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EXHAUST EMISSIONS EVALUATION FOR MULTI-ROLE FIGHTER AIRCRAFT OPERATION

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Abstract

Multi-role aircraft as a technical object of a certain functional purpose and operating characteristics resulting from its construction, affects the operating environment mechanically, as a source of disturbance of the medium in which it moves and chemically, by generating the emission of harmful substances resulting from the need to use consumable fuels. Operation of multi-role aircraft, in contrast to civil aircraft, is characterized by high volatility of flight data resulting from the diversity of performed tasks. Therefore it seems desirable to attempt the ecological evaluation of the drive in terms of emissions on the basis of a dedicated test for a particular group of aircraft. An attempt at such an assessment is presented in this article.

Keywords: exhaust emissions, harmful compounds, aircraft operation, turbine engine, multi-role aircraft

1. Introduction

Multi-role aircraft as a technical object of a certain functional purpose and operating characteristics resulting from its construction, affects the operating environment mechanically, as a source of disturbance of the medium in which it moves and chemically, by generating the emission of harmful substances resulting from the need to use consumable fuels. The issue of the environmental impact of aircraft is included in Annex 16 of the Chicago Convention, which is in force in the countries belonging to the International Civil Aviation Organization (ICAO). The findings contained in Annex 16 do not apply to military aircraft, and the verification procedures of harmful exhaust components emission from the engines relate to tests developed using the standard takeoff and landing test procedure LTO (landing and take-off) [13]. In contrast to civil aircraft the operation of multi-role military aircraft is characterized high volatility of flight parameters. One of the characteristics of multi-role military aircraft is the ability to perform various tasks related to chasing other aircraft, air combat maneuvering at different altitudes, interception, reconnaissance of the battlefield and patrol flights. All these tasks differ by the character of defined parameters, such as: flight altitude, speed or type of maneuvers performed. These parameters are reflected in the performance characteristics of the drive unit, and thus the harmful compounds emission in the engine exhaust gases. Therefore it seems important to verify the real impact of multi-role military aircraft operation on the environment [1-7, 9, 11]. The current level of measurement techniques related to the study of harmful exhaust emissions, is not yet enough to make it possible to perform emission measurements of harmful compounds contained in exhaust gases in the real operating conditions during ongoing flight. The big problem is the issue of exhaust sampling for analysis and safe mounting of the measuring apparatus. Due to these limitations the harmful emissions testing of exhaust gases are all so far carried out on engines in stationary tests. These types of studies can, however, allow to determine the level of emissions of individual harmful exhaust compounds emissions under real operating conditions, based on the analysis of operating parameters recorded by the on-board flight data recorders [3, 6]. Out of the many operating parameters recorded several may be used for operating conditions analysis of the aircraft and in particular the drive unit. Data that can be used to evaluate the aircraft operating conditions includes the recordings of: aircraft airspeed, barometric altitude, output power lever settings, the crankshaft rotational speed, exhaust gas temperature, and information about the afterburner operation (Fig. 1). Analysis of the data available in the literature [3, 8, 12] indicates the possibility of evaluating the emission of harmful exhaust components from the engine of a multi-role military aircraft.

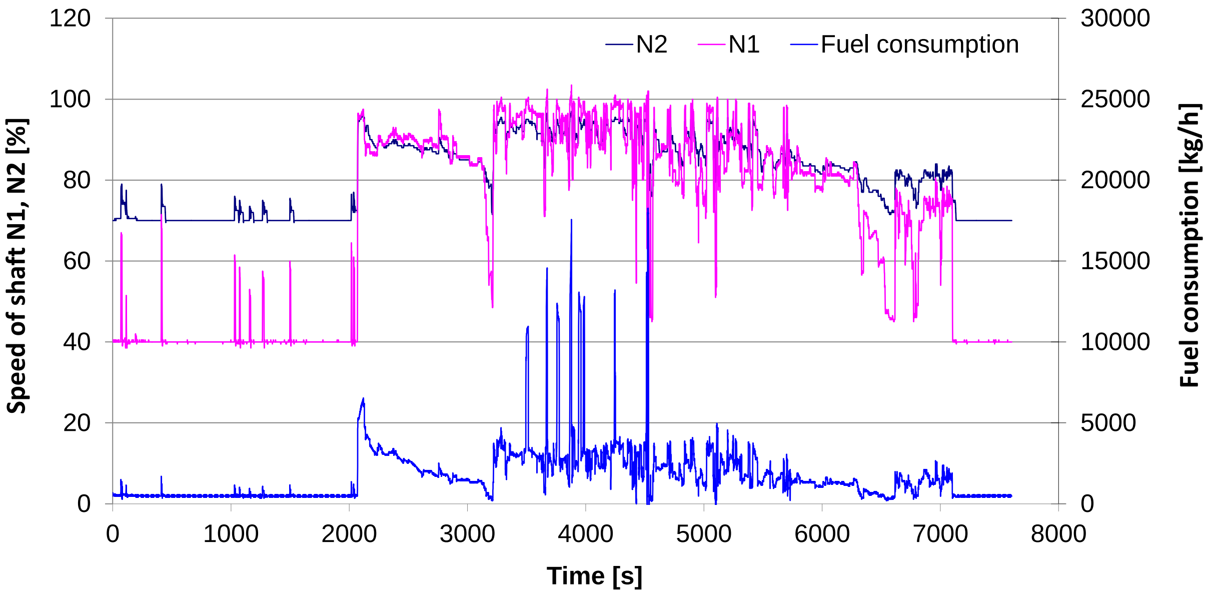

Fig. 1. An example of the operating parameters of F-16 aircraft and the engine F100-PW-229 recorded during flight

2. Research methodology

The emission evaluation of the harmful compounds contained in the multi-role aircraft engine exhaust, due to the characteristics of the available equipment and specific operation of the aircraft cannot be carried out on the basis of actual operation measurements in flight. The analysis of the emission of harmful compounds was performed for the F-16 multi-role fighter aircraft, equipped with a F100-PW-229 turbofan engine.

The test aircraft was equipped with a flight data recorder. In order to assess the harmful exhaust emissions it is necessary to analyze the operating parameters recorded by the flight data recorder in the aircraft, and in particular the parameters that describe the engine operating conditions. Crankshaft speeds N1 and N2, output power lever settings, fuel consumption, exhaust gas temperature, and information on the afterburner switch have been selected for the analysis.

Analysis of the literature on research of the harmful gases emission from turbine jet engines [3, 4, 5] points to the need to conduct measurements under the conditions of aircraft immobilization. This indicates two stages of the harmful exhaust emissions evaluation. The first stage is the measurement of the concentration of harmful substances in the exhaust gases realized when stationary, and the other is a numerical analysis aimed to determine the operating conditions of the engine during actual flight conditions. Therefore, an analysis of the operating procedures of the aircraft was conducted. The analysis shows that before operating the F-16 in the field, a preflight test consisting of verifying proper operation of all aircraft devices and systems is performed. During this test the drive properties of the engine are also evaluated. The preflight engine test is interesting, thus an analysis of the plane pilot's procedural options was done, aiming to develop the measurement methods of the harmful substances concentration in the exhaust gases during the preflight test. Particular attention was paid to the possibility of installing a probe into the stream of exhaust gases flowing out of the nozzle of an aircraft engine positioned and mounted on a test station. The evaluation of the test station showed the possibility of attaching simple structural elements to the concrete slab beyond the railings, to which the plane was attached. On the station dedicated to engine dynamometer tests, or airframe engine tests the probe was mounted on a structure attached to the elements of the exhaust outlet channel of the building (Fig. 2). Ducts for the exhaust gas analyzer were attached to the support structure constructed, and the analyzer was positioned at a safe distance from the nozzle of the engine.

Fig. 2. Exhaust sampling probe mounting location

For the measurement of the toxic compounds concentration the mobile Semtech-DS of Sensors company (Sensors EMission TECHnology) exhaust gas analyzer was used (Tab. 1) [5, 6, 7, 8, 10, 11].

Tab.1 Characterystics analyzer Semtech-DS [10, 14]

Parameter	Measurememt method	Measurememt accuracy
Concentration exhaust compounds:		
CO	NDIR, meas. range 0÷10%	±3% meas. range
HC	FID, meas. range 0÷10 000 ppm	±2,5% meas. range
NO_x = (NO + NO_2)	NDUV, meas. range 0÷3000 ppm	±3% meas. range
CO_2	NDIR, meas. range 0÷20%	±3% meas. range
O_2	elektrochemical analyzer, meas. range 0÷20%	±1% meas. range
Exhaust gas flow	Mass flow	±2,5% meas. range
	Exhaust gas temperature max. 700^{o}C	±1% meas. range

The analyzer allows the measurement of the concentration of carbon monoxide, hydrocarbons, nitrogen oxides and carbon dioxide. All components of the Semtech-DS analyzer were designed to match the highest class laboratory measuring devices, and at the same time be able to meet the device requirements to monitor emissions of internal combustion engines under real operating conditions. Compliance with these objectives require maximum decrease in the weight, size and power consumption of the device while reducing sensitivity to shocks, vibrations, temperature changes and other external factors that may interfere with the measurements.

The main advantage of the analyzer is its compact and relatively small size, which gives great possibilities of mobility and usage in machines tested in their actual operating conditions. The analyzer is dedicated to this kind of research, but can also be used in research on stationary dynamometer benches in laboratory conditions. The analyzer meets the requirements of the 1065 standard for PEMS (Portable Emission Measurement Systems). It is based on a number of stand-alone measurement modules:

– flame ionization analyzer FID (Flame Ionization Detector) used for determining the total exhaust concentration of hydrocarbons known as HC or THC (Total Hydrocarbons),

– NDUV type analyzer (Non-Dispersive Ultraviolet), which is the non-ultraviolet radiation for the measurement of nitrogen oxide and nitrogen dioxide,

– NIDR type analyzer (Non-Dispersive Infrared), or the non-infrared radiation for the measurement of carbon monoxide and carbon dioxide,

– electrochemical analyzer for determining the oxygen level in the exhaust gas.

The exhaust gases are introduced into the analyzer using a probe maintained at 191°C, in the next step the particulate matter is filtered followed by the concentration measurement of hydrocarbons in the flame ionization analyzer. Then, the exhaust gases are cooled to a temperature of 4°C and the concentration measurement of the nitrogen oxides (by nondispersive ultraviolet irradiation allowing for simultaneous measurement of nitrogen oxide and nitrogen dioxide), carbon monoxide, carbon dioxide (by nondispersive method using infrared radiation) and oxygen (electrochemical analyzer) is performed. In addition to measuring harmful emissions the analyzer also allows the measurement of the exhaust gases mass flow (Fig. 3).

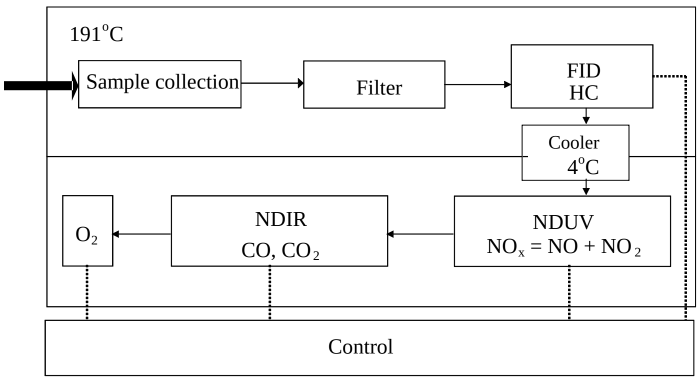

Fig. 3. Semtech-DS analyzer schematic with additional systems shown [10]

The aim of the study was to measure the harmful exhaust gases emission from the turbine jet engine, which is the source of propulsion for an F-16 aircraft. Measurements of the toxic compounds concentration in the exhaust were made continuously, for the operating parameters of the engine load corresponding to the values of the preflight engine test [5]. During the tests the concentrations of carbon monoxide, carbon dioxide, hydrocarbons and nitrogen oxides were measured. The decision to measure the engine operating parameters in the preflight test was made, because it is imposed by the aircraft manufacturer and is obligatory to verify the operational status of the aircraft engine before flight. The preflight engine test is implemented in accordance with the instructions recommended by the manufacturer of the drive unit. The course of the test and the various engine operating parameters have been recorded by the test aircraft recorder. Measurements of the harmful exhaust compounds concentrations were recorded at the same time while saving engine operating parameters during the undertaken preflight trials. This allowed for a comparative analysis of the recorded data, and assigning individual engine operating parameters to the corresponding concentrations of harmful compounds emission. Knowing the concentration of harmful substances in relation to the various operating parameters of the engine enabled the calculation of the harmful compounds emission intensity at certain engine load values.

Data on the emission intensity of harmful exhaust components at a given engine load was used to try and assess the actual emissivity of the multi-role fighter aircraft. This assessment was made on the basis of available records selected from the aircraft's flight recorder, which were evaluated statistically on the incidence of engine load conditions in actual operation performed during the flights. As a result of these activities proposals for stationary test were developed. The assignment of the resulting load histograms with the corresponding harmful exhaust gases emission intensity allowed to assess the plane's emission in the proposed stationary test and thus allowed an assessment of emissions under real driving conditions. It should be noted that the analysis carried out is subject to a degree of uncertainty, but its verification requires a series of numerical investigations which encompass a wider range of engine operating parameters in real flight conditions within its scope.

3. Harmful exhaust components emission evaluation of multi-role fighter aircraft based on stationary test

3.1. Emission tests of harmful engine exhaust components for F100-PW-229 in a preflight test of an F-16 fighter aircraft

The measurements of harmful compounds exhaust emissions for F100-PW-229 engine of the multi-role fighter F-16 were carried out in the preflight engine test. The aircraft was equipped with a flight data recorder, which allowed for the recording of the engine operating parameters during the test. A sample recording of the selected parameters is shown in Figure 4.

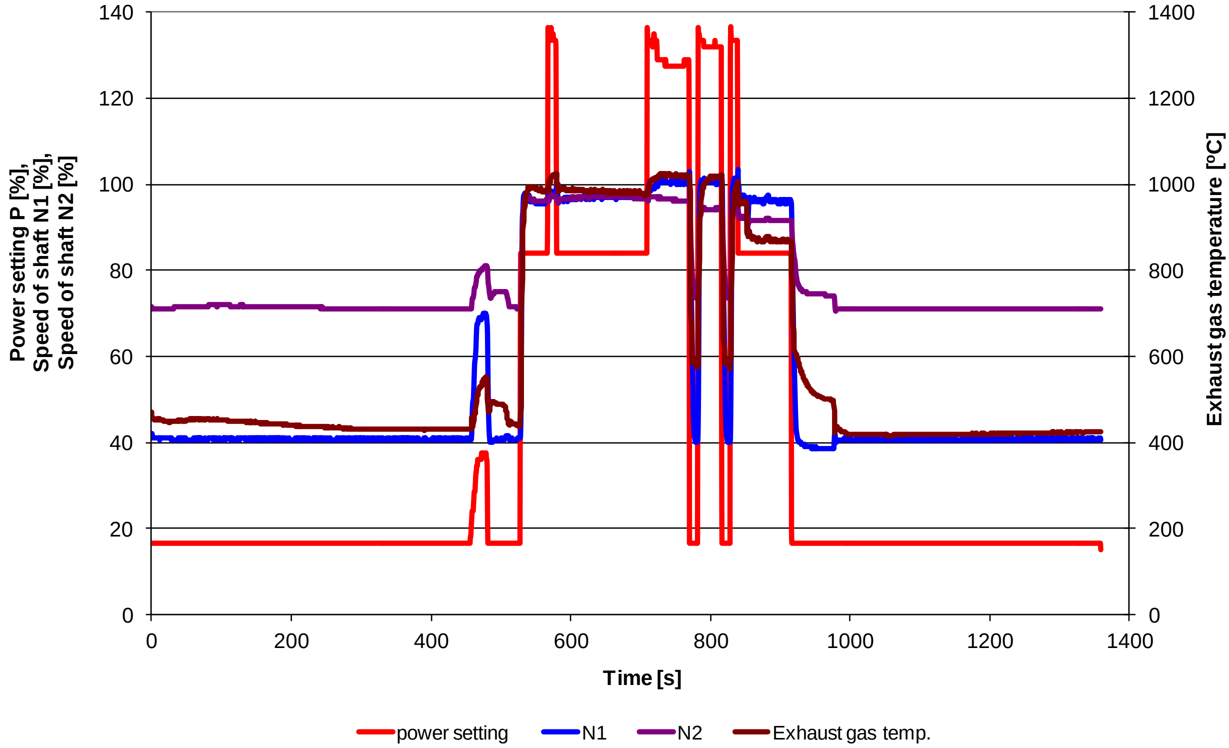

Fig. 4. An example of the engine operating parameters during a preflight test recorded by the flight data recorder of the F-16 aircraft

This record contains the full data on the preflight test, along with the operation range of the engine running with the afterburner engaged. These ranges are for the output power lever setting above 100%. A fragment of the preflight test before the afterburner was engaged was used for the purpose of measuring the harmful compounds emission. The decision to shorten the measurements during the preflight test was taken because of the possibility of thermal damage to the probe and apparatus. The technical removal of the probe from the exhaust gas stream was carried out as follows. Engine after verification of the maximum operating parameters without using the afterburner, was set to the minimum parameters to lower exhaust gas stream temperature, and then switched off. The harmful exhaust compounds emissions measuring system was dismantled and the engine was started again in order to carry out the remainder of the test. The introduction of these changes can be seen on the operating parameters recording made by the flight data recorder while trying measure emission of harmful exhaust gases (Fig. 5). Operating data for the drive unit were recorded as a function of time, along with a continuous measurement of the emissions concentration of selected harmful exhaust compounds. This way it is possible to synchronize the different phases of engine test with the measurements of harmful compounds emissions.

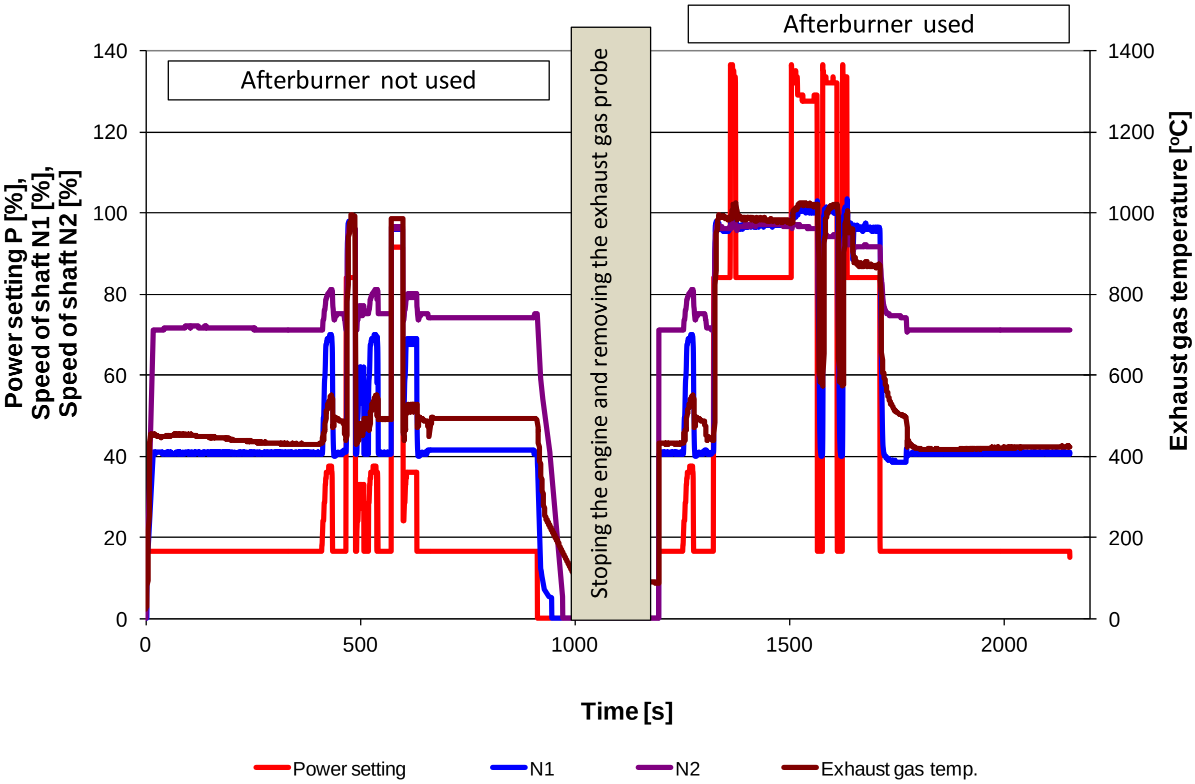

Fig. 5. A recording of the operating parameters made by the flight data recorder during preflight test with simultaneous measurement of harmful exhaust emissions

Considering the first portion of the carried out preflight test recording (Fig. 6), and the parameters shown along with the instantaneous values of the hourly fuel consumption, were compared with the concentration values of toxic compounds in the exhaust gas (Fig. 7).

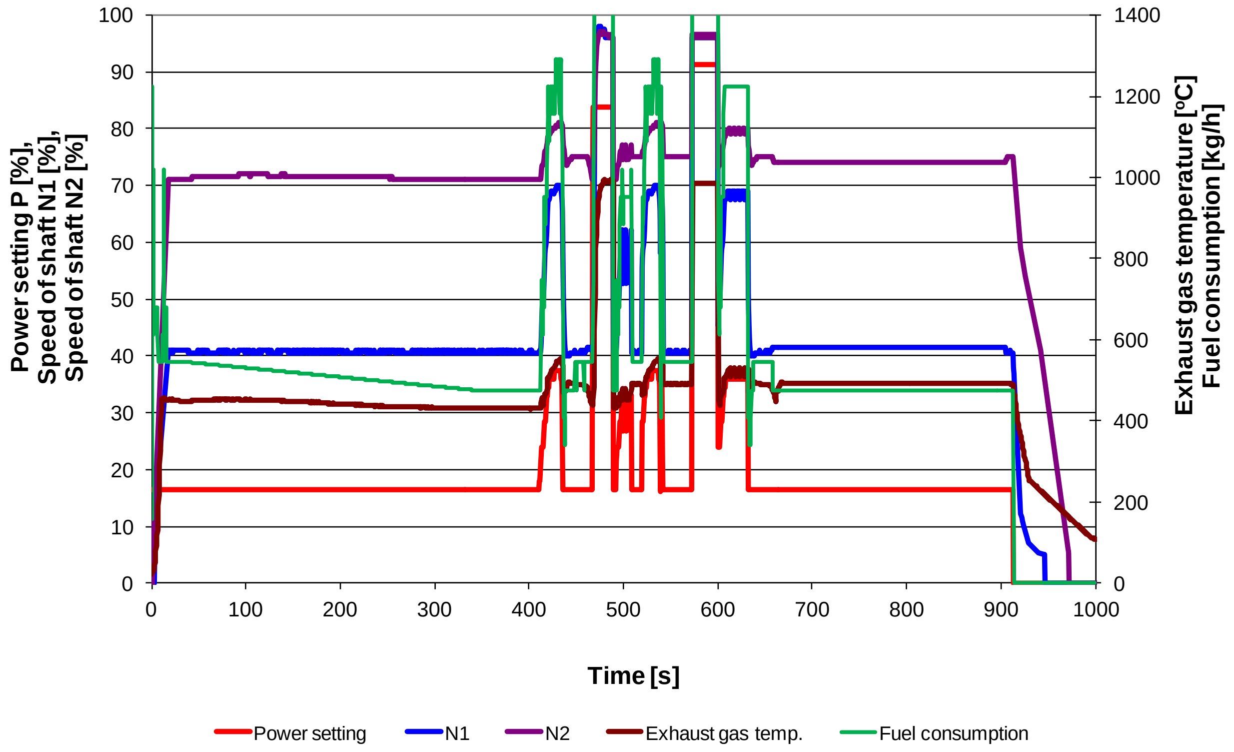

Fig. 6. A graph of values of the operating parameters selected for the analysis during the preflight test procedure with simultaneous measurement of harmful exhaust emissions

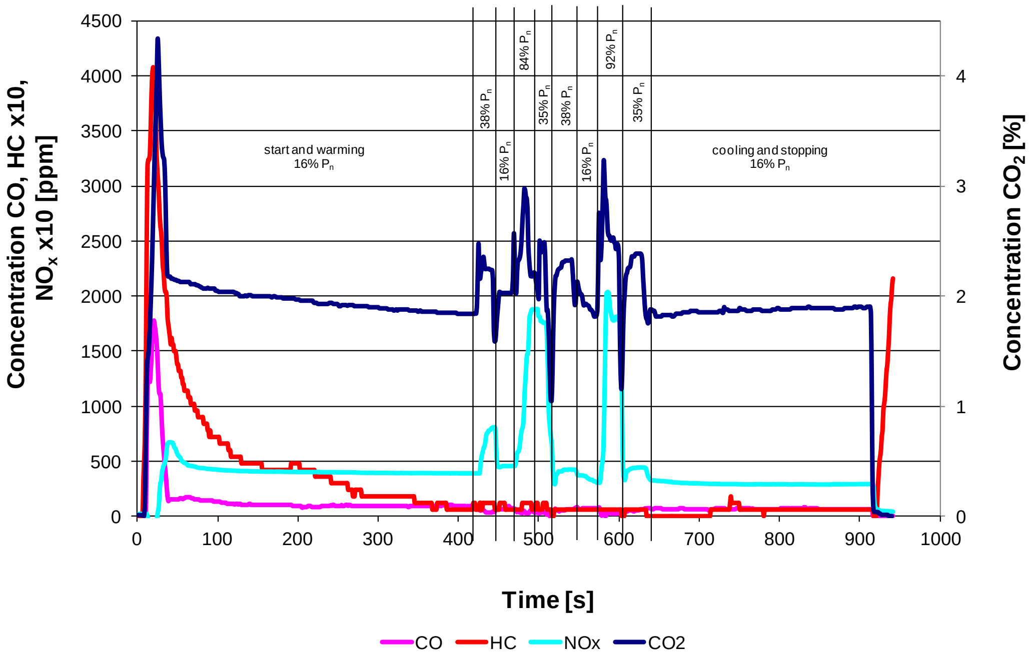

Fig. 7. The results of emission measurements of the harmful exhaust compounds concentrations as a function of time during the preflight F100-PW-229 engine test run

The analysis of parameter changes compared to the procedures for implementation of the preflight engine test allowed for the isolation of the individual engine load states. The vertical lines in figure 7 detail the various preflight test phases and the percentage load index.

The engine start is characteristic for turbine engines. In this portion of the test a high concentration of hydrocarbons can be seen, which directly depends on the amount of fuel delivered to the combustion chamber. Then, at the time of ignition in the combustion chamber the concentration of CO, CO_2 and HC rapidly increases. Increase in these compounds is a consequence of the combustion process, which is initially very inefficient. As the combustion chamber warms up and all of the other engine components obtain their proper thermal state the concentration levels of these compounds decline rapidly.

Heating of the combustion chamber contributes to the increase of thermodynamic parameters of the combustion process, thereby increasing the concentration of NO_x in the exhaust gas. With the increasing engine thermal state the nitrogen oxides concentration in the exhaust gas assumes a fixed value of about 45 ppm, corresponding to an engine load of about 17% of maximum power and the obtained N2 turbine shaft rotational speed of about 70% of the maximum speed. With the increase of load up to 40% of normal and the turbine speed (increase in the engine load) to 80% of the maximum speed, the concentration of NO_x in the exhaust gas is about 80 ppm. Increasing the output power setting to 85% of maximum power and increasing the turbine rotational speed to about 98% of maximum velocity increases the NO_x concentration in the exhaust gas to about 190 ppm. While increasing the output power setting to 92% of maximum power and the turbine rotational speed to about 98% of maximum velocity increases the NO_x concentration in the exhaust gas to about 200 ppm. Similar changes occur to the carbon dioxide concentration in the exhaust. The maximum values of the CO_2 concentration in the individual operating points are as follows: at 70% of maximum N2 turbine speed – about 2% CO_2, for 80% of the maximum N2 turbine speed – 2.3% of CO_2, and at 98% of maximum N2 turbine speed – 2.5% of CO_2. The concentration of carbon monoxide in the exhaust gas reaches the maximum value of 1,700 ppm at the engine start after the initiation of fuel ignition in the combustion chamber. It then rapidly decreases, and remains at 50-200 ppm. The hydrocarbon concentrations have a similar character. The maximum values of HC concentration – 400 ppm, are present at the point of engine ignition, then as the combustion chamber warms up and the engine reaches an optimal thermodynamic state, and as a result the concentration of hydrocarbons is reduced to about 25 ppm. Relatively small concentration values of the respective compounds in the exhaust gas are associated with a large excess air ratio in the combustion chamber, which in the case of turbine engines results in a dilution of the exhaust gases.

3.2. Correlation analysis of the performance level of engine F100-PW-229 in real operating conditions of an F-16 fighter and preflight test conditions

The data obtained by the flight recorders of an F-16 fighter aircraft from several patrol and training flights was analyzed. An example of the engine operating parameters recorded during one of the flights is shown in Figure 8. Given the N2 shaft rotational speed occurring at different operating phases it can be represented as a function of temperature T2, which is dependent on the engine power.

From the presented relations it follows, that the operation of the F100-PW-229 engine used in the F-16 aircraft is in the range of 70-100% for the N2 shaft speed and 40-100% of the maximum temperature T2. The classification of values the N2 shaft speeds as a function of temperature T2 on operational phases enabled the range separation of these phases. Values of shaft speed below 60% $T2_{max}$ relate mostly to the engine start, the warm-up, taxiing and its cooling phase. T2 temperature range above 55% of $T2_{max}$ is largely in the take-off and flight phases of the aircraft operation including a portion of the landing phase. The operating ranges also show the engine operating points with the afterburner engaged, these are the operating points corresponding to the take-off phase and the maximum engine operating parameters when performing special maneuvers during the flight. The power output lever settings in this engine operating range are above 100% P. The gas temperature before the turbine T2 has a value close to the maximum value of approximately 1000°C.

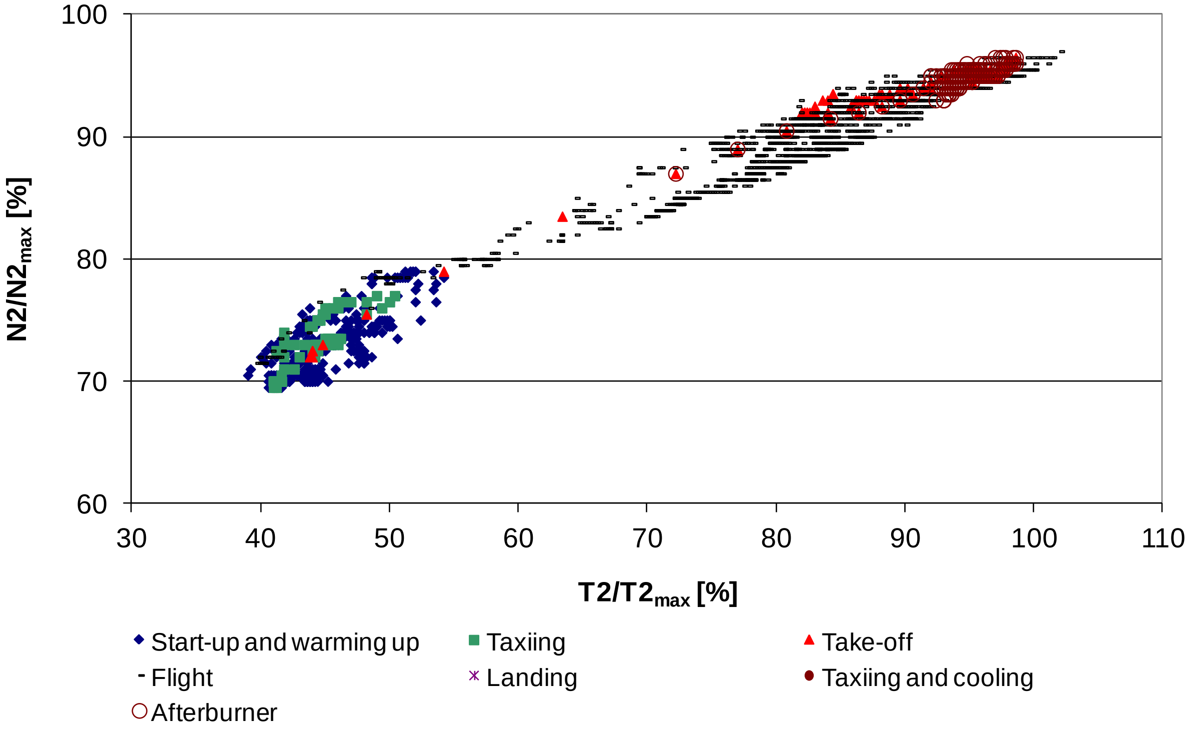

Fig. 8. Distribution of the analyzed parameters in the operating range of the F100-PW-299 engine recorded during the F-16 flight

When making a parameter comparison of N2 as a function of $T2/T2_{max}$ for the aircraft flight operating conditions and the preflight test conditions (Fig. 9), a large compliance of the analyzed parameter values can be found.

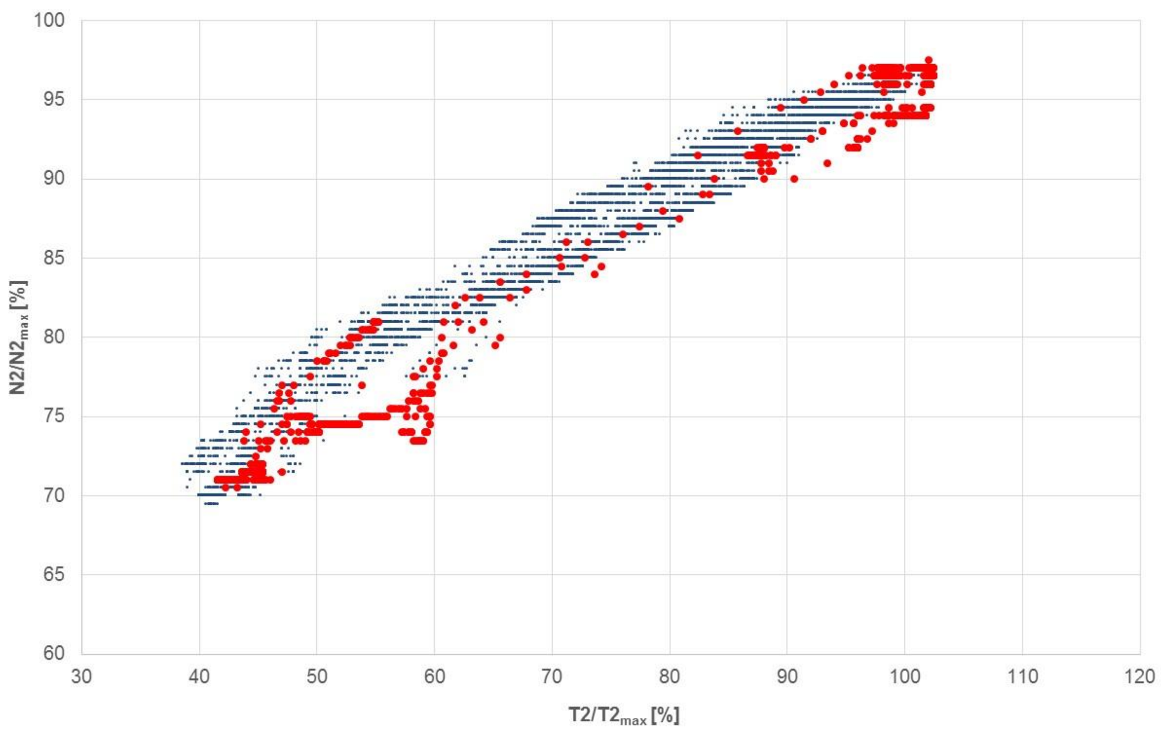

Fig. 9. The comparison of parameters in the F100-PW-299 engine operating range recorded during preflight tests (•)of an F-16 fighter (·)

The distribution of analyzed parameters in the engine operating range indicates the possibility of designating the field of engine work. The field engine work with the afterburner engaged can be easily distinguished. From the point of view of harmful compounds emissions, this area is very interesting because the instantaneous hourly fuel consumption is about 25,400 kg/h and the combustion process is carried out in the afterburner chamber, nozzle, and open space, but is insignificant due to its low share in the total engine operation. Therefore, their analysis will be omitted in the preflight tests on stationary engine bench tests.

3.3. The designing of the test to assess the harmful compounds emission in the exhaust of the F100-PW-299 engine in the real operating conditions of an F-16 aircraft

Knowledge of the turbine engines performance criteria, and the similar distribution of operating parameters for the preflight test conditions and operating conditions of the aircraft during the flight, allows for the development of a universal test to assess the harmful compounds emission from turbine aircraft engines. Test development and its implementation in the field of diagnostic procedures could help reduce the laborious and time-consuming tests to verify the technical condition of the aircraft drive systems. Therefore, the development of a test was done while adopting the following assumptions:

– the test should be representative of all multi-role fighter aircraft powered by turbojet engines; the results of emissions measurements during the stationary test should be similar to the results obtained during the exhaust emission tests carried out in real operating conditions,

– the test should not exceed 3 phases, and their selection should be close to the most commonly occurring load parameters of the drive system during its operation (using idling, partial and maximum engine load),

– the test should be within the range of carried out preflight tests.

The third of these assumptions is very important, due to the fact that the duration of the preflight test is counted as operational service life of an aircraft engine. Therefore, it would be advisable that the duration of the test did not reduce the aircraft lifespan.

The recorded operating parameter values of selected flights were also used as the input for the construction of the harmful compounds emissions test. After the initial statistical processing the available data was divided into three ranges of the N2 turbine shaft speed (Fig. 10). Accepted ranges of rotational speed of the N1 turbine shaft are: A – 70-80% of $N2_{max}$, B – 81-90% of $N2_{max}$, C – 91-100% of $N2_{max}$. The engine operating time for these ranges of N2 shaft speed was specified as percentage shares of total flight time. These percentage shares of total flight time for the different ranges are as follows: for A – 13%, B – 57%, and C – 30% of the total flight time. Thus, the test points were determined at the individual operating parameter settings with the corresponding phase involving the specific harmful compounds emission (Tab. 2). A visualization of the accepted test is shown in Figure 11.

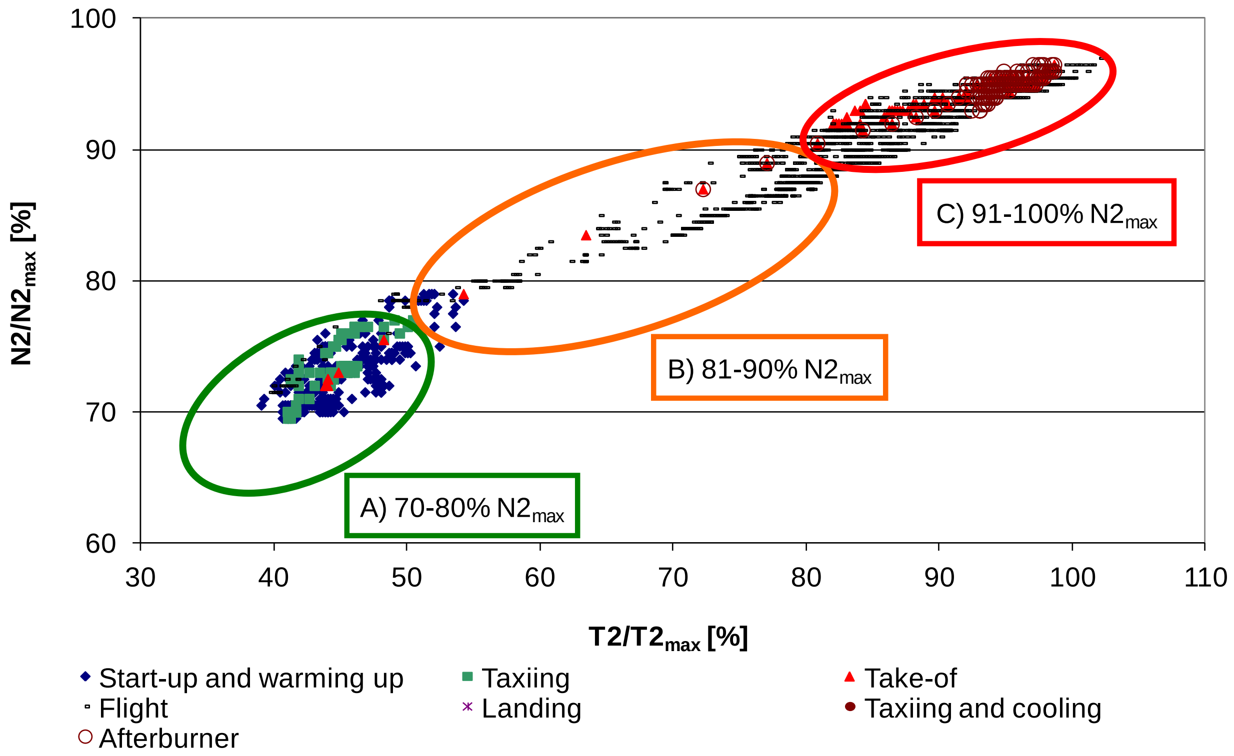

Fig. 10. N2 shaft speed ranges divided into test phases

Tab. 2 Tests phase charactersytics

Test phase	A	B	C
$N2/N2_{max.}$	0.75	0.85	0.93
P/Pn	0.75	0.85	0.93
Phase involving	13	57	30

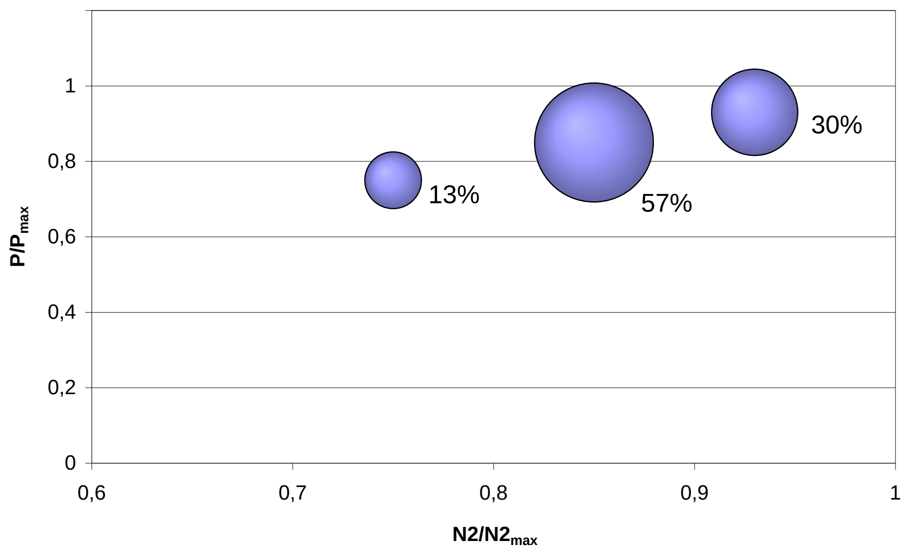

Fig. 11. Characteristics of the phases and their shares in the proposed universal stationary test for multi-role aircraft with turbine engines

Determining the average share of the different phases duration in the overall airplane flight time (Tab. 2), and summing the product of the emission values in a particular flight phase with the overall time share of that phase, the emission values for individual compounds during the whole flight can be determined, using the equation (1):

$$E_j = \sum E_{ji} \cdot u_i \; [g] \qquad (1)$$

where:

E_{ji} – specific emission value for a given load [g],

u_i – the share of time for a given load in the whole test [–].

3.4. Evaluation of the harmful compounds emission in the exhaust of the F100-PW-299 engine under the emission test conditions for the F-16 fighter aircraft

To determine the emission of harmful compounds contained in the exhaust gas of a turbine jet engine in the proposed test it is necessary to determine the flow of the gas stream at the designated values of the operating conditions. The value of the exhaust mass flow and information about the concentration values of various toxic compounds contained within it will determine the value of the emission of these compounds. Flue gas stream flowing from the engine nozzle was determined on the basis of the measured excess air ratio in the exhaust stream flow axis (Fig. 12).

Fig. 12: Positioning of the probe in the axis of the exhaust stream from the engine outlet nozzle

About fourteen kilograms of air is necessary in order to obtain a total and complete combustion of one kilogram of fuel, and for such conditions of the combustion process the excess air ratio equals one. By measuring the value of the excess air ratio in the exhaust and a fuel consumption measurement at a given operating point the engine exhaust mass flow rate can be determined. The values of the excess air ratio in the exhaust gas, fuel consumption and the calculated value of the exhaust mass flow rate at the respective operating points is shown in Table 3. This table also contains the concentrations of the respective compounds in the exhaust gas at the designated operating points.

Tab. 3 The values of excess air ratio in the exhaust gas, fuel consumption, exhaust mass flow rate and the concentration of harmful substances in exhaust gases at set parameters of the test phases

Test phase	A	B	C
Excess air ratio in the exhaust gas [–]	8	7	5
Fuel consumption [kg/s]	0.17	0.19	1.71
Exhaust mass flow rate [kg/s]	18.8	22.3	167
Concentration CO_2 [%]	2.0	2.3	2.6
Concentration CO [ppm]	80	80	75
Concentration HC [ppm]	15	15	15
Concentration NO_x [ppm]	40	70	200

Through determining the exhaust mass flow rate and the harmful substances concentration in exhaust gases the harmful compounds emission intensity in the exhaust gases during engine operation at the individual operating points was obtained (Tab. 4).

Tab. 4 The values of the harmful gases emission intensity at the designated parameters of the test phases

Phase	A	B	C
Emission intensity CO_2 [g/s]	376	513	4359
Emission intensity CO [g/s]	0.015	0.018	0.126
Emission intensity HC [g/s]	0.0028	0.0033	0.0252
Emission intensity NO_x [g/s]	0.0075	0.0156	0.3354

Using the previously presented equation (1), the calculation of the harmful compounds emission in exhaust gases for the developed emission test representing the actual operating conditions of the F-16 aircraft in flight was carried out. The products of emissions intensity and time shares of each test phase have been summed. The results are shown in Figure 13. Emission of harmful substances contained in exhaust in the proposed test was: CO_2 – 164,959 g, for CO – 4.99g, HC – 0.98 g, NO_x – 11.05 g.

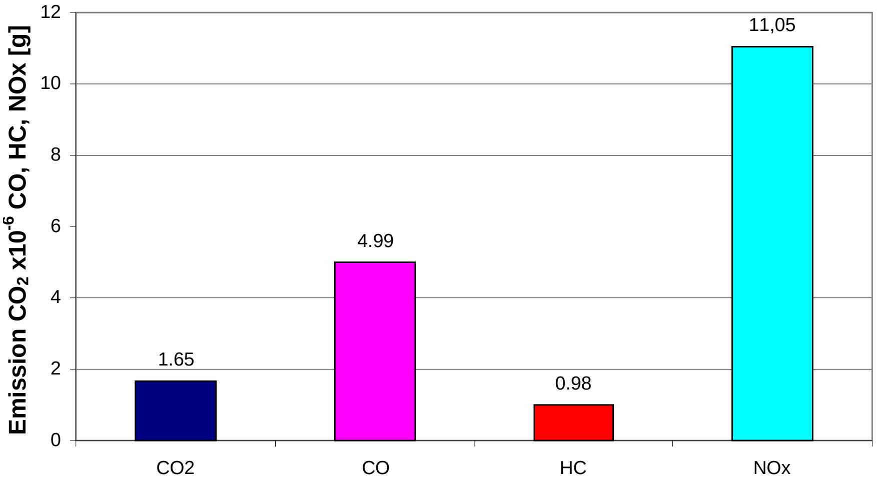

Fig. 13. Emission of toxic compounds contained in the exhaust of the F-16 engine during the proposed test

4. Conclusions

The evaluation of harmful compounds emissions found in the exhaust of the F-16 fighter's F100-PW-299 engine was an attempt to develop a research methodology, aimed at the use of harmful exhaust components emission measurements in the process of diagnosing the operational state of the multi-role fighter aircraft. The information obtained can be used to further verify and develop test procedures. The study should be regarded as a preliminary attempt in developing new procedures. Analysis of the results indicated a significant problem of increased concentrations of carbon monoxide and hydrocarbons in the initial engine operating range, which includes the start-up and warming. These results should be correlated with results obtained for several of the same aircraft types. Finally, the implementation of this type of research may help determine universal test procedures for defining the aircraft emissivity and their environmental impact.

The emission evaluation of a F100-PW-299 engine exhaust's harmful compounds of an F-16 fighter aircraft is an attempt to develop a research methodology, aimed at the use of emission measurements of harmful exhaust compounds in the multi-role aircraft operational state diagnostic process. The information obtained can be used to verify and develop test procedures. The study should be regarded as of preliminary nature. Analysis of the results indicated a significant problem of increased concentrations of carbon monoxide and hydrocarbons in the initial engine operating range, which includes start-up and warming. These results should be correlated with results obtained for several of the same aircraft types. Finally, the implementation of this type of research may help determine universal test procedures for defining the aircraft emissivity and their impact on the environment.

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