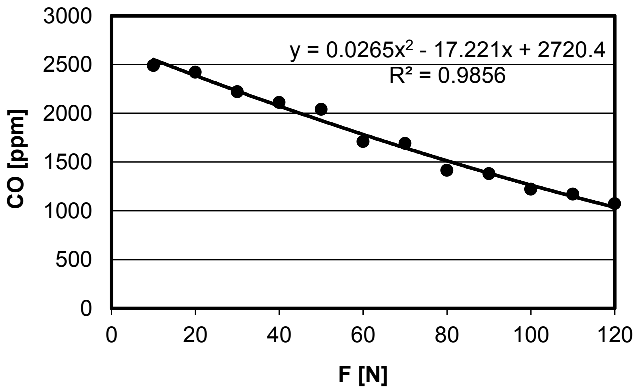

Fig. 7. Values for concentration of carbon monoxide in the exhaust gas as a function of engine thrust for GTM 120

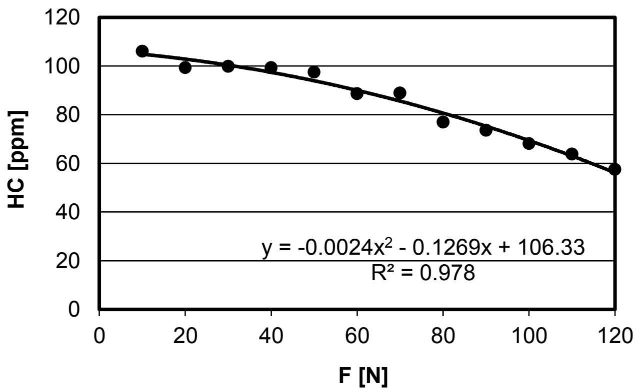

Fig. 8. Values for concentration of hydrocarbons in the exhaust gas as a function of engine thrust for GTM 120

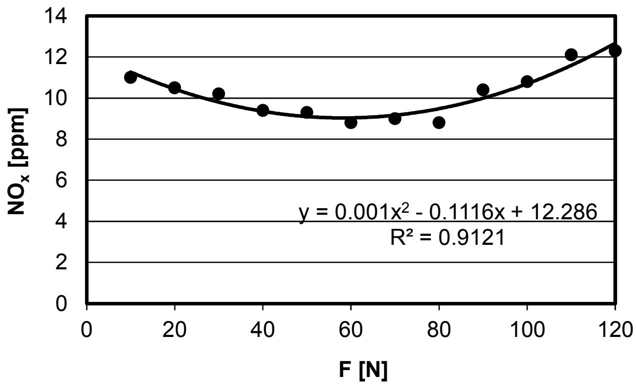

Fig. 9. Values for concentration of nitrogen oxides in the exhaust gas as a function of engine thrust for GTM 120

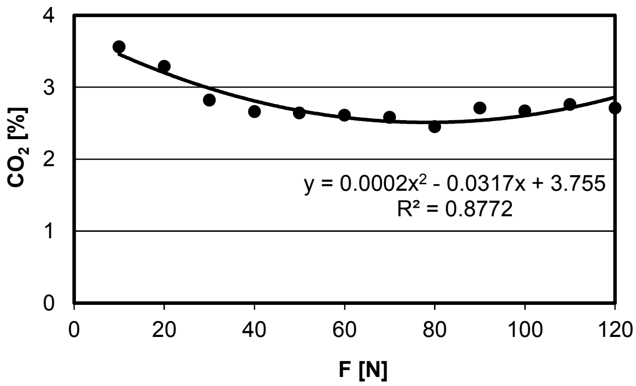

Fig. 10. Values for concentration of carbon dioxide in the exhaust gas as a function of engine thrust for GTM 120

3.2. Test results for GTD 350 engine

Similar studies were carried out for the GTD 350 turboshaft engine, which led to the values of the measured parameters as a function of load in the form of torque at the output of the engine transmission and power generated by the engine. Hourly fuel consumption (Fig. 11), the concentration of toxic compounds in the exhaust gases (Fig. 12–14), and the oxygen concentration (Fig. 15) were measured. As before, trend lines described by second degree polynomial equations were determined for the obtained distribution values.

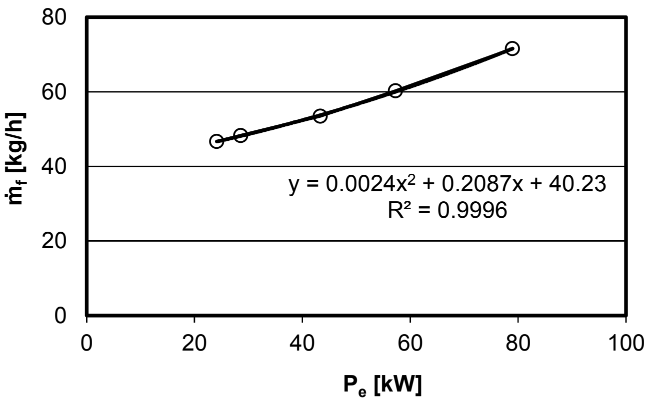

Fig. 11. The values of hourly fuel consumption as a function of engine power output for GTD 350

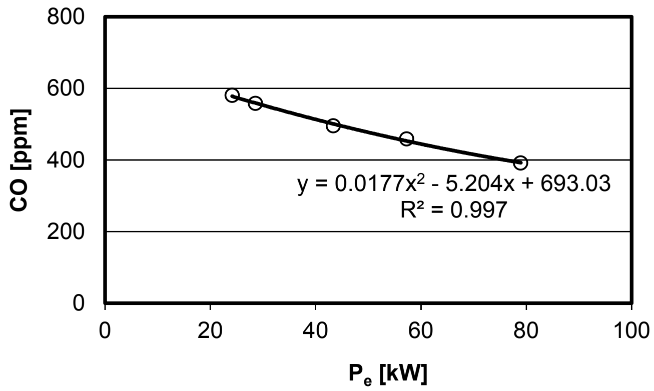

Fig. 12. Values for concentration of carbon monoxide in the exhaust gas as a function of engine power output for GTD 350

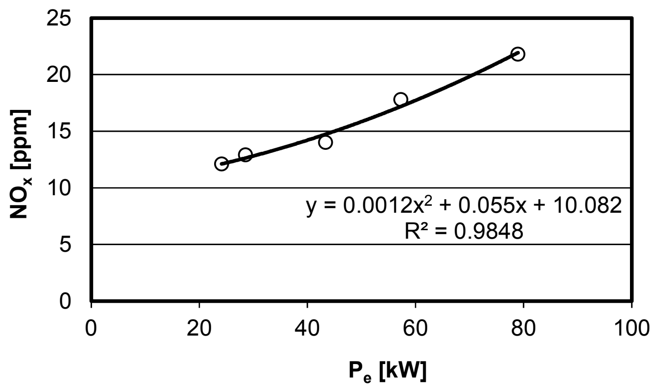

Fig. 13. Values for concentration of nitrogen oxides in the exhaust gas as a function of engine power output for GTD 350

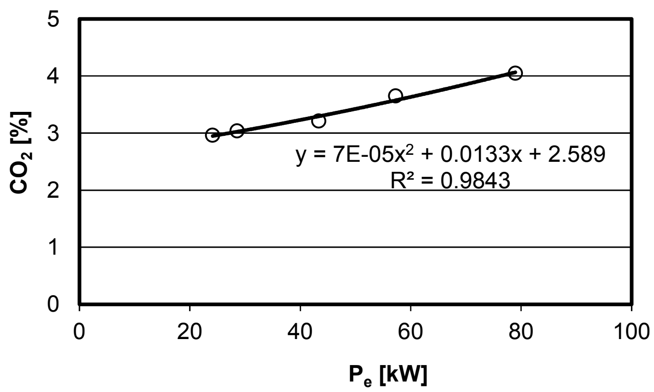

Fig. 14. Values for concentration of carbon dioxide in the exhaust gas as a function of engine power output for GTD 350

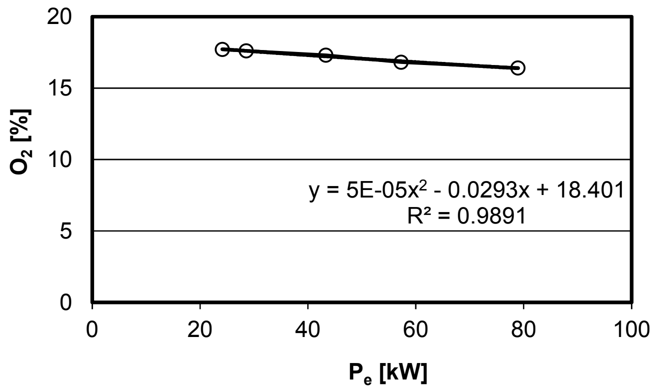

Fig. 15. Values for concentration of oxygen in the exhaust gas as a function of engine power output for GTD 350

4. Analysis of the test results

Knowing the characteristics of the concentration of individual compounds as a function of thrust, or the load of the engine and the equation that relates them, and by adding to that the information on fuel consumption and air-fuel ratio or oxygen concentration, one could estimate the instantaneous value of the turbine engine emissions in actual operating conditions. It should be emphasized, however, that knowing the value of air-fuel ratio or oxygen concentration in the exhaust gas is essential. An overall evaluation of the combustion parameters may be performed on the basis of the air-fuel ratio contained in the exhaust gas or on the basis of the oxygen concentration in the exhaust gas (Fig. 16). This is confirmed by the interdependence between these parameters (Fig. 17). Their relation can be described with a trend line with a high coefficient of determination $R^2 = 0.95$. The resulting function can be used to evaluate the air-fuel ratio in the exhaust gas based on the measured value of the oxygen concentration. This analysis can be used when the exhaust gas analyzer of the gas composition does not have the option to measure the air-fuel ratio but does measure the oxygen concentration of the exhaust has.

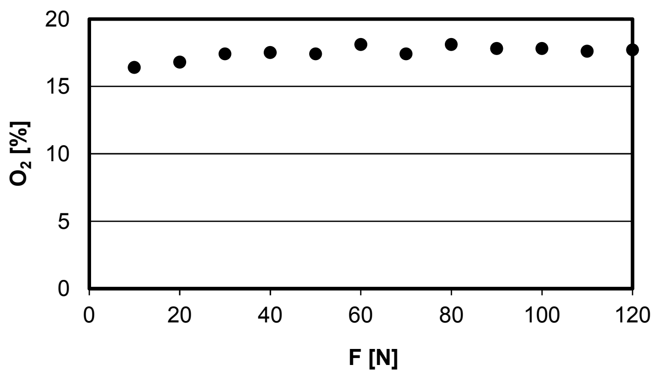

Fig. 16. Values for concentration of oxygen in the exhaust gas as a function of engine thrust for GTM 120

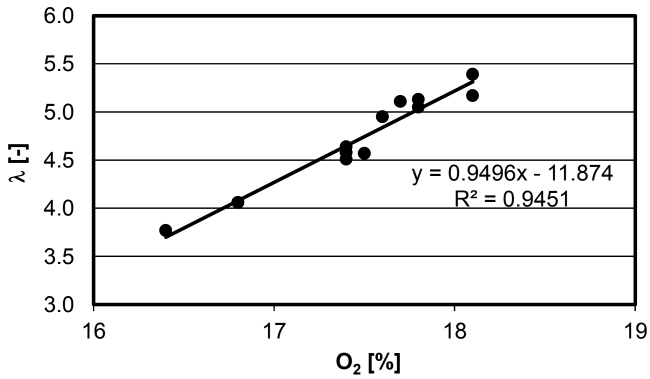

Fig. 17. Values of air-fuel ratio as a function of oxygen concentration in the exhaust gas stream of the GTM 120

The resulting relation of the air-fuel ratio as a function of the concentration of oxygen in the exhaust gas of a turbine engine was revised and verified for a greater number of measurement points (Fig. 18) and the results confirm that relation.

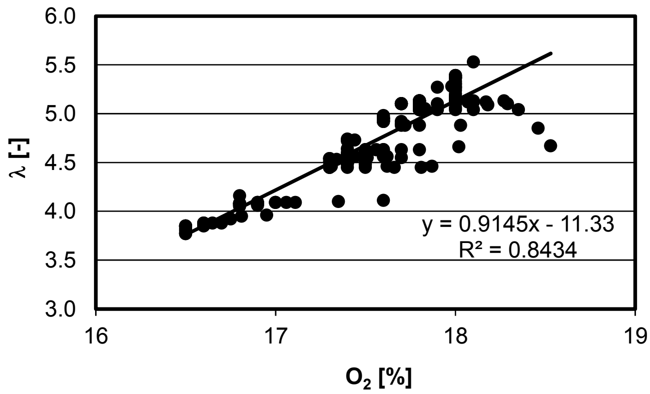

Fig. 18. The relation of the value of the air-fuel ratio as a function of oxygen concentration in the exhaust gas of a turbine engine

Finding of the value of air-fuel is necessary to determine the exhaust gas mass flow in accordance with the earlier equation (2). Complementing that equation with the functional relation of the air-fuel ratio and engine load, the mass flow of exhaust gas is obtained as a function of load (3). Similarly using functional relation changes, of the concentration of harmful substances in relation to the load, a relation of the emission of the compound as a function of thrust and engine load can be established (4).

$$\dot{m}_{exh}(F) = \dot{m}_f \cdot (1 + \lambda(F) \cdot 14.2) \quad \left[\frac{\text{kg}}{\text{h}}\right], \tag{3}$$

$$E_i(F) = a_i \cdot \dot{m}_{exh}(F) \cdot c_i(F) \quad \left[\frac{\text{g}}{\text{h}}\right], \tag{4}$$

where:
a_i – emission factor of the i-th compound,
E_i – emission of the i-th compound,
c_i – concentration of the i-th compound in the exhaust gas,
F – engine thrust or load.

When the measurement results of the oxygen concentration in the exhaust are available and the functional relation of changes in oxygen concentration as a function of load is known, the relation (3) takes the form (5), in which the value of lambda is a functional relation of the oxygen concentration $\lambda(F) = f(c_{O_2}(F))$.

$$\dot{m}_{exh}(F) = \dot{m}_f \cdot \left(1 + f\left(c_{O_2}(F)\right) \cdot 14.2\right) \quad \left[\frac{\text{kg}}{\text{h}}\right], \tag{5}$$

Introducing the exhaust gas mass flow equation (5), which is a function dependent on the engine load including the functional character of individual elements of the equation, to equation (4), values of emission of pollutants by the turbine engine at different operating points (Fig. 19) were determined. The emission values of the individual harmful compounds obtained through estimation are characterized by a similar distribution as the values obtained from the measurements. Relative differences in most operating points reach up to 15% (Fig. 20). The exception is the emission corresponding to the operating point with the engine thrust of 80 N, where the percentage differences of the results obtained through estimates are largest at around 25–35%. This situation could indicate possible measurement inaccuracies during testing at this operating point. The percentage comparisons of the results of estimating emissions based on the existing relations to the results obtained in experimental research indicates the possibility of using a simplified method for estimating exhaust emissions based on the known set of concentrations of individual compounds relative to the engine load.

A similar analysis was done for the testing of emissions in real operating conditions for the GTD 350 engine.

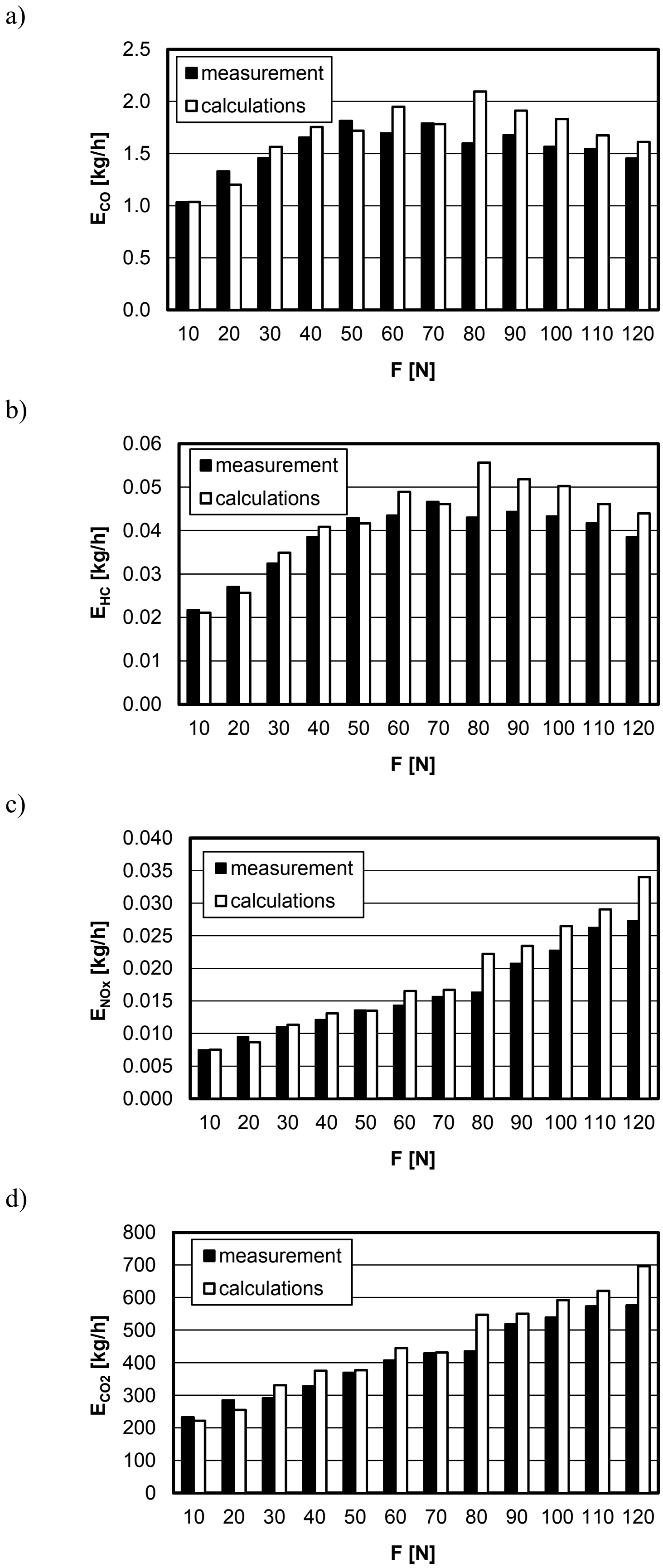

Fig. 19. Results comparison of the emission of individual harmful compounds in the engine exhaust of GTM 120 obtained from real measurement and the outcome of the estimates: a) carbon monoxide, b) hydrocarbons, c) nitrogen oxides, d) carbon dioxide

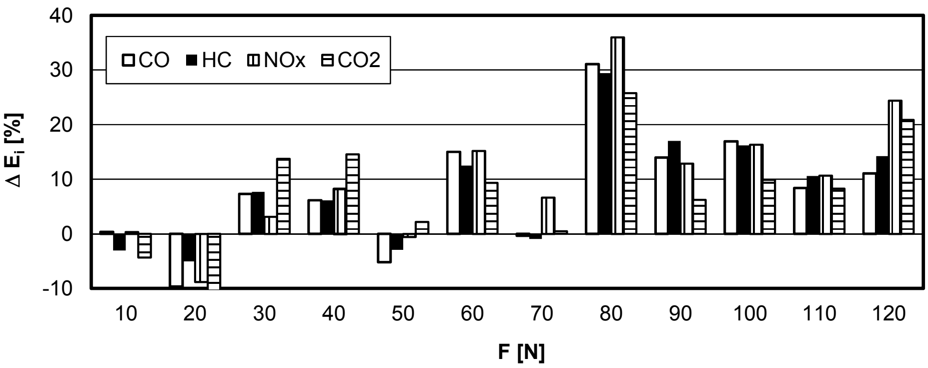

Fig. 20. The relative difference (as percentage) of the emissions of individual harmful compounds in the engine exhaust of GTM 120 derived from real measurement and the outcome of the estimates

In accordance with the procedure outlined above, values of emissions in the GTD 350 engine exhaust for individual operating points have been determined. Also, the estimation of emissions using the functional relations resulting from the distribution of concentration values as a function of engine load was performed. The resulting values of emission obtained in two ways were then compared (Fig. 21). Again, the obtained emission values for each of the harmful compounds measured exhibit a similar distribution.

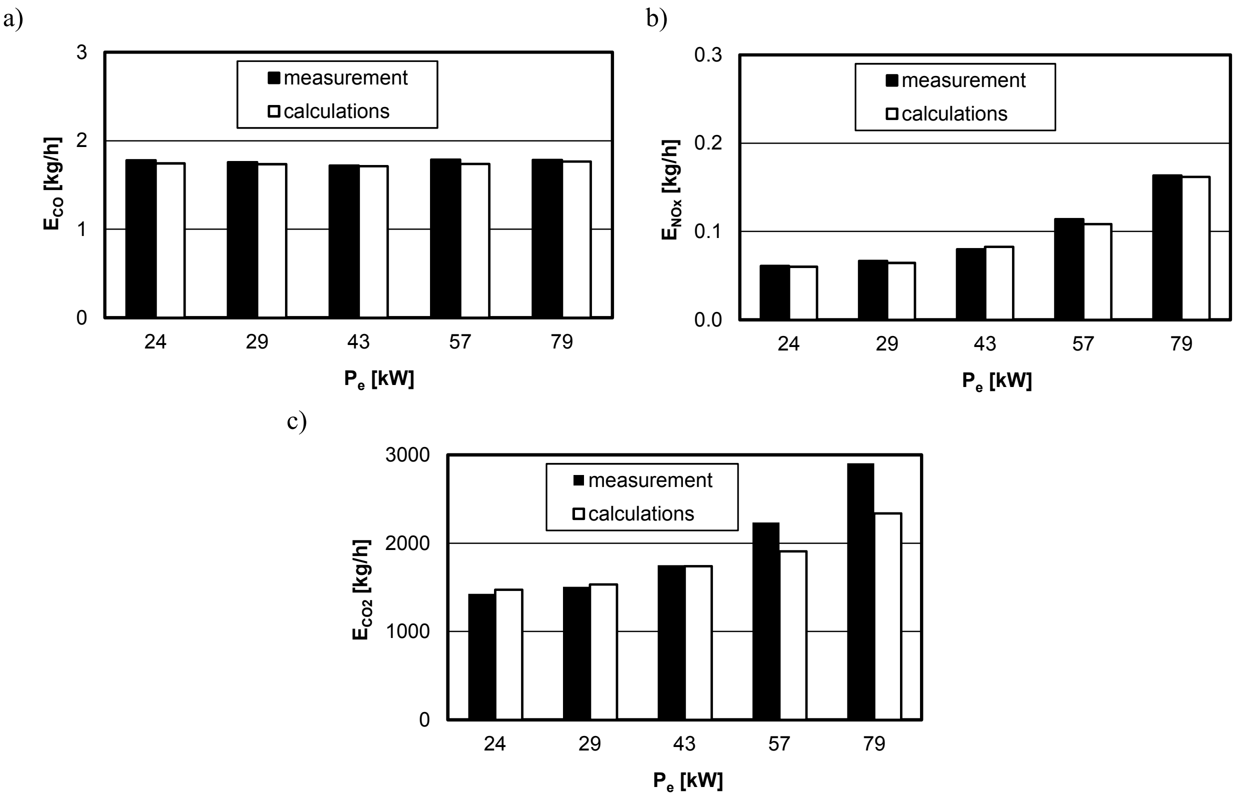

Fig. 21. Results comparison of the emission of individual harmful compounds in the engine exhaust of GTD 350 obtained from real measurement and the outcome of the estimates: a) carbon monoxide, a) nitrogen oxide, c) carbon dioxide

The comparison of the obtained values indicates that the relative differences for most operating points did not exceed 5%. An exception is the comparison of the relative values of CO_2 emissions, which achieved a difference of 15% and 20% for points at high load (Fig. 22). The resulting situation requires broadening the scope of research to other operating points at a higher engine load.

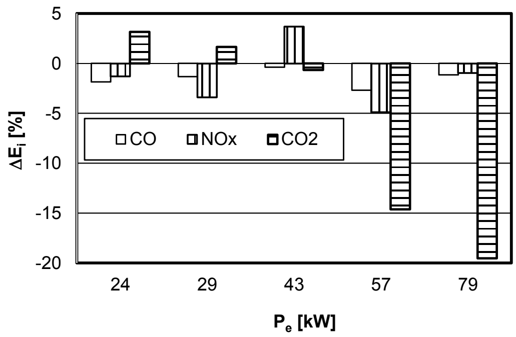

Fig. 22. The relative difference (as percentage) of the emissions of individual harmful compounds in the engine exhaust of GTD 350 derived from real measurement and the outcome of the estimates

5. Conclusions

Conducted analysis of research results of jet engine operating parameters, for turbine and turboshaft engines, aimed at assessing the methodology for estimating emissions in the exhaust gas based on the functional relations between the concentration of individual compounds and the engine load, point to the viability of the proposed method. This is indicated by the relative percentage differences in compared emission values obtained. These do not exceed 15% for most of the compared values. The exceptions are some values where these differences amount to 15–35%, but the nature of occurrence of such values indicates that they are most likely the result of a measurement error, which needs to be identified. The obtained results of the conducted analysis indicate that the method for estimating emissions in the exhaust gas based on existing functional relations between the emission parameters and the operating parameters, such as the engine load, can be a tool used in the evaluation of pollutant emissions from gas turbine engines during their operation.

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