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Measurements of exhaust emissions from the GTM-120 UAV turbine engine using atmosFIR measuring equipment

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The article provides a detailed description of the design and key parameters of the GTM-120 turbine engine, along with flow calculations for this power unit at a selected operating point. These calculations were performed using GasTurb software, which is also capable of assessing nitrogen oxide emissions. Additionally, the article outlines the test stand and the methodology used to determine toxic compounds emitted by the engine. It analyzes the measured results of various exhaust components produced during the engine's operation, specifically focusing on the levels of nitrogen oxides and carbon oxides as influenced by rotational speed and temperature. Conducted studies have established a testing methodology for aviation turbine engines, based on the type of analyzer used. This methodology will facilitate the evaluation of other aviation turbine engines on stationary test stands.

Key words: *miniature aircraft turbine engine, emissions of toxic compounds, exhaust gas measurements*

1. Introduction

UAV turbine engines are becoming increasingly popular as power units for testing toxic emissions and exploring the use of sustainable aviation fuels. They serve as a cost-effective alternative in the initial stages of research, facilitating the transfer of knowledge to full-size power units that power large aircraft. Analyzing the composition of exhaust gases in UAV engines is essential for evaluating their efficiency, environmental impact, and the potential for optimizing the combustion process. These engines are utilized both as power sources in experimental aircrafts and as units for scientific research. Through this, researchers can examine the exhaust gas composition, which helps assess the quality of the combustion process, identify issues related to incomplete combustion, and evaluate harmful emissions such as nitrogen oxides, carbon monoxide, and unburned hydrocarbons. This analysis not only enables improvements in engine efficiency but also reduces the engine's negative environmental impact.

Increasing numbers of authors are addressing the issue of exhaust emissions in their works. Measurements are conducted using portable exhaust analyzers, such as the SEMTECH DS, and the results obtained are analyzed [7, 19].

Research has also been conducted on the GTM 120 engine mentioned in this article. The authors have previously analyzed particle emissions [15], studied noise identification [4], and performed numerical analyses of cold flow in the GTM-120 engine [8]. This article focuses on measurements of toxic combustion compounds emissions, which will enhance the existing literature on this engine and facilitate future numerical analyses of the combustion process, along with comparisons of the results obtained. As a result, upcoming studies will be able to explore possibilities, such as modifying the combustion chamber design.

2. Research object

The tests were conducted using a test bench manufactured by TomSerwis, along with a specially modified version of the GTM 120 engine based on the WML WAT (Faculty of Mechatronics, Armament and Aerospace – Military University of Technology) design. This engine was equipped with measuring probes, which allowed for pressure and temperature measurements. These tubes were installed in the combustion chamber casing, located behind the compressor and in front of the turbine (Fig. 1).

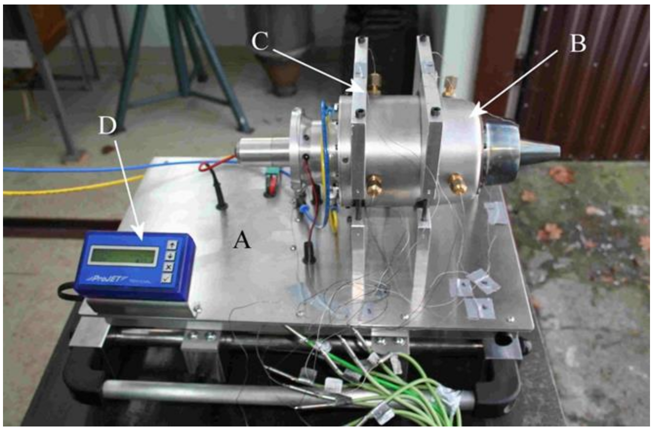

Fig. 1. Test bench of the GTM 120 engine: A – test bench; B – GTM 120 engine; C – engine bed; D – GSU panel of the engine control system

The engine for the GTM 120 is designed similarly to miniature turbine engines, offering a thrust of up to 500 N (see Fig. 2). Its design is based on the KJ 66 engine and is produced by several companies, including JETPOL [12], JetCat [11], AMT Netherlands [2], Turbine Solutions [23], PBS Aerospace [21], King Tech Turbines [14], Frank Turbine Engine Systems [5], ALM-Meca Engineering [1], JetBeetle [10], and others [13].

The engine features an axially symmetrical subsonic inlet, with an electric starter mounted on three supports in front of it. It utilizes a single-stage radial compressor and an annular combustion chamber that incorporates jet injectors and evaporators located in the rear section. The compressor rotor is driven by a single-stage axial turbine. Although this engine model underwent further modifications by the manufacturer to meet current research needs, which did not affect its performance, the original exhaust system – featuring a central cone that extends beyond the nozzle outlet cross-section was retained.

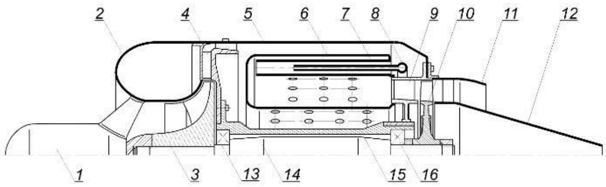

Fig. 2. Cross section of the GTM 120 engine and its basic elements: 1 – electric starter, 2 – inlet, 3 – compressor rotor, 4 – diffuser, 5 – combustion chamber case, 6 – combustion liner, 7 – evaporators, 8 – fuel manifold, 9 – turbine nozzle ring, 10 – turbine rotor, 11 – outlet nozzle, 12 – central cone of the exhaust system, 13, 16 – bearings, 14 – shaft, 15 – shaft sleeve (own elaboration)

The engine is controlled by the Hornet III [9] ProJet electronic system, which generates and sends a signal in the form of the desired voltage value for the electric motor supplying the fuel pump located at the bottom of the mobile test bench platform. The electronic and electrical systems of the engine are powered by a 12 V battery.

Operating parameters of the engine are displayed on the Ground Support Unit (GSU) panel, which works in conjunction with the Hornet III system. The GSU panel allows for starting and stopping the engine, as well as adjusting its operational range. The display shows current values for the exhaust gas temperature (EGT), engine rotor speed, fuel pump supply voltage, and the set engine operating range.

Unlike most engines, this one does not have a typical lubrication system. Instead of oil, a small amount of fuel mixed with 5% oil is supplied to the bearings. The engine typically uses aviation fuel (aviation kerosene), but can also operate on other fuels such as diesel oil, biofuels, etc. During testing, JET A-1 fuel mixed with Aeroshell 500 synthetic oil, commonly used in turbine engine lubrication systems, was utilized.

Table 1 presents the basic technical data for the engine in its original version [3].

Table 1. Basic technical data of the GTM 120 engine parameters in the basic version and the actual [3]

Parameter	Unit	Value
Dry engine weight	kg	1.5
Maximum diameter	mm	110
Length	mm	265
Maximum thrust	N	120
Maximum RPM	rpm	110 000
Air mass flow	kg/s	0.3
Compression	–	2.1
Max temperature after the turbine	K	898

2. Determination of flow parameters of the GTM 120 engine

The necessary data for modeling the performance of turbine engines can be found in various literature sources, such as "Propulsion and Power. An Exploration of Gas Turbine Performance Modeling" by Kurzke et al. [16]. Kurzke is also the author of GasTurb, a software program developed for the MTU company that calculates flow parameters in full-size engines. GasTurb is specifically designed for gas turbine performance calculation and optimization. In this work, the GasTurb 14 software was utilized for calculations, which enables the modeling of various basic types of aircraft turbine engines.

The calculations were based on actual engine operating parameters determined from previous tests, specifically a thrust of 127.3 N and a maximum temperature of 950 K behind the turbine. The results of the calculations are shown in Table 2. Additionally, the distribution of the working medium's flow velocity, pressure, and static temperature in key engine cross-sections during operation at maximum range under static conditions (V = 0 m/s, H = 0 m) is illustrated in Fig. 3. Localization of stations at which parameters were calculated is presented in Fig. 4.

Table 2. Results of calculations of the GTM 120 engine operating parameters performed in the GasTurb 14 program

Parameter	Unit	Value
FN	kN	0.13
TSFC	g/kNs	44.1384
WF	kg/s	0.00595
S NOx	g/kg	0.04059
where: FN – thrust, TSFC – specific fuel consumption, WF – mass flow rate of fuel, S NO_x – NO_x content in exhaust gases.		

The S_{NOx} value is determined from the equation:

$$S_{NO_x} = \left(\frac{P_3}{2965\ \mathrm{kPa}}\right)^{0.4} \cdot e^{\left(\frac{T_3-826\ \mathrm{K}}{194\ \mathrm{K}}+\frac{6.29-100\ \mathrm{war}}{53.2}\right)} \qquad (1)$$

where: war – water-air-ratio.

The higher nitrogen oxide values observed in the GasTurb 14 may be due to the positioning of the measuring probe, which captures data from a single point. Additionally, the intake of air can affect the readings.

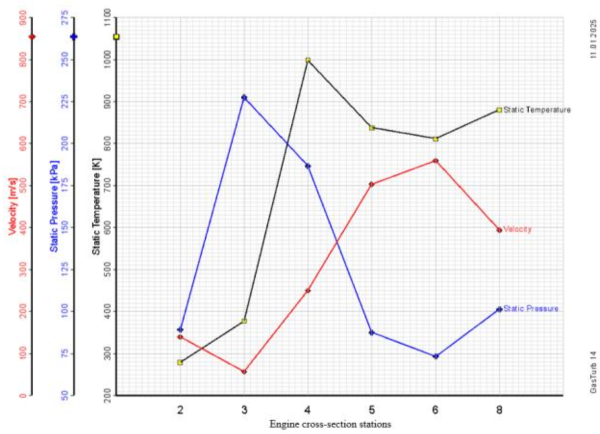

Fig. 3. Distribution of the flow velocity of the working medium and its static pressure and static temperature in characteristic stations of the GTM 120 engine (graph generated by the GasTurb 14 program)

Developing an accurate model of the GTM 120 engine in the GasTurb 14 program proved challenging due to the engine's unique design of the combustion chamber and exhaust system. This complexity made it difficult to select the appropriate input parameters. Nevertheless, the thrust value obtained from the model is within 2.08% of the measured value, and the difference between the measured and calculated exhaust gas temperatures does not exceed 0.29%.

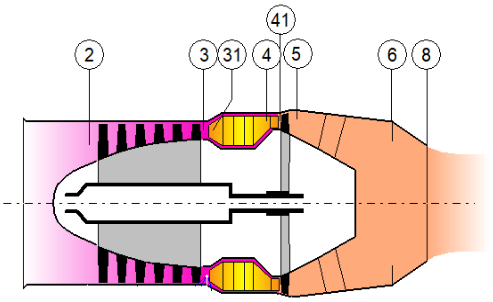

Fig. 4. Engine cross-section with stations, at which parameters were calculated, used in the GasTurb 14 (diagram taken from the GasTurb 14)

3. Research methodology

To measure the exhaust emissions from the GTM-120 the atmosFIR mobile exhaust gas analyzer was utilized. Both the engine and the measuring probe were positioned on a stable base. The measuring station is depicted in Fig. 5.

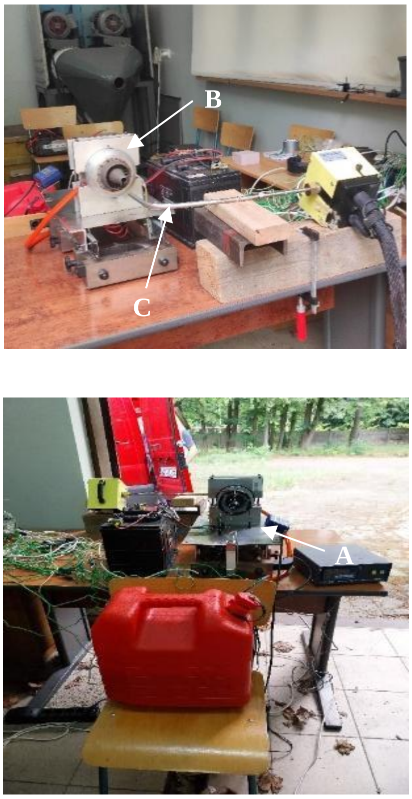

Fig. 5. Measuring station: A –test bench; B – GTM 120 engine; C – measuring probe

The AtmosFIR exhaust gas analyzer is a device made by Protea. It is a multi-component and multi-range analyzer capable of measuring up to 100 different components. This device connects to the PAS-Pro control and data processing program. During the tests, measurements were taken for components such as carbon dioxide, carbon oxides, nitrogen oxides, and sulfur oxides. The specifications and applications of the analyzer are detailed in Table 3. For clarification, the resolution in wavenumbers (cm^{-1}) refers to the instrument's ability to distinguish between closely spaced spectral lines.

Table 3. Protea AtmosFIR analyzer applications and specifications [20]

Typical measurement ranges	0–10 ppm, 0–100 ppm, 0–1000 ppm
Typical detection limit	< 0.2 ppm
Typical spectral resolutions	1 cm^{-1}, 2 cm^{-1}, 4 cm^{-1}, 8 cm^{-1}
Spectral range	485–8500 cm^{-1}
Weight	18–20 kg
Dimensions	440 × 450 × 222 mm

Figure 6 shows an element of the measurement station, which is the central unit of atmosFIR equipment.

Fig. 6. Exhaust gas analyzer atmosFIR

During the measurements, a thermal analysis of the power unit was conducted using a thermal imaging camera. The image captured after completing the measurements is shown in Fig. 7.

Fig. 7. View from the thermal imaging camera after completing the measurements

The measurements of exhaust gas components concentration were conducted over the full engine operation cycle. After starting, the engine automatically increased the rotor speed to approximately 48,000 rpm to assess the parameters of the fuel supply system. It then decreased the speed to 33,000 rpm, which corresponded to idle speed. Following this, the rotational speed was increased in increments of 20,000 rpm, ranging from 40,000 to 100,000 rpm. The operating range was then expanded to achieve a maximum rotational speed of 110,000 rpm. The rotor speed was subsequently reduced to the idle speed range before the engine was turned off. Each measurement was taken over a period of 2 minutes for every speed range, as shown in Fig. 8.

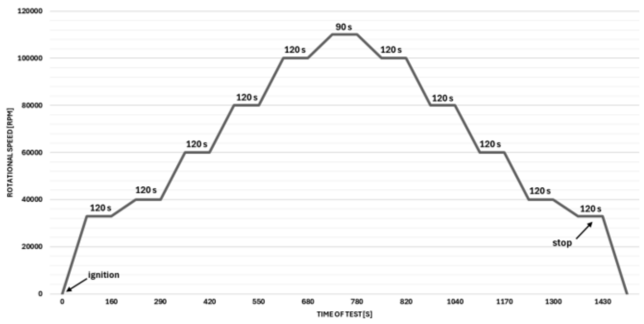

Fig. 8. Profile of engine test idea

4. Research results

During measurements conducted with the atmosFIR analyzer, we obtained results for a wide range of combustion components from the test object. Due to their predominance and harmful effects, we decided to focus our analysis on carbon dioxide, carbon monoxide, and nitrogen oxides. The concentrations of these components are presented as a function of time, considering the rotational speed [18, 22], and as a function of temperature – Fig. 8 and Fig. 9. To better illustrate the relationship between the amount of nitrogen oxides produced and temperature, we derived a separate characteristic.

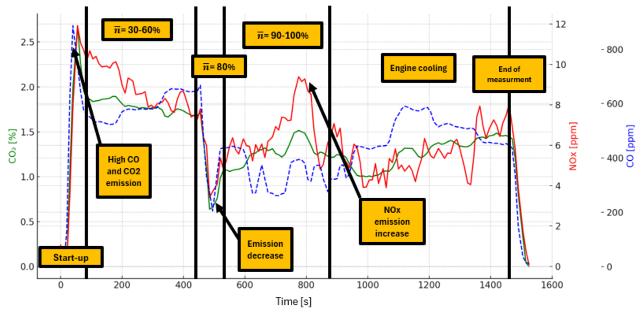

Fig. 9. Measurement results of toxic compounds produced during the operation of the GTM-120 engine as a function of time, considering the ranges of rotational speeds, where: n = 30–60% of maximum rotational speed – engine warm-up, n = 80% of maximum rotational speed – cruise range, n = 90–100% – maximum rotational speed

Figure 8 illustrates the measured data over time, covering a duration of approximately 25 minutes. To enhance clarity, vertical lines indicating the different phases of engine operation have been plotted on the graph.

During the initial phase of engine operation, which is the start-up phase, a high concentration of carbon oxides and carbon dioxide is observed. This phenomenon is typical for turbine engines and results from incomplete combustion shortly after the fuel is injected into the combustion chamber. This observation is further supported by the results shown in Fig. 9, which indicates a low exhaust gas temperature during the engine start-up phase.

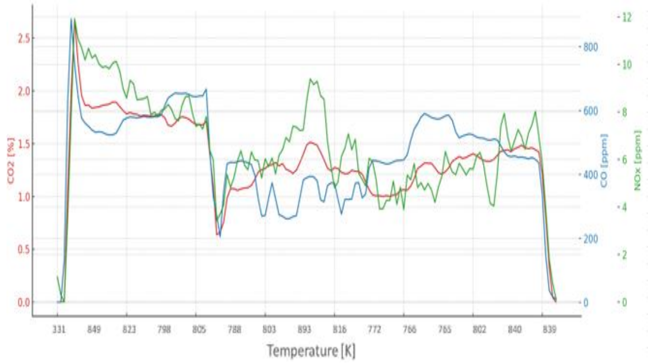

Fig. 10. Results of measurements of harmful compounds produced during the operation of the GTM-120 engine as a function of the measured engine temperature

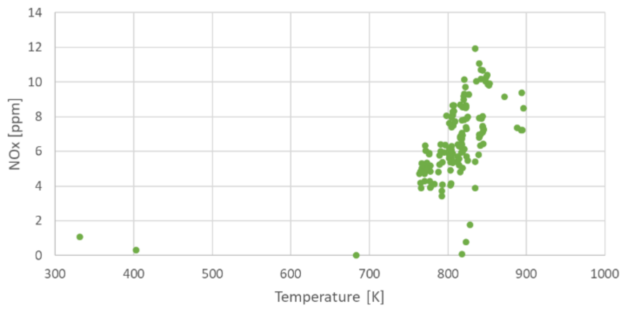

Fig. 11. Measurement results of nitrogen oxides produced during the operation of the GTM-120 engine as a function of the measured engine temperature in front of the turbine

Conversely, Fig. 10 demonstrates that the concentration of nitrogen oxides during this phase remains below 2 parts per million (ppm). In the subsequent phase, which ranges from 30% to 60% of maximum engine speed, the exhaust gas temperature begins to rise, reaching approximately 800 K. This increase in temperature leads to a decrease in the concentrations of CO_2 and CO. As the combustion chamber temperature rises, the concentration of nitrogen oxides in the exhaust gas also increases, peaking at around 11 ppm. During the next phase of engine operation, which corresponds to the cruise range, the engine rotor speed stabilizes at about 80% of the maximum value. In this phase, a notable decrease in the concentration of all analyzed exhaust gas components is observed, indicating that this range represents the optimal operating conditions for maximum combustion chamber efficiency. As the engine reaches its maximum rotational speed, the exhaust gas temperature also escalates, peaking at approximately 896 K. Compared to the cruise phase, the concentrations of CO and CO_2 rise due to the increased fuel supply to the combustion chamber. It is important to note that nitrogen oxides reach their highest concentration during this phase, peaking at around 12 ppm. This relationship aligns with existing literature [17], which indicates that nitrogen oxides typically achieve peak concentrations at elevated exhaust gas temperatures. In the final cooling phase of the engine, there is another increase in the concentrations of carbon oxides and carbon dioxide, which correlates with a drop in temperature and a decline in combustion efficiency. As the measurements conclude, a reduction in the concentration of all combustion components is recorded. The accompanying Table 4 presents the maximum concentration values of harmful combustion components across the various phases of engine operation.

Table 4. Maximum concentrations of combustion components during individual engine operation phases

Engine operating phase	CO_2 [%] max rpm	CO [ppm]	NO_x [ppm]
1. Start-up	2.7	887.1	1.1
2. Warm-up	1.9	667.3	11.0
3. Cruising range	0.6	204.7	3.4
4. Maximum range	1.5	439.6	11.9
5. Cooling	1.0	585.0	8.0
6. End of operation	0.0	0.4	1.8

The data from Table 4 are also presented in the form of approximation graphs.

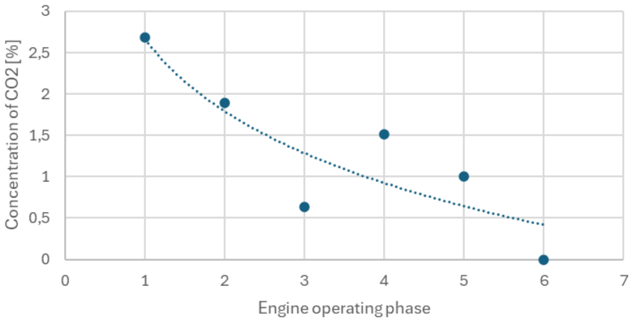

Fig. 12. Concentration of CO_2 during individual engine operation phases – approximation graphs

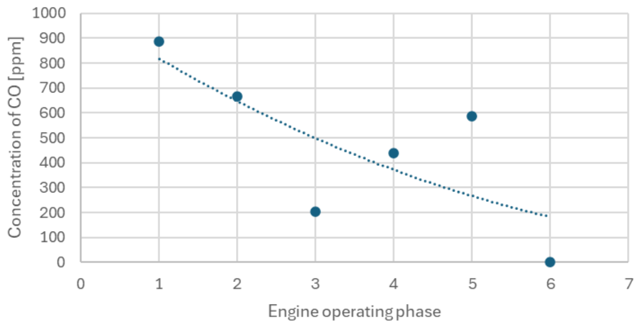

Fig. 13. Concentration of CO during individual engine operation phases – approximation graphs

Calculations performed using the GasTurb 14 program indicated a NO_x concentration of 0.04059 g/kg at maximum rotational speed. However, actual tests revealed this value to be significantly lower, at 11 ppm, or 0.011 g/kg. This discrepancy amounts to about 73%. By employing an exhaust gas analyzer, we can accurately determine the range of nitrogen oxide emissions and use the results to adjust the parameters in the GasTurb 14 software. The team is working to reduce discrepancies between results. Recently, retests were conducted using a modified system and a new engine. The results are still in development.

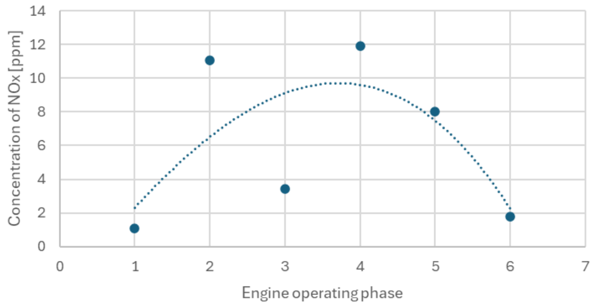

Fig. 14. Concentration of NO_x during individual engine operation phases – approximation graphs

5. Conclusions

The research conducted has determined the influence of the range of work of a UAV turbine engine on the formation of toxic combustion components. The presence of nitrogen oxides at low rotational speeds results from the combustion of nitrogen contained in the fuel, while at high rotational speeds it is associated with a high combustion temperature. At the same time, comparing the results of calculations carried from GasTurb 14 with the results of actual tests allowed analyses of selection of parameters in the software. It may be the direction of further work to obtain greater data compatibility. UAV turbine engines can, with the adoption of appropriate ranges of coefficients, be a reference for full-size power units. Carrying out analyses on small-sized engines allows us to develop measurement methodologies, thanks to which it is possible to make tests carried out on full-size engines more economical. Thanks to the research on UAV engines, it is also possible to test the use of sustainable aviation fuels [6, 24] in further work, which will allow us to compare the amount of exhaust gases in relation to standard aviation fuel.

Acknowledgements

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Nomenclature

CO_2	carbon dioxide
CO	carbon monoxide
EGT	exhaust gas temperature
GSU	ground support unit
NO_x	nitrogen oxides

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