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Number and mass analysis of particles emitted by aircraft engine

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Abstract. Exhaust emissions from aircraft is a complex issue because of the limited possibility of measurements in flight conditions. Most of the studies on this subject were performed on the basis of stationary test. Engine certification data is used to calculate total emissions generated by air transport. However, it doesnt provide any information about the local effects of air traffic. The main threat to local communities is particulate matter emissions, which adversely affects human health. Emissions from air transport affect air quality, particularly in the vicinity of the airports; it also contributes to the greenhouse effect. The article presents the measurement results of the concentration and size distribution of particles emitted during aircraft landing operation. Measurements were carried out during the landings of aircraft at a civilian airport. It was found that a single landing operation causes particle number concentration value increase of several ten-fold in a short period of time. Using aircraft engine certification data, the methodology for determination of the total number of particles emitted during a single landing operation was introduced.

1 Introduction

Air transport is part of the global transport system due to the high speed and intercontinental range of transport operations. For many years, there has been a strong correlation between the rate of growth in major world economies and the development of air transport [1]. Comparing the growth of world GDP (Gross World Product) and air traffic, it can be noted that the growth rate of air is greater than the growth of the world economy. According to the analysis of the largest aircraft manufacturers (Airbus and Boeing) this is due to a very dynamic development of low-cost transportation, increase in the aircraft capacity, fleet modernization, and the dynamic growth in emerging markets such as China, India and Japan. The Far East market, according to forecasts, will generate the highest growth of 31% of world traffic to year 2029. The rapid development of the Asian market will mean that 27% of the entire global air transport will be taking place in Asia [2]. In the last decade, a twofold increase in global passenger air transport was reported (Fig. 1), while the global cargo increased by 50% (Fig. 2).

The development of air transport is associated with increased external environmental costs which, in accordance with the definition of the European Union includes the impact of the air transport related to: air pollution, climate change and noise among others [3, 4]. Next to the nitrogen oxides, the most dangerous toxic compound of exhaust are particles. Particles emitted by aircraft are responsible for heart disease, lung disease, and early mortality. The above fact was the subject of many research in which it was found that the particles may penetrate deep into the respiratory system [5-8]. Most of studies investigate the effect of the particulate matter mass on humans, without consideration the particle origin [9]. The most dangerous are particles with diameters less than one micron, which mainly come from combustion processes and are referred to as ultrafine particles [10-13].

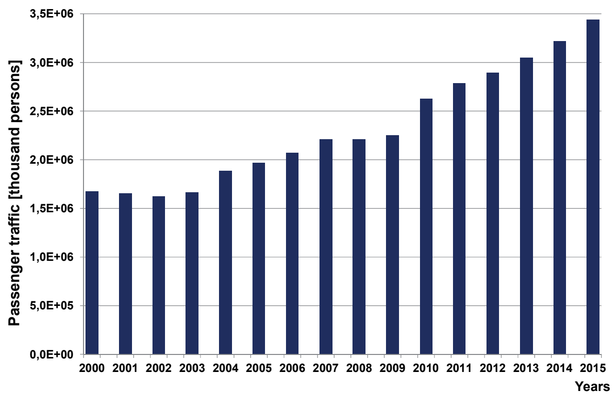

Fig. 1. World passenger air transport in the years 2000-2015 (Central Statistical Office of Poland).

Most of the studies aimed at determining the particle size distribution of the aircraft engines were made within a few hundred meters of the airport. In many studies it has been found that the particle number (PN) emission factors are higher for the operating conditions of engines with low thrust values [14-19]. Therefore, special attention is required for such operations as landing and

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taxiing of aircraft, due to engine conditions that favor high particulate emissions with relatively long periods of time. Under these conditions dominates PN with dimensions of 20–30 nm, resulting from nucleation mode. Besides nucleation mode, there are many processes of forming particles such as: “Aitken mode” with particles in the size range between 25 and 100 nm , “accumulation mode” with particles between 30 and 300 nm, condensation/evaporation, coagulation, dry deposition and dilution [20-25]. In terms of combustion engines the highest particle number concentrations are in the nucleation mode, while most of the mass is found in the accumulation mode [26, 27]. Nucleation particles are particularly formed by condensation within a few seconds after emissions in ambient air. Particles in the accumulation mode are primarily formed in the combustion chamber [20, 28]. Research shows that ultrafine particles may be associated with cardiovascular diseases, while the mass of particles is more important for respiratory effects [29].

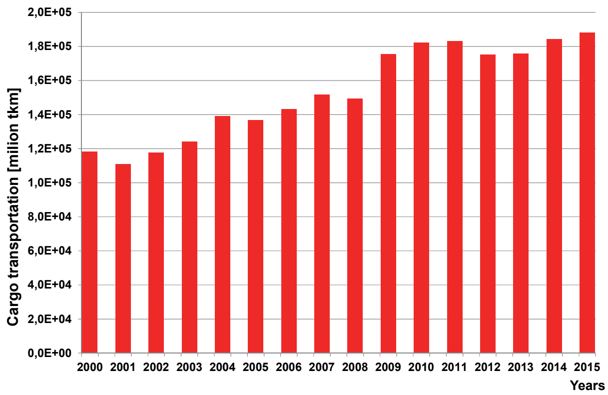

Fig. 2. Global cargo air transport in the years 2000-2015 (Central Statistical Office of Poland).

One of the most important source of nanoparticles (submicron) are airports [30-32]. More and more research is being conducted to evaluate the impact of airport operations on air quality in areas adjacent to airports [33]. In the case of airports, engines are not the only source of particulate matter. Other sources of particulate matter are aircraft tires, brakes, ground handling equipment and others vehicles. In view of the above, it is essential that, in the case of an airport ecological assessment, all sources of particulate matter should be included.

More and more research is about areas adjacent to the airports. In this case, it is necessary to make an effort to model the dynamics of the aircraft plume and the dispersion of pollutants [34]. Publications indicate that nanoparticles from aircraft engines dominate in the radius of 10 km from the airport, and their concentration is up to 4 times higher than in the other areas [35]. This fact confirms the belief that air quality standards based on mass concentrations of particles do not explicitly answer the question of the degree of threat to human health. Air quality standards should be extended by measuring the number of particles. In addition, the LTO (Landing and Take-off) test, which is the basis of aircraft certification, does not really include particulate matter testing. It includes only Smoke Number which is more a measure of exhaust smoke. The conventional approach to toxic emissions from aircraft engines assumes its control only in the phases of take-off, landing and taxiing of the aircraft (LTO). Considered air operations, which are subject to analyzes of the impact of air transport on air quality are held at altitude of up to 3000 feet. This is evidenced by the provisions of the aircraft engines certification (ICAO Annex 16), made with the aim to reduce emissions in areas adjacent to airports. Current research indicates, however, that the issue at cruising altitudes (above 3000 feet) can provide a significant portion of the total emissions affecting human health [4, 36-38]. It may turn out that further research and future assessment of the impact of aviation on air quality will include the full emissions to take account of the overall impact of aircraft on the environment.

Current world trends in the field of environmental assessment of the engines lead to measurements in real operating conditions of the means of transport. This type of measurements are difficult in the case of aircraft because of the size of the measuring apparatus but also for safety reasons. For this reason, attempts of assessment the impact of airports on air quality in areas adjacent take into account the dependencies resulting from measurements of exhaust emissions in stationary conditions. For a deeper analysis of airport operations and their impact on environmental pollution, it is advisable to look for the relationship between measurements made under stationary but also real operating conditions. Due to the technical difficulties associated with the placement of equipment on an aircraft, it is possible to make the assessment of the aircraft operation under specific conditions (such as landing operation) and looking for relationship with results obtained under stationary conditions.

2 Methodology

2.1 Stationary research

Stationary tests were performed on the engine dynamometer during the service test. The research was conducted in 31st Tactical Aviation Base in Krzesiny in western Poland. Due to the fact that the research was conducted at military facility some details of the test object are confidential.

The research object was Pratt & Whitney engine, F100-PW-229 (Fig. 3). 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.

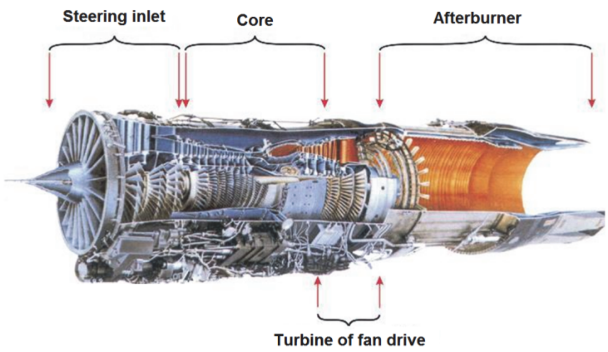

Fig. 3. Cross section of the engine Pratt & Whitney F100-PW-229 [12].

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 (Fig. 4). 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).

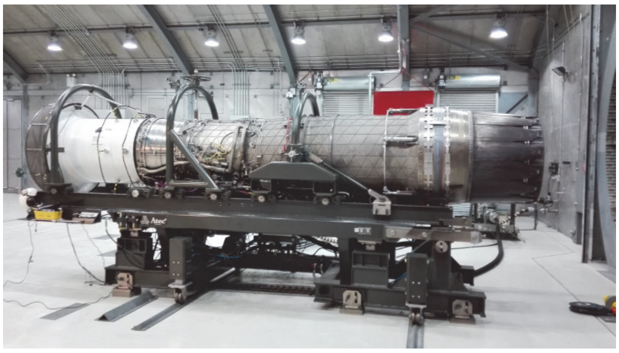

Fig. 4. The view of Pratt & Whitney F100-PW-229.

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 [39].

2.2 Research under real operating conditions

Studies at the military airport were conducted in 31st Tactical Aviation Base in Krzesiny in western Poland, approximately 1.5 km from the aircraft touchdown point. The aircraft used in the tests was F-16 Fighting Falcon Multirole Fighter (Fig. 5). Meteorological conditions on the day of the measurements were characterized by lack of precipitation and wind speed of 10 km/h (Fig. 6). The measuring apparatus was set up in the approach axis for the landing of passenger aircraft (Fig. 7).

Fig. 5. The view of F-16 Fighting Falcon.

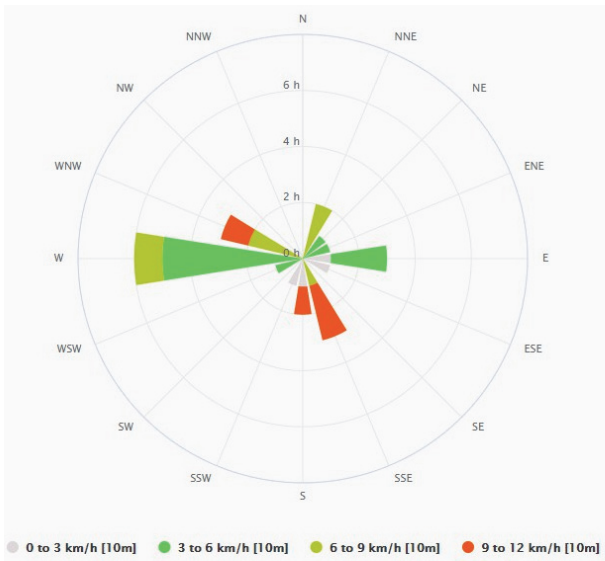

Fig. 6. Wind rose of the research day [meteoblue.com].

The measurements were divided into three phases: pre-landing measurement – to determine the measurement background; measurement during the landing – to determine changes in the concentration of particles during the landing operation; measurement after landing – to determine the maximum concentration of particles.

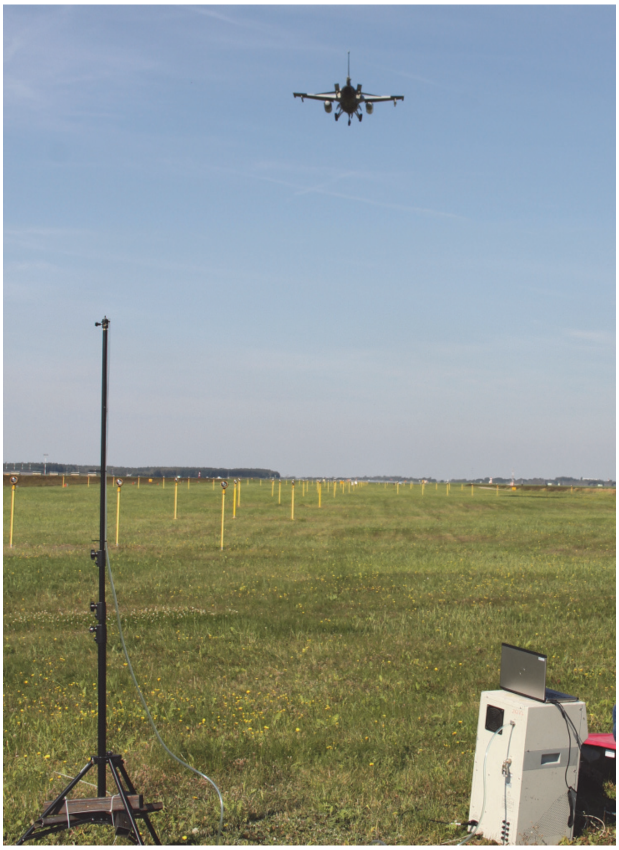

Fig. 7. The view of F-16 Fighting Falcon.

Measurements of the concentration of particles in the ambient air during the landing of the fighter were made 13 times. Landings were made at 15% throttle opening. The same parameters of the engine were set up during engine dynamometer measurements. The descent angle was about the standard 3°.

3 Results and analysis

3.1 Stationary research

The purpose of the research on the engine dynamometer was to determine the concentration of the particles (PN) in the jet engine exhaust gases, operating at the parameters corresponding to the landing of the F-16 fighter. In the initial phase of the measurements, the engine was working at the thrust corresponding to the idling. After engine stabilization (and stabilization of PN concentration), the engine parameters have been changed so that they correspond to the landing (Fig. 8). This was associated with an increase in the value of thrust. According to the literature [14, 15], the increase of thrust value was associated with a decrease in PN concentration directly behind the confusor.

Particles size distribution obtained from the engine during engine dynamometer test is shown in the Figure 9. Particles with diameters of 5–15 nm were dominated. The characteristic value of the diameter of the particles (the most common) obtained distribution was 9 nm. Particles with diameters greater than 20 nm were negligible part of the total concentration of PN. Particles emitted by the jet engine were of the nanoparticle type, mainly formed in nucleation mode.

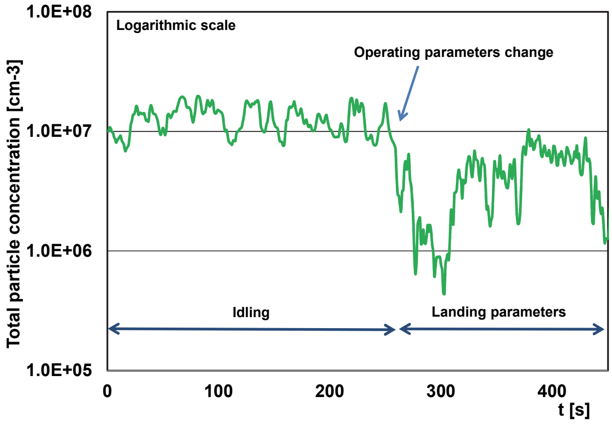

Fig. 8. Total concentration of particles obtained during stationary test.

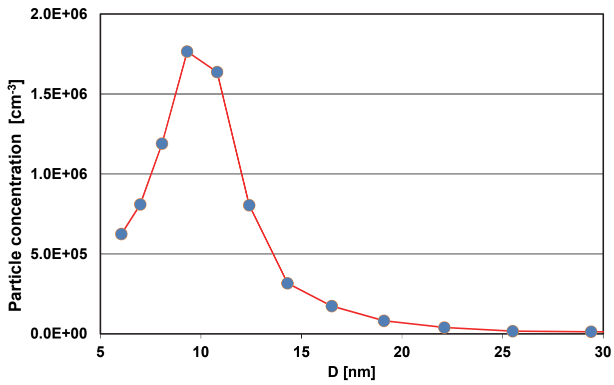

Fig. 9. Size distribution of particles obtained during stationary test.

3.2 Research under real operating conditions

Research of the particles concentration in the air during landing of the aircraft were conducted before, during and after the landings. The measurements were made during the landing of 13 planes, all in the same configuration. The measurements were carried out for few hours. Recorded results are shown in Figure 10. Presented data were reduced of periods in which the concentration of particles was close to the measuring background (long before or after the landing operation).

A detailed record of the change in PN concentration during landing and the process of return to the measured background value is shown in Figure 11. The PN concentration specified as the measuring background was 10^4 cm^{-3}. The landing operation resulted in a 100-fold increase in the concentration of PN which reached 10^6 cm^{-3}. Approximate to maximum PN concentration persisted for about 20 seconds. Then another landing took place, which led to the return to the maximum PN concentration. After about a minute, the particles emitted by the landed aircraft dispersed, which appeared as a return to the measured background value.

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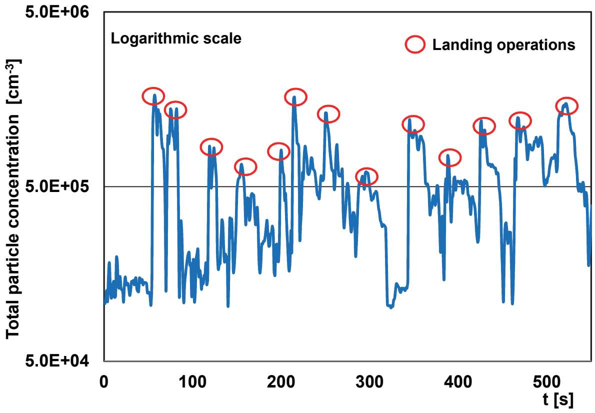

Fig. 10. The record of the PN concentration during research.

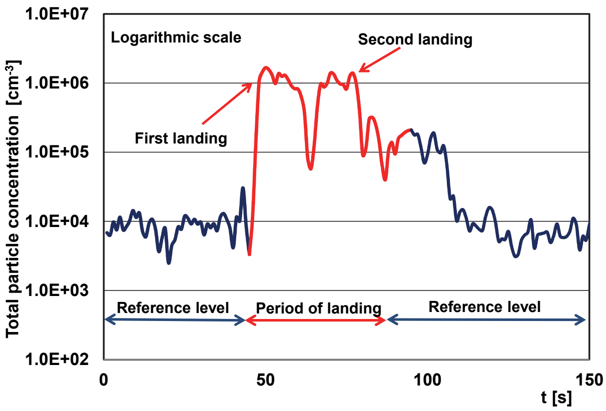

Fig. 11. The process of changes in the concentration of PN during landing.

In the process of analyzing the received measurement results, the maximum PN concentration values during the thirteen landing operations were selected. The data are shown in Figure 12, while the average maximum PN concentration of all tests was 1.13 × 10^6 cm^{-3}. Received value reduced by measuring background was 8 times lower than the PN concentration in stationary tests, just behind the engine exit.

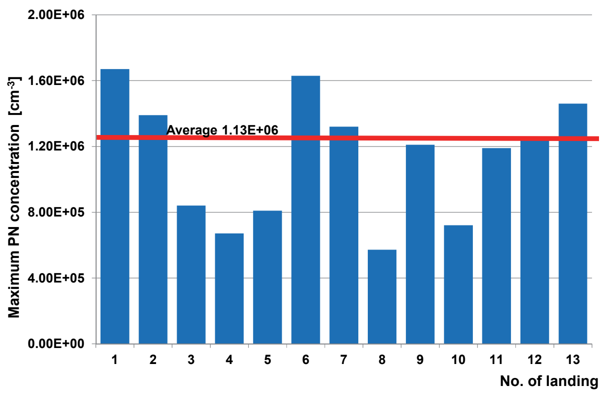

Fig. 12. The process of changes in the concentration of PN during landing.

Particle size distributions obtained during all thirteen landings are shown in Figures 13–15. The resulting distributions are similar to the distribution obtained during stationary measurements.

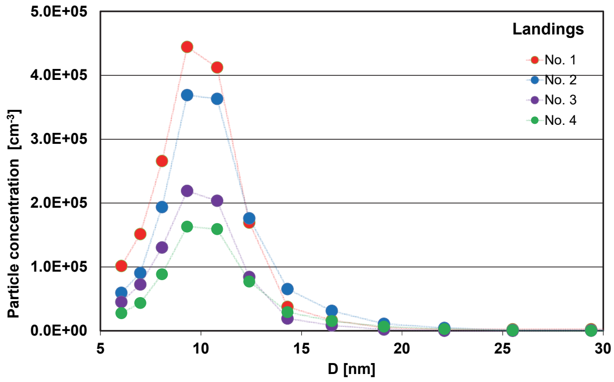

Fig. 13. Size distributions obtained during landings (No. 1–4).

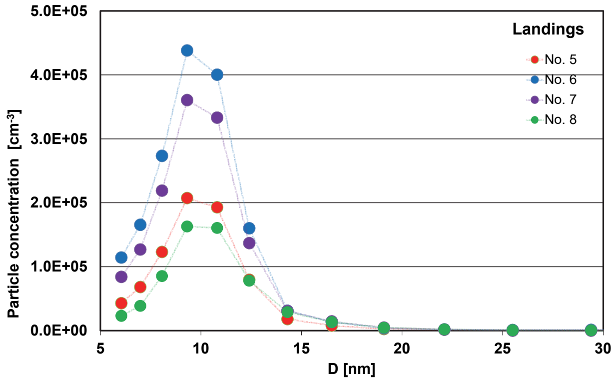

Fig. 14. Size distributions obtained during landings (No. 5–8).

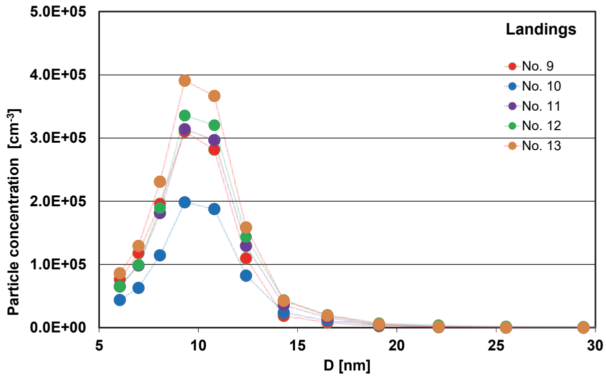

Fig. 15. Size distributions obtained during landings (No. 9–13).

All particle size distributions obtained from the engine during measurements in area adjacent to the airport are close to each other. This proves that the results are characterized by high repeatability. Particles with diameters of 5–15 nm were dominated. The characteristic value of the diameter of the particles was 9 nm (same as in distribution obtained during stationary tests). Particles with diameters greater than 20 nm were negligible part of the total concentration of PN.

4 Conclusions

Landing aircrafts have a significant impact on the concentration of particulate matter in the area adjacent to the airport. A single landing operation causes an increase of the value of particle number concentration tens of times. In addition, even up to 100 times higher concentration of PN in air and the dominance of particulates characteristic for jet engine emissivity, proves that approximately one minute after aircraft landing the air has (in terms of PN) a similar composition as exhaust gases of the internal combustion engine. Obtained particle size distributions indicate that particles emitted by jet engines are characterized by a set of dimensions in the range 5–15 nm.

Such a large number of particles with very small diameters has a negligible effect on the mass concentration of the particles in the air. Due to their small size, however, they represent a very serious threat to human health. This fact confirms the belief that air quality standards based on mass concentrations of particles do not explicitly answer the question of the degree of threat to human health. Air quality standards should be extended by measuring the number of particles.

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References

1. D. Tłoczyński, Logistyka **3** (2015)
2. Boeing, Business & Market Environment (2015)
3. S. Huderek-Glapska, Logistyka **2** (2014)
4. J. Merkisz, J. Pielecha, S. Radzimirski, *Springer Tracts on Transportation and Traffic* **4**, 1-170 (2014), DOI: 10.1007/978-3-319-02705-0
5. G. Hoek, B. Brunekreef, S. Goldbohm, P. Fisch-Er, P.A. Van Den Brandt, Lancet **360**, 1203-1209 (2002)
6. L. Bayer-Oglesby, C. Schindler, M.E. Hazenkamp-Von Arx, C. Braun-Fahrlander, D. Keidel, R. Rapp, American Journal of Epidemiology **164**, 190-1198 (2006)
7. N. Künzli, R. Kaiser, S. Medina, M. Studnicka, O. Chanel, P. Filliger, Lancet **356**, 795-801 (2000)
8. B. Brunekreef, R. Beelen, G. Hoek, L. Schou-Ten, S. Bausch-Goldbohm, P. Fischer, B. Armstrong, E. Hughes, M. Jerrett, P. Van Den Brandt, HEI Research Report (2009)
9. H.R. Anderson, Atmospheric Environment **43**, 142-152 (2009)
10. J. Merkisz, J. Pielecha, *Springer Tracts on Transportation and Traffic* **8**, 9-17 (2015), DOI: 10.1007/978-3-319-15928-7_2
11. J. Merkisz, J. Pielecha, *Springer Tracts on Transportation and Traffic* **8**, 69-92 (2015), DOI: 10.1007/978-3-319-15928-7_7
12. C. Sioutas, R.J, Definno, M. Singh, Environmental Health Perspectives **113**, 947-955 (2005)
13. D. Taler, A. Cebula, Inzynieria Chemiczna i Procesowa **25**, 2331-2342 (2004)
14. S.C. Herndon, J.T. Jayne, P. Lobo, T.B. Onasch, G. Fleming, D.E. Hagen, P.D. Whitefield, R.C. Miake-Lye, Environmental Science & Technology **42**, 1877-1883 (2008)
15. S.C. Herndon, T.B. Onasch, B.P. Frank, L.C. Marr, J.T. Jayne, M.R. Canagaratna, J. Grygas, T. Lanni, B.E. Anderson, D. Worsnop, R.C. Miake-Lye, Aerosol Science and Technology **39**, 799-809 (2005)
16. M.T. Timko, E. Fortner, J. Franklin, Z. Yu, H.W. Wong, T.B. Onasch, R.C. Miake-Lye, S.C. Herndon, Environmental Science & Technology **47**, 3513-3520 (2013)
17. C.C. Wey, B.E. Anderson, C. Wey, R.C. Miake-Lye, P.D. Whitefield, R. Howard, Journal of Propulsion and Power **23**, 898-905 (2007)
18. J. Merkisz, J. Markowski, J. Pielecha, *WIT Transactions on Ecology and the Environment* **174**, 219-230 (2013), DOI: 10.2495/AIR130191
19. J. Merkisz, J. Pielecha, S. Radzimirski, Springer Tracts on Transportation and Traffic **4**, 67-90 (2014), DOI: 10.1007/978-3-319-02705-0_4
20. M.M. Maricq, Aerosol Science **38**, 1079-1118 (2007)
21. M. Ketzel, R. Berkowicz, Atmospheric Environment **38**, 2639-2652 (2004)
22. P. Kumar, M. Ketzel, S. Vardoulakis, L. Pirjola, R. Britter, Journal of Aerosol Science **42**, 580-603 (2011)
23. J. Merkisz, J. Pielecha, *Springer Tracts on Transportation and Traffic* **8**, 27-46 (2015), DOI: 10.1007/978-3-319-15928-7_4
24. J. Merkisz, J. Pielecha, *Springer Tracts on Transportation and Traffic* **8**, 1-139 (2015), DOI: 10.1007/978-3-319-15928-7
25. J. Merkisz, J. Pielecha, P. Lijewski, A. Merkisz-Guranowska, M. Nowak, *WIT Transactions on Ecology and the Environment* **174**, 27-38 (2013), DOI: 10.2495/AIR130031
26. M.P. Keuken, J.S. Henzing, P. Zandveld, S. Van Den Elshout, M. Karl, Atmospheric Environment **54**, 320-327 (2012)
27. J. Merkisz, J. Pielecha, *Springer Tracts on Transportation and Traffic* **8**, 131-139 (2015), DOI: 10.1007/978-3-319-15928-7_10
28. Z. Stelmasiak, D. Pietras, *IOP Conference Series Materials Science and Engineering* **148** (2016), DOI: 10.1088/1757-899X/148/1/012087
29. R.W. Atkinson, G.W. Fuller, H.R. Anderson, R.M. Harrison, B. Armstrong, Epidemiology **21**, 501-511 (2010)
30. J.S. Kinsey, Y. Dong, D.C. Williams, R. Logan, Atmospheric Environment **44**, 2147-2156 (2010)

31. M. Mazaheri, G.R. Johnson, L. Morawska, Atmospheric Environment **45**, 3500-3507 (2011)
32. J. Merkisz, J. Markowski, J. Pielecha, *IEEE Vehicle Power and Propulsion Conference VPPC*, 897-902 (2012)
33. D. Westerdahl, S.A. Fruin, P.L. Fine, C. Sioutas, Atmospheric Environment **42**, 3143-3155 (2008)
34. R.H. Barrett, R.E. Britter, I.A. Waitz, Atmospheric Environment **74**, 247-258 (2013)
35. N. Hudda, T. Gould, K. Hartin, T. Larson, S. Fruin, Environmental Science & Technology **48**, 6628-6635 (2014)
36. US EPA, Integrated science assessment for oxides of nitrogen – health criteria (2008)
37. US EPA, Integrated science assessment for sulphur oxides – health criteria (2008)
38. US FAA, Environmental tool suite frequently asked questions.
39. J. Merkisz, J. Markowski, J. Pielecha, *Selected issues in exhaust emissions from aviation engines*, (Nova Science Publishers, 2014)