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Estimation of particles emissions from a jet engine in real flight

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Abstract. The article presents the results of particles measurements from a jet engine. Engine parameters were analysed during the actual flight and an attempt was made to map it in stationary tests. Research results were supported by correlation analysis. Based on measurements of particulate matter it was found that the most favourable conditions for particle formation occur during taxiing. Mass distributions were presented and emission factors were determined for three basic phases: taxiing, take-off and approach. The applied research methodology was based on the latest guidelines and was expanded to include propositions related to the analysis of engine operation in real flight conditions.

1 Introduction

Particles emitted by aircraft engines adversely affect human health and contribute to deterioration of air quality. Particles with a diameter of 10 μm or less can cause various diseases and related deaths. The severity of diseases is combined with the long-term effects of particles in the environment. They contribute to the occurrence of diseases such as asthma and bronchitis. They are also one of the causes of cardiac arrhythmia and heart attacks. The most important problems arise from the interaction of fine particles. The lowest resistance to the negative effect of particles is demonstrated by people with heart and lung diseases, the elderly and children [1, 2]. It is assumed that the diameters of particles emitted by aircraft engines are not larger than 2.5 μm and can be divided into primary and secondary particles. Primary particles consist of a non-volatile fraction of carbon (mainly black carbon) and other components that accumulate on the carbon core, using it as the nucleus of condensation. Primary particles include nitric and sulfuric acid, water and heavy hydrocarbons containing up to 30 carbon atoms. The diameters of the discussed particles reach values of several dozen nanometers.

The secondary particles are formed as a reaction result of the primary particles and other exhaust toxic components, such as nitrogen oxides, sulfur oxides and light hydrocarbons. The products of reactions occurring on particles that can be found in the composition of secondary particles are: ammonium sulphate, ammonium nitrate and other compounds, mainly hydrocarbons. Research shows that as much as 70% of the particles emitted by aircraft engines are associated with the emission of nitrogen oxides, 14% are primary

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particles, 12% of particles are associated with sulfur oxides, and 4% are formed with hydrocarbons [3–5]. Due to complicated processes of particle formation, the measurement of their emissions is very difficult. The approval process for jet engines with thrusts greater than 26.7 kN is based on the LTO (Landing and Take-Off) test but it doesn't include particles measurements. The main assumption of the LTO test is to reduce exhaust emissions in areas adjacent to airports, which is why it includes operations performed by the aircraft at an altitude of less than 3000 feet. The individual phases of the test (taxiing, takeoff, climb and approach) correspond to the constants of thrust force, so the procedure can be described as a four-point test. There are procedures for estimating particles emissions, but they are based on the LTO test, which is a clear simplification of engine operation conditions during air operations. Due to the above fact, the search for a methodology allowing to carry out reliable measurements of particles emission while maintaining the actual engine operation parameters is underway.

2 Methodology

2.1 Purpose and scope of the research

The research was divided into three stages. The first was a research flight made to get information about the engine's operation parameters during taxiing, takeoff and approach. Then, the engine test on the dynamometer and the measurement of particles number (PN) was made. Engine parameters obtained during the flight and in stationary tests were subjected to correlation analysis. In the last step, the most important parameters of PN emission were determined.

2.2 Research objects

The research flight was made by a multi-task F-16 fighter (Fig. 1). On-board equipment allowed the registration of drive system parameters. The aircraft was equipped with the Pratt & Whitney F100-PW-229 engine. The research object was Pratt & Whitney engine, F100-PW-229. It is a turbofan, twin-shaft engine with three-stage low pressure compressor and a ten-stage high pressure compressor. More detailed specification of the engine is shown in Table 1.

Fig. 1. The view of F-16 fighter.

Table 1. Technical data of the F100-PW-229 engine.

Parameter	Value
Maximum diameter	1080 mm
Length	4855 mm
Engine weight	1370 kg
Maximum thrust	79.13 kN

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2.3 Measuring apparatus

Measurement of particle diameters was performed with an EEPS 3090 (engine exhaust particle sizer™) (Fig. 2a). It enabled the measurement of a discrete range of particle diameters (from 5.6 nm to 560 nm) on the basis of their differing speeds. The degree of electric mobility of particulate matter is changed exponentially, and measurement of their size is carried out at a frequency of 10 Hz. In addition, the Semtech DS gas analyzer (Fig. 2a) was used. The above apparatus is used to measure the concentration of exhaust gas compounds. It allows, however, to additionally determine the excess air coefficient, which allowed to perform additional calculations to determine the exhaust mass flow. Measurements of carbon dioxide allowed to determine the dilution coefficient. Diagram of the measurement system used for testing was shown in Fig. 2b.

a) b)

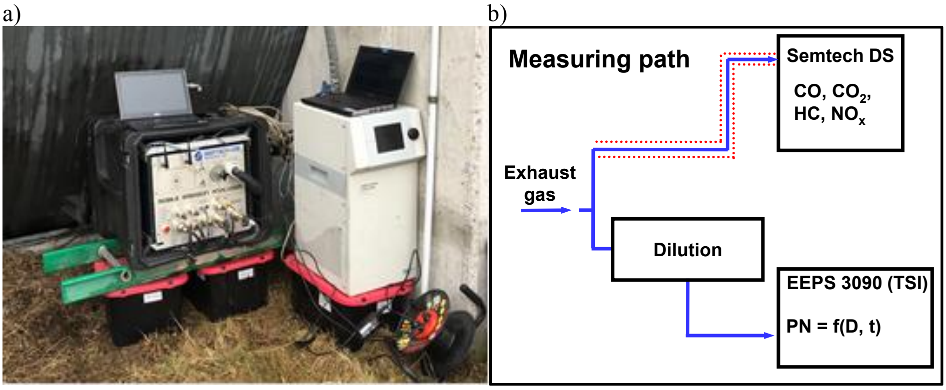

Fig. 2. The view of the apparatus during measurements (a) and diagram of the measurement system.

According to the literature, particles forming behind the engine nozzle have a significant contribution to the total particulate matter emission [6–9]. This is due to the presence in the exhaust gases chemical compounds containing sulfur, hydrocarbons and nitrogen, which in contact with air and other particles cause the formation of the so-called of secondary particles. Due to the above fact, it is necessary to measure the PN at an appropriate distance from the engine outlet nozzle, which is necessary to ensure a specific contact time of the exhaust gas with the air. Based on the literature analysis, it was assumed that the PN measurement should be carried out approximately 25 m behind the engine [8–10]. Figure 3 shows the probe 25 m behind the engine outlet nozzle.

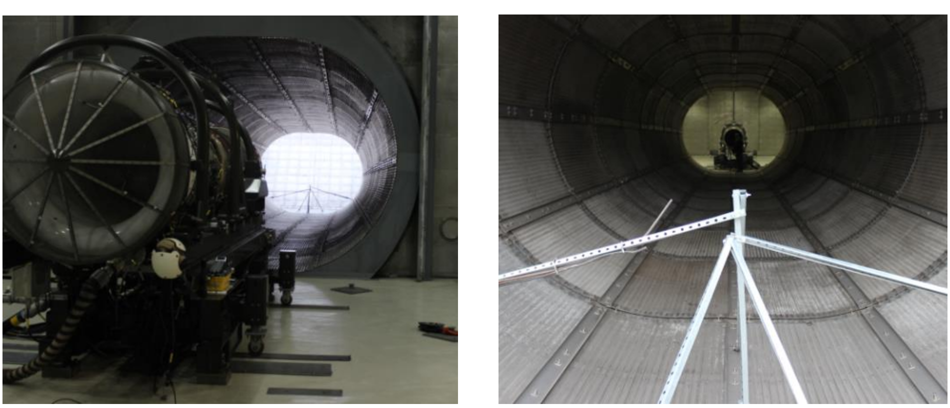

Fig. 3. Location of the measuring probe.

Due to the mixing of exhaust gases with air during the PN concentration measurement, there is a significant dilution of the exhaust gases. In order to determine the dilution rate, it was necessary to measure the carbon dioxide immediately after the engine outlet nozzle and at a distance of 25 m. Additionally, to correctly determine the number of particles created due to the engine's operation, it is necessary to determine the PN concentration in the air.

3 Results and analysis

3.1 Research flight

The record of the propulsion parameters of the combat aircraft was carried out during a training flight. The data recording was carried out by on-board recorders, being a standard equipment of the F-16 fighter. The data from the recorders was divided into three phases: taxiing, take-off and approach. The taxiing phase refers to the time in which the aircraft is traveling on or before the runaway. In the case of a research flight, the total time of taxiing before take-off and after landing was 964 s, which accounted for 81% of the total test flight time. The take-off phase is defined as the period in which the aircraft increases speed in order to achieve the minimum lift force value needed to tear off the aircraft and initial climb to 1000 m above sea-level. The take-off phase accounted for 7% of the total flight time of the test flight and lasted 78 seconds. The approach is a period in which the aircraft reduces its height (from 1000 m above sea-level) in order to touch down and start taxiing. The approach took 150 seconds, which was 12% of the duration of the research flight. The average speed of descent during the maneuver was equal to 5.3 m/s.

The parameter relative to which the drive system is directly controlled is the position of the power lever. Due to the above fact, a further analysis of the operating parameters of the propulsion system registered in the research flight was carried out in the field of the power lever position (Z). The most important parameters of the engine operation were fuel consumption (FC) and fan speed (N_1), which are shown in Figure 4.

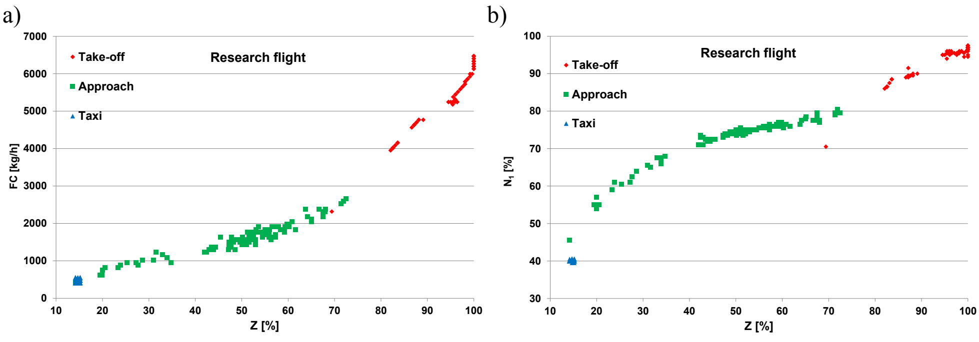

Fig. 4. Fuel consumption (a) and fan speed (b) obtained during individual phases of research flight.

Recorded parameters of the propulsion system have been grouped into phases (taxi, takeoff, approach) based on the time of each maneuver. The above fact allowed assigning ranges of power lever position values to individual phases according to Table 2. Additionally for the purpose of further analyzes, the above intervals were divided into smaller ones in order to determine the time share of particular groups of points in the given phases of the research flight. The taxi phase due to the small range of changes in the power lever position has not been further divided.

Table 2. Division of engine work points relative to the power lever position.

Taxi					
Interval (Z)	<14;20)%				
Time share	100%				
Approach					
Interval (Z)	<20;30)%	<30;40)%	<40;50)%	<50;60)%	<61;75>%
Time share	6%	6%	28%	51%	9%
Take-off					
Interval (Z)	<80;90)%		<90;100>%		
Time share	27%		73%		

3.2 Stationary tests

3.2.1 Engine parameters

Measurements of the engine operation parameters were carried out as part of a trial after standard engine service. The engine test lasted 87 min and included an engine test at various work points. For the purpose of analysis of engine operating parameters during stationary tests, only those work points were selected which were considered useful due to the mapping of engine operation during the research flight. The selected points have been classified in relation to the position of the power lever in accordance with Table 2. Fuel consumption (FC) and fan speed (N_1) measured on stationary test are shown in Figure 5.

a) b)

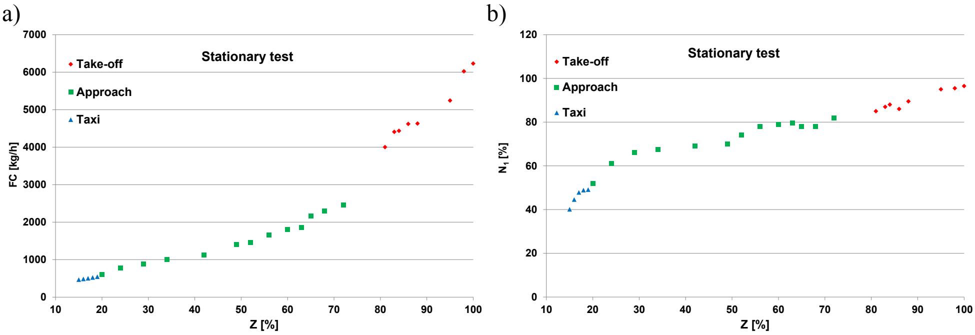

Fig. 5. Fuel consumption (a) and fan speed (b) obtained during stationary test.

3.2.2 Correlation of engine parameters

In order to show the dependence between engine operation in flight conditions and in stationary tests, a correlation analysis of obtained parameters in relation to the position of the power levers was performed. Parameters analyzed were fuel consumption (FC) and fan speed (N1). Figure 6 presents the results of the correlation according to Pearson's correlation coefficient. Obtained data in both cases show very strong dependence of parameters obtained in flight conditions and stationary tests. The above fact indicates very good mapping in the stationary test of the engine's operating conditions during the actual flight. This provides the basis for analyzing the results of particles measurement and relating them to individual operations performed by the aircraft in real operating conditions.

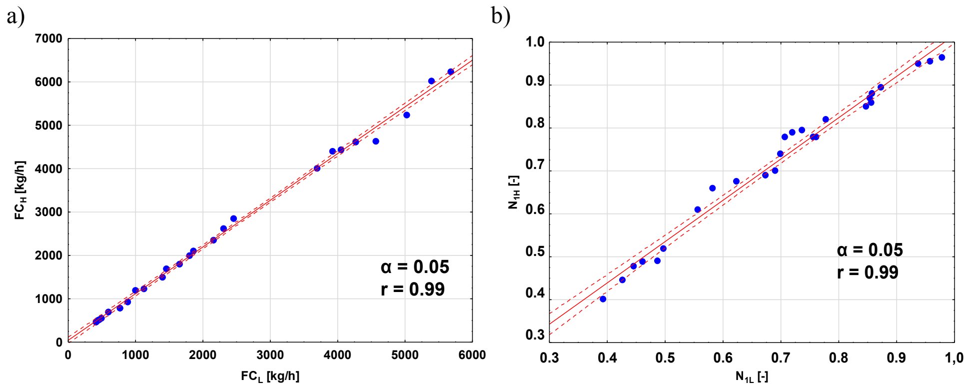

Fig. 6. Correlation analysis results of engine parameters obtained during flight (FC_L, N_{1L}) and stationary test (FC_H, N_{1H}).

3.2.3 Particles measurement results

At individual points of the engine operation, the particles mass distributions were measured. In order to present the particles mass concentration results (PM) depending on the diameter, it was necessary to average the obtained dimensional distributions in the individual phases of the research. Due to the fact that the time share of individual work points differed, it was necessary to assign weights. The weights were determined on the basis of the individual work points timeshare presented in Table 2. On this basis, the equation 1 was determined, which allows to determine the average dimensional distribution in a given phase on a weighted average basis.

$$PM_p(D) = \frac{\sum_{i=1}^{n} a_i PM_i(D)}{\sum_{i=1}^{n} a_i} \qquad (1)$$

where:
$PM_p(D)$ – average mass distribution of particles emitted in each phase,
$PM_i(D)$ – mass distribution of particles in each engine work point,
a_i – weights of each mass distribution based on time share of each work point in whole phase,
n – number of engine work points in each phase,
D – diameter of particles.

During determining the average particle mass distributions (Fig. 7), the degree of exhaust gas dilution resulting from the sampling of exhaust gases at a certain distance from the outlet nozzle was taken into account. The degree of exhaust gases dilution was determined on the basis of the measurement of the carbon dioxide concentration immediately after the outlet nozzle and at the place of analyzed gas sample collection. All obtained mass distributions are bimodal with distinct characteristic diameters. In the case of taxiing, the main part of emitted particulate matter corresponds to particles with the size of 8–40 nm. Solid particles with dimensions greater than 100 nm correspond to approximately 20% of the total mass emitted. Landing is characterized by a more balanced distribution. Most of particulate matter emission is caused by the particles with diameters greater than

50 nm. The take-off operation in terms of particles mass emission was dominated by particles with diameters in the range of 6–40 nm. This is due to the fact that at a high combustion temperature nucleating fraction of the particles predominates.

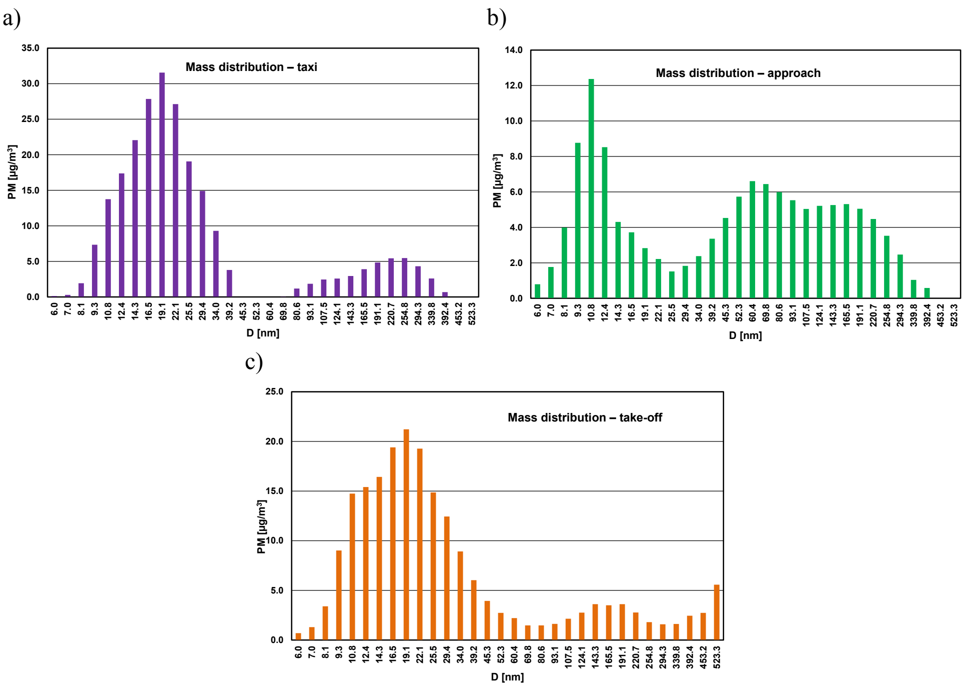

Fig. 7. Particulate matter distribution in each phase: taxi (a), approach (b) and take-off (c).

On the basis of the excess air coefficient and fuel consumption measurements, the emission factor of the particulate mass per 1 kg of fuel was determined according to the formula:

$$WPM = \frac{m_f \cdot TPM}{G_e} \left[\frac{\mu g}{kg_{fuel}} \right] \tag{2}$$

where:
m_f – exhaust mass flow,
TPM – total concentration of particles in averaged mass distribution for each phase,
G_e – fuel mass flow.

Figure 8 shows the values of the WPM coefficient for individual phases. The largest mass of particles is generated during taxiing. From one kilogram of fuel the engine produces $2.7 \cdot 10^5$ µg. The above fact results from the dimensional distribution of the emitted particles. During taxiing, larger particles are emitted than in case of landing or taking-off. Taxiing is an operation that lasts the longest and is directly affecting the quality of air, which is breathed by airport employees and passengers.

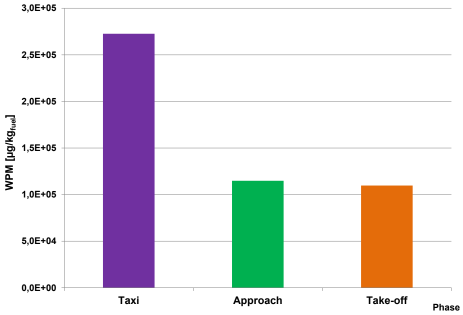

Fig. 8. Value of WPM coefficient in each phase.

4 Conclusions

The research has been carried out in accordance with the latest guidelines for the measurement of particles emissions from jet engines. The extension of the methodology with the analysis of engine operation parameters in real flight and their correlation analysis with the parameters in stationary tests is the author's contribution. The results of particulate matter emission tests showed significant differences between individual aircraft operations. The presented test results indicate that during taxiing operation from one kilogram of fuel the biggest mass of particulate matter is produced. This is extremely disadvantageous from the point of view of air pollution, because the emission takes place on the ground, therefore the dispersion of particulate matter is more difficult in comparison to the other air operations. Particles emission from air transport contribute to environmental pollution mainly in the local aspect. Cities are increasingly closer to airports, and because of that air traffic contributes to increase the concentration of particles in urban areas. This mainly concerns particles of the smallest size (up to 500 nm), whose mass is relatively small and therefore they do not increase the value of the mass concentration to which the assessment of air quality is carried out. However, it should be noticed that the smallest particles (mainly from combustion engines) are the most dangerous for human health.

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