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# Particle emission parameter analysis from multirole fighter aircraft engine

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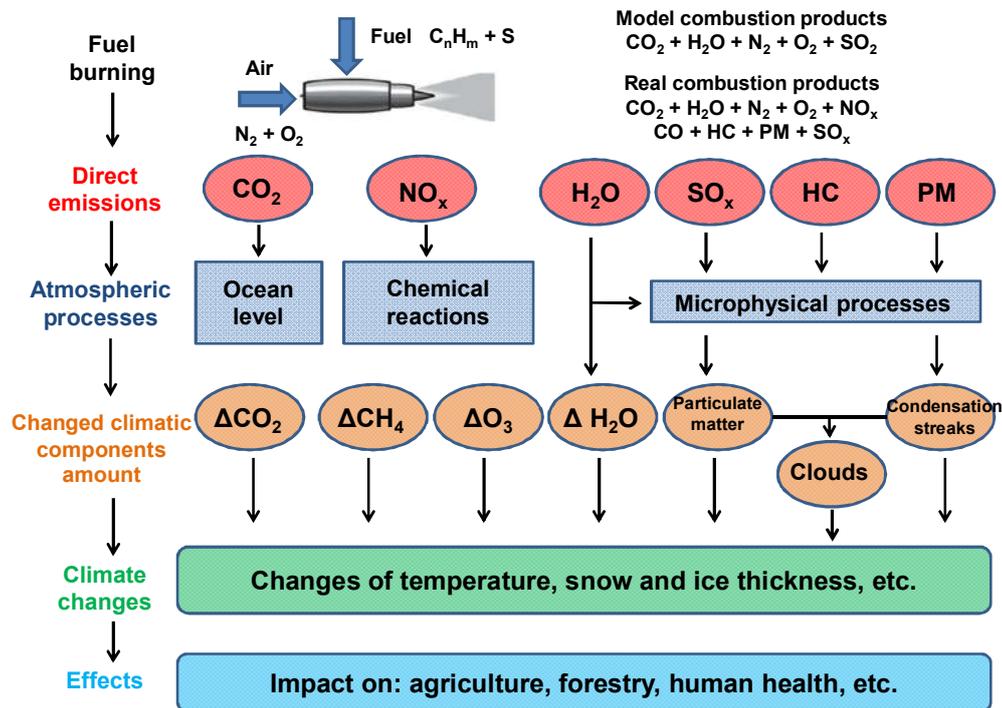
**Abstract.** The topic of emissions from combustion engines has gained a lot of interest in the scientific community and involved public opinion due to the known association between exposure to multiple air pollutants and short and long-term effects on human health. The growing knowledge of the processes involved in the creation of air pollution from combustion engines and a dynamic development of emission measuring devices lead to the creation of new rules and conditions for the certification of aircraft engines. The article presents an analysis of the size distribution of particles emitted from jet engine. Studies were performed in stationary conditions on an engine dynamometer. The aim of the study was to determine the size and mass distributions of particles emitted by jet engine in different operating parameters. The main subject of the analysis were total concentration and size distribution of particles. On the basis of those data, mass distributions of particles were calculated.

## 1. Introduction

The dynamic development of aviation and increase in volume of air transport are not environmentally indifferent. During fuel burning in an aviation engine, many toxic substances such as carbon monoxide, nitrogen oxides, hydrocarbons and particles are formed (figure 1) [1, 2]. All identified substances negatively affect environment, human health and contribute to premature mortality. The effects of air transport activities are particularly dangerous in the immediate vicinity of the airport. There are a number of scientific publications [3-5] presenting quality of the air in the vicinity of the airports that indicate the existence of the threat.

One of the fundamental issues in assessing air quality is the concentration of particulate matter. Particulate matter is a term generally used for the type of air pollutants, consisting of a complex of different mixtures of suspended particles that differ in size, composition and location of formation [6]. The main sources of this type of pollution include: factories, power plants, motor vehicles and many more. The basic particle classification results from their aerodynamic diameter, which allowed for the identification of two main groups: PM<sub>2.5</sub> and PM<sub>10</sub> (Particulate Matter) for diameters of less than 2.5 μm and 10 μm, respectively [7]. The dynamic development of the knowledge about particulate matter and the changes in its properties, depending on the size, have forced a more detailed division. It has been assumed that ultrafine particles are particles with a diameter of less than 0.1 μm and fine particles (also called nanoparticles) are particles smaller than 1 μm [8].





**Figure 1.** Impact of aircraft engines on people and the environment.

The main reason of the particles classification respectively to their size is due to their different effects on human health. Particles classified as  $PM_{2.5}$  can very easy get into the respiratory system, from where they penetrate into the blood. The most serious problems arise from the action of fine particles. The smallest resistance to negative impact of solid particles is shown by people with heart and lung diseases, the elderly and children. Exposure to particles results in increased risk of cardiovascular and respiratory diseases and causes premature mortality. Many publications indicate that particle emissions are significantly predominant in terms of negative health effects and far outweigh the emission of other toxic components of flue gases [9, 10, 11].

As regards particles impact on the climate, the term black carbon is used. Black carbon is a constituent of solid particles with very strong light absorption. It is due to incomplete combustion of fossil fuels, biofuels and biomass. Apart from anthropogenic origin, it can also be natural. It is defined as a solid form of pure carbon that absorbs sunlight (light) over the entire wavelength range. Black coal warms the planet and promotes melting glaciers, reducing the albedo, the ability to reflect sunlight directed at snow or ice [12].

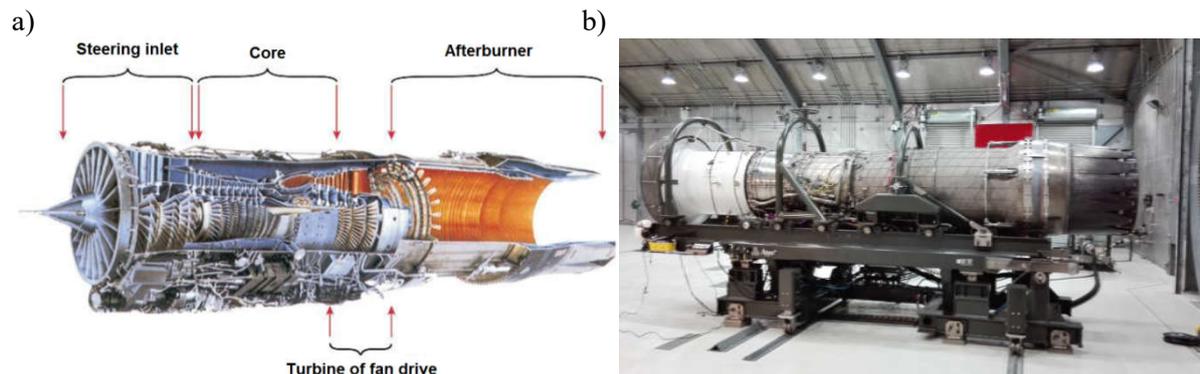
Environmental standards as the primary parameter for air pollution represent the mass concentration of particulate matter. The above fact results in the lack of the possibility of dimensional analysis of the particles. As indicated above, the basic parameter to assess the threat of particles is their size. The relatively small mass concentration of particulates can be linked to their large number and small sizes. The above situation is much more dangerous to human health than the high concentration of large particles.

The paper presents the study of the concentration of particles in the exhaust gas of a turbine engine under stationary conditions. Results obtained were analyzed and the dimensional and mass distributions of emitted particles were determined. The research and analysis of the obtained results allowed to determine the relationship between the number and the mass of the particles from aircraft engine. Conducted studies show that the mass concentration of the particulate matter should not be the only parameter on the basis of which the air quality assessment is performed.

## 2. Methodology

### 2.1. Test object

The research object was Pratt & Whitney engine, F100-PW-229 (Figure 2). This engine is a drive of fighter aircraft F-16. Its maximum values of thrust are 79.13 kN – without the use of afterburner, and 128.91 kN with afterburner. It is a turbofan, twin-shaft engine with hydraulically adjustable nozzle. It is equipped with three-stage low pressure compressor and a ten-stage high pressure compressor. The combustion chamber is annular.



**Figure 2.** Scheme (a) and view (b) of F100-PW-229 engine.

The engine is fitted with anti-icing system, wherein the heating of the engine inlet is managed by air taken from the relief valve at the compressor fifth stage. Technical parameters of the engine are as follows:

- Maximum diameter: 1080 mm,
- Length: 4855 mm,
- Engine weight: 1370 kg,
- Specific fuel consumption: 0.693 kg/(kG h),
- Specific fuel consumption with afterburner: up to 2.6 kg/(kG h).

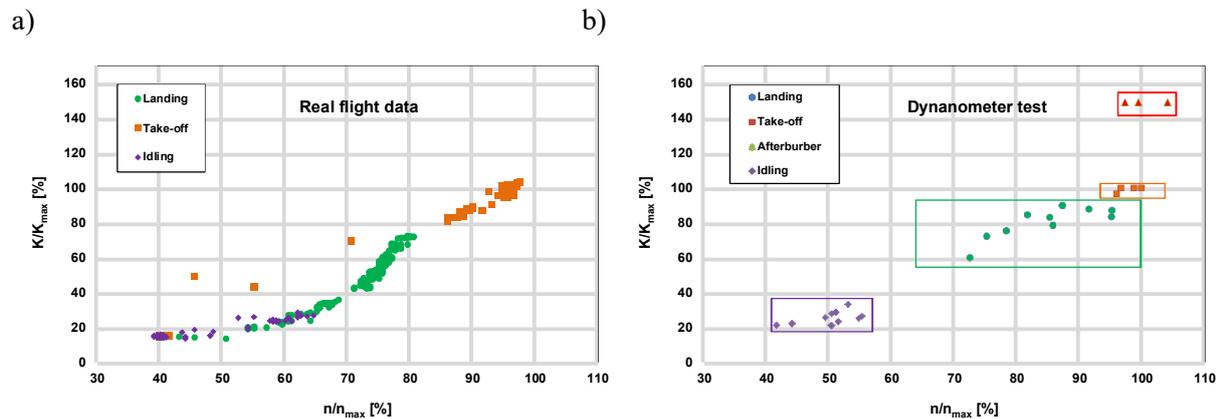
### 2.2. Test conditions

Stationary tests on the engine dynamometer were performed to determine the concentration of particles in the exhaust during engine operation at various parameters. Measurement of particle diameters was performed with a EEPS 3090 (engine exhaust particle sizer™ spectrometer) mass spectrometer. 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. The exhaust gases are routed through a dilution system and to the mass spectrometer while maintaining at the desired temperature. The initial filter retains particles with a diameter greater than 1 micron, which are outside of the measuring range of the device. After passing through the neutralizer the particles are directed to the charging electrode; after getting electrically charged they can be classed by their size. The particles deflected by the high-voltage electrode go to an annular slit, which is the space between the two cylinders. The gap is surrounded by a stream of clean air supplied from outside. Exhaust cylinder is built in a stack of sensitive electrodes isolated from one another and arranged in a ring. The electric field present between the cylinders causes the repulsion of particles from the positively charged electrode; then the particles are collected on the outer electrodes. When striking the electrodes, the particles generate an electric current, which is read by a processing circuit [13].

The engine test was a technical check for various operating parameters. On this basis, particle concentration measurements were made for various engine operating points, giving the opportunity to evaluate the operation of the power unit over the whole speed range and thrust.

### 3. Research results and their analysis

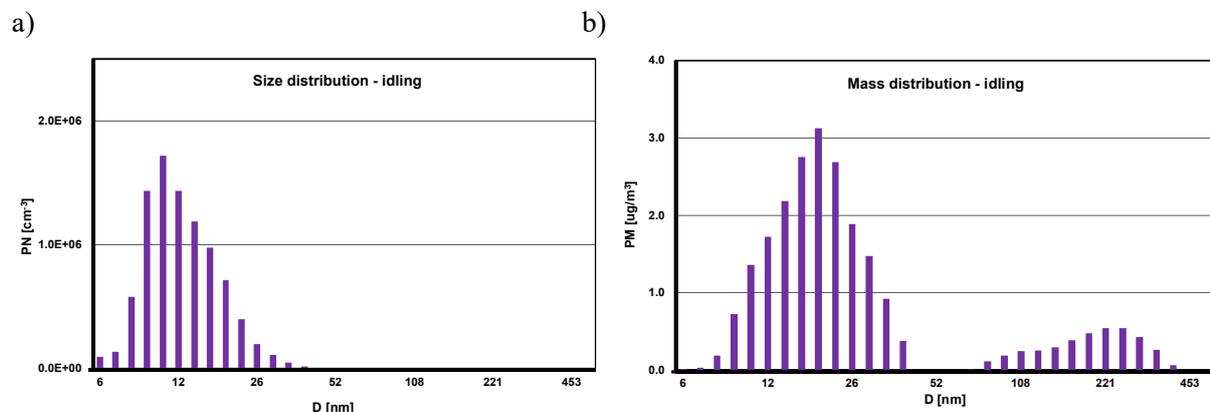
The engine dynamometer test was performed for the whole range of fan speed and the entire thrust range (including the afterburner test). In order to properly interpret and qualify specific points of the engine operation, a data of the propulsion system performance during the actual flight was used (Figure 3).



**Figure 3.** Parameters of the propulsion system during the flight (a) and dynamometer test (b).

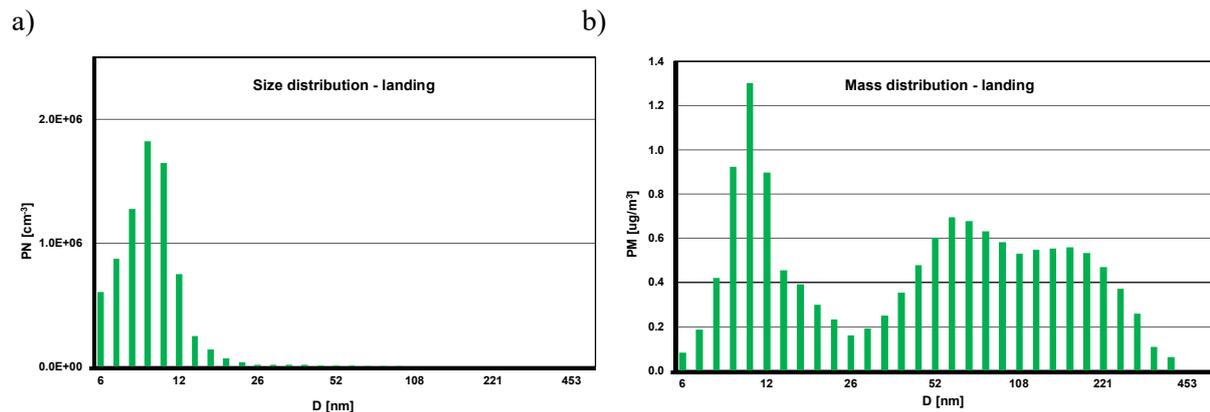
Based on information from the onboard recorder of the operating characteristics of the propulsion system during the flight, the specific engine work points determined during the dynamometer test were allocated to the corresponding flight phases of the aircraft. In this way, the engine's operating points were divided into taxi (20–40% of  $K/K_{max}$ , 40–55% of  $n/n_{max}$ ), landing (40–95% of  $K/K_{max}$ , 55–95% of  $n/n_{max}$ ), take-off (95–100% of  $K/K_{max}$ , 95–100% of  $n/n_{max}$ ), and afterburner (100–150% of  $K/K_{max}$ , 95–105% of  $n/n_{max}$ ). For the above points a particle emission test was carried out, the results of which are shown in figures 4–7. The number of particles, dimensional distribution and mass distribution were determined.

The mean results of dimensional and mass distribution of particles emitted during the propulsion system operating in the conditions corresponding to the taxiing were showed in figure 4. Particles with diameters in range of 10–30 nm were dominant. In the case of the mass distribution, it can be noted that it is represented by two normal distributions. They can be observed for diameters in the range of 20–30 nm and 100–400 nm. By analyzing the above characteristics it can be concluded that apparently insignificant from the number point of view particles (range 100–400 nm) may be very important for mass distribution. In this case those particles accounts for about 30% of the total mass.



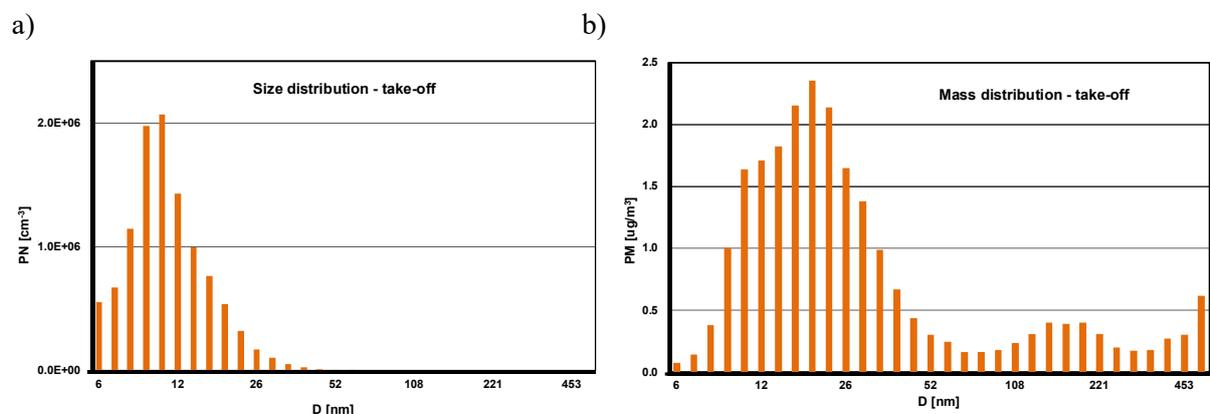
**Figure 4.** Dimensional (a) and mass (b) distribution of particles emitted during the engine operating conditions corresponding to taxiing.

In case of engine operation at the parameters corresponding to the aircraft landing (figure 5), the particle number distribution clearly indicates that particles with diameters in range of 5–25 nm are dominant. Particles with diameters greater than 100 nm represent less than 1% of the total number. However, when analyzing the mass distribution, particles greater than 100 nm are important because they represent more than 30% of the total mass. On the basis of particle mass distribution can be said that the largest share of particles total mass emitted during the landing operation are particles with diameters in range of 20–20 nm and 60–350 nm.



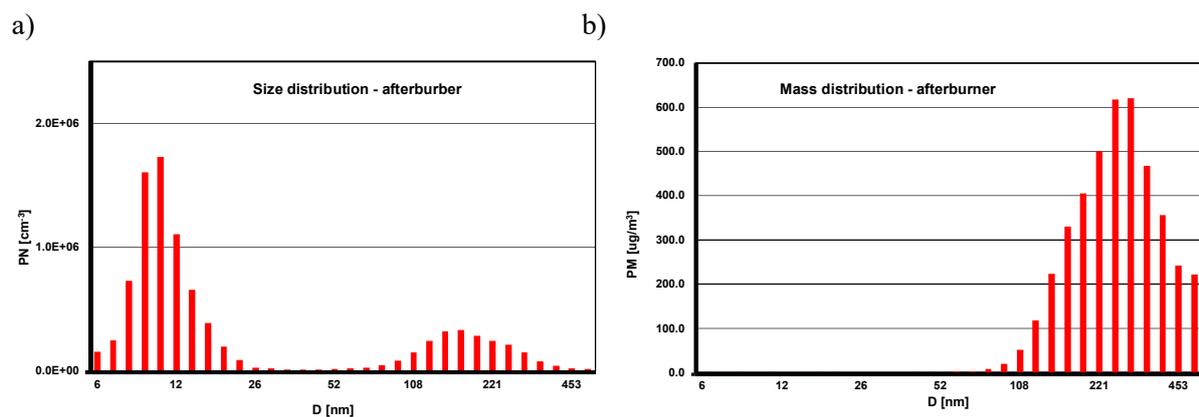
**Figure 5.** Dimensional (a) and mass (b) distribution of particles emitted during the engine operating conditions corresponding to landing.

Characteristics of particles emitted during engine operation under conditions corresponding to the take-off operation were shown in figure 6. The operating conditions of the engine corresponding to the take-off operation are related to the maximum load and its full power. In spite of different operating conditions, particle concentration and dimensional distribution are not significantly different from those of particles emitted during landing or taxiing. Particles in the range of 10–20 nm dominate. It should be noted that even though the concentration of particles is similar to the measured concentration during the landing operation, the emission is significantly different due to the very high increase of the exhaust mass flow, which accompanies the maximum engine power. The resulting particle mass distribution indicates that particles in range of 20–100 nm have a major share of the emitted mass.



**Figure 6.** Dimensional (a) and mass (b) distribution of particles emitted during the engine operating conditions corresponding to take-off.

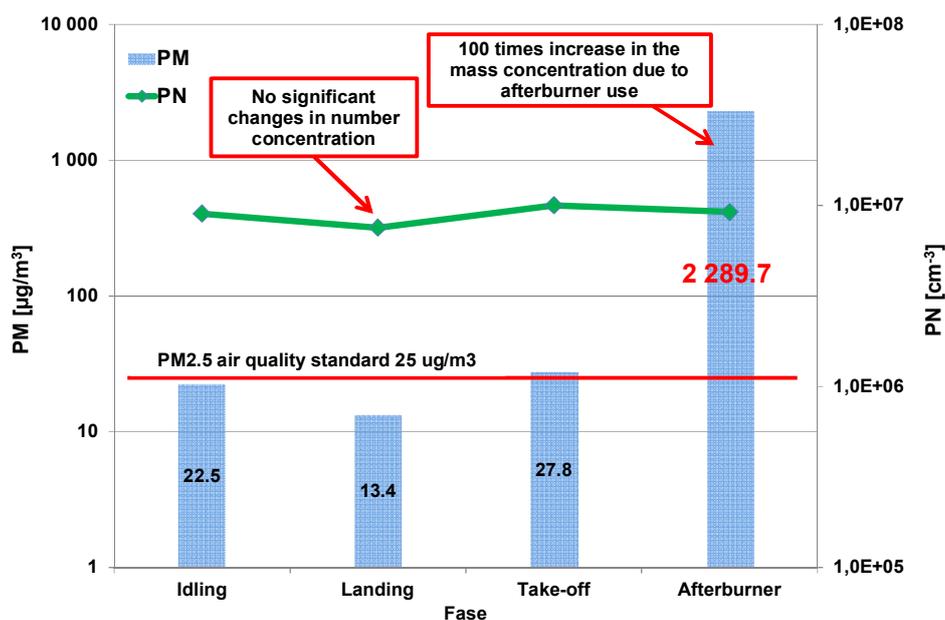
The use of the afterburner involves insertion an additional dose of fuel directly into the exhaust for explosive combustion and generating additional thrust. The above process results in the formation of particles with diameters greater than 100 nm (figure 7). Particles with diameters of 5–30 nm still dominate, but significant share of size distribution have particles with dimensions of 100–300 nm. By analyzing the mass distribution obtained during engine operation with afterburner, it can be seen that the predominant number of particles (range of 10–30 nm) have practically no significance in terms of mass emission. There was a 100 fold increase in the mass concentration of the particulate matter due to the use of the afterburner.



**Figure 7.** Dimensional (a) and mass (b) distribution of particles emitted during the engine operating conditions corresponding to afterburner use.

#### 4. Conclusions

The measurements and the data of the propulsion system parameters during the actual flight allowed the parameterization of the particles emitted by the jet engine during the individual flight phases. The parameters considered were number concentration (dimension distribution) and mass concentration during idling, landing, take-off and afterburner use (figure 8).



**Figure 8.** The sum of number and mass concentration during engine operation at each phase.

The particle concentration in the various phases of the propulsion system is similar. As the engine operating parameters change, the mass flow is changed, so it can be stated that emissions of particles during take-off is bigger than landing or idling. Very important conclusion from the study is that the mass concentration of the particles during landing, taxiing and take-off is approximately  $25 \mu\text{g}/\text{m}^3$ . This value is lower than the air quality standard, which provides  $40 \mu\text{g}/\text{m}^3$ . On this basis it can be stated that the exhaust from the aircraft engine is clear enough to breath accordance with the air quality standard. Obviously aware of the huge number of particles with small diameters, the above statement makes no sense because the fumes are highly cancerogenic and cause diseases and premature mortality. As a result, it is necessary to extend the air quality limit by limiting the number of particles, as the mass concentration does not allow proper determination of the air quality.

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