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Effective density and mass–mobility exponents of particulate matter in aircraft turbine exhaust: Dependence on engine thrust and particle size



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ABSTRACT

The mass and electrical mobility size of nascent soot generated by aircraft turbine engines were measured using a Differential Mobility Analyzer, a Centrifugal Particle Mass Analyzer and a Condensation Particle Counter in series. The measurements were conducted with a commonly used engine at a maintenance facility at airport Zurich, Switzerland. The aircraft engine under investigation was a CFM56-7B26/3. The used standardized sampling system conforms to the emission certification regulations captured by the “Society of Automotive Engineers, Aerospace Information Report 6241”. Effective densities of the aircraft soot were derived using measured power-law relationships between mass and electrical mobility size. The values ranged from 530 kg/m³ to 1865 kg/m³ depending on the particle mobility size and applied engine thrust. Trends in these effective densities suggest that the size of primary particles in the soot aggregates increase with increasing thrust. The mass-mobility exponents associated with these engine thrusts ranged from 2.54 to 2.79 and 1.86 to 2.32 for thrust levels above 30% and below 30%, respectively. Comparison with a second engine, a CFM56-5B4/2P, revealed higher effective densities for particles smaller than 40 nm.

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1. Introduction

Knowledge of soot particle morphology is of major research interest because it influences several factors, such as the particles transport behavior, radiative properties (Bond et al., 2013; Zhang et al., 2008) and health effects (Lighty, Veranth, & Sarofim, 2000; Maricq & Xu, 2004). The most important aerosol-radiation interaction of soot is its ability to absorb solar radiation over a broad range of wavelengths and thereby directly cause a warming in the atmosphere and a dimming at the surface (Bond et al., 2013). This light absorption stands in contrast to most other atmospheric aerosol particles, which mainly scatter solar radiation. Furthermore, aerosol-cloud interactions lead to indirect radiative effects by altering cloud properties, such as changing the albedo and lifetime of clouds (Boucher et al., 2013). The overall effects of soot on the global

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radiation budget are likely to be positive but they still remain uncertain (Bond et al., 2013; Myhre et al., 2013) due to the variety in morphology amongst soot particles (Burtcher, 2005). Thus, morphology is one of the key quantities influencing soot aerosol optical and cloud forming properties (Boucher et al., 2013). Also, the morphology of soot particles does not remain constant over their atmospheric lifetime (Miljevic, Surawski, Bostrom, & Ristovski, 2012) which is typically one to two weeks (Cape, Coyle, & Dumitrescu, 2012). Regarding health effects arising from soot, several epidemiological studies have concluded that diesel engine soot is likely to be carcinogenic to humans (Ris, 2008). Recently, the importance of a better characterization of diesel exhaust from cars for investigating effects on humans was mentioned and targeted (Wierzbicka et al., 2014).

Carbonaceous aerosol particles formed during various combustion processes largely differ in their physical properties such as size, mass, and morphology. The term soot will be used hereafter to describe the carbon containing particle agglomerates from fossil fuel combustion, excluding any organic species chemically combined with carbon such as hydrogen, nitrogen, oxygen, phosphorus, sulfur, chlorine, etc. (Petzold et al., 2013). Soot particles grow from nearly spherical primary particles into fractal-like aggregates. The primary particles emerge by nucleation and combine by coagulation to form chain-like structures. Hence, their morphology depends on the number and size of the primary particles as well as on the degree of compaction. A value often used to describe the morphology of fractal particles is the fractal dimension (Maricq, 2007; Shapiro et al., 2012). It relates the number of primary particles to the radius of gyration of the aggregate (Friedlander, 2000).

The combustion process itself determines the initial morphology of soot particles. Once emitted, changes in the morphology of soot particles take place as the particles age due to atmospheric processing (Zhang et al., 2008). This involves condensation of secondary organic substance and/or water onto the particles as well as the collapsing of the chain-like primary structure, which results in a more spherical and compact aggregate (Ghazi & Olfert, 2013; Ma, Zangmeister, Gigault, Mulholland, & Zachariah, 2013; Zhang et al., 2008). Therefore, information on the initial fundamental properties of these particles is needed to understand these changes in the atmosphere and their effects on the Earth's radiation budget.

Aircraft soot emissions have been increasingly studied because of the above mentioned issues, combined with the fact that air traffic is steadily growing. In terms of revenue passenger kilometers, commercial air traffic is predicted to increase from 5 billion in 2010 to 13 billion in 2030 (ICAO, Environmental Report, 2013). During taxiing and takeoff, the emissions are released in the vicinity of airports in large quantities, directly affecting the local air quality and thereby the airport personnel and local population. During flight, emissions take place in the upper troposphere where they are a unique source of fresh soot. These emissions can lead to contrail formation and cirrus-cloud initiation, influencing the radiative budget of the Earth. These processes are still little studied due to the difficulties in collecting such particles (Popovicheva & Starik, 2007). To properly capture, quantify, and explore the implications of such aircraft emissions, it is important to know how physical properties such as effective density and morphology of the soot particles change at various thrust levels.

The physical properties of fresh combustion generated particulate matter (PM) have been investigated for diesel engines, emissions from which are thought to be similar to aircraft emissions regarding their physical properties: Onasch et al. (2009) conducted measurements on fresh exhaust from a CFM56-2-C1 aircraft engine. The soot particles showed a similar morphology and fractal nature as diesel and premixed flame soot of the same mobility diameters. The measured size range however, was significantly lower for the aircraft engine than for diesel cars.

Limited data is available on the effective density of the PM emitted by aircraft engines. Onasch et al. (2009) calculated an effective density of $\sim 1000 \text{ kg/m}^3$ for particles from a CFM56-2-C1, using combined measurements of the aerodynamic diameter in the free molecular regime and mobility diameter at rated thrusts $> 56\%$. The same method was applied by Timko et al. (2010) investigating a PW308 turbine. Values for the effective density found ranged from 710 kg/m^3 to 840 kg/m^3 for rated thrusts $< 50\%$. However, as both of these measurements were based on aerodynamic diameters in the free molecular regime, the calculated effective density is differently defined than the hereinafter presented effective density resulting in an error when estimating particulate mass (DeCarlo, Slowik, Worsnop, Davidovits, & Jimenez, 2004, Eq. (45)). A need for mobility based effective density measurements therefore remains.

To derive morphological information of aerosol particles such as radius of gyration, number of primary particles, density and fractal dimension, the most common techniques use light scattering measurements (Khalizov, Xue, Wang, Zheng, & Zhang, 2009; Kiselev et al., 2010; Sorensen, 2001) and/or Transmission Electron Microscopy (TEM) (Mathis et al., 2005; Mazaheri, Bostrom, Johnson, & Morawska, 2013). Effective density measurements may also provide information on morphology if the particle material density is known. Moreover, mobility based effective densities allow commonly available mobility size measurements to be translated into mass based PM emission indices. Various other studies have characterized aircraft PM (Cheng et al., 2008; Rogers et al., 2005; Williams et al., 2012). Still, it remains challenging to sample exhaust from an aircraft engine at a distance close enough to avoid mixing with ambient aerosol and associated condensation of organic substances onto the soot particles. For instance, Petzold et al. (2005) simulated an aircraft engine using a modified combustor which had the same thermodynamic data and emissions.

Here, we present comprehensive size selected mass measurements on freshly emitted soot particles, sampled directly ($\sim 0.7 \text{ m}$) behind a CFM56-7B26/3 engine, which is widely used on commercial aircraft. The engine has a single annular combustor for improved emissions and is applied in Boeing 737 aircraft. In order to measure fresh, non-aged aircraft exhaust, a distance of 1 m behind the engine exit plane has been previously shown to sample only refractory carbon soot particles (Onasch et al., 2009). Two different sampling probes, a single-point and a multi-point probe, were used which span the entire thrust and measured size distribution range. The measurements were conducted at an engine maintenance

facility at Zurich airport, Switzerland. The test facility is run by SR Technics, a company that provides technical solutions to airlines. The presented measurements were performed during the so-called “dedicated” tests. This means that a rented aircraft engine was run according to the needs of the scientific staff. The measurements provide information on the effective density and the mass-mobility exponent, which is associated to the fractal dimension. Note that [Durdina et al. \(2014\)](#) also used effective density values of the CFM56-7B26/3 engine exhaust particles to derive thrust dependent PM line losses for the presented experimental set-up and discussed them accordingly. We also compare with literature data ([Johnson et al., 2015](#)) for the same engine type and effective density measurements from a CFM56-5B4/2P engine, a dual annular combustor turbofan for low NO_x emissions.

2. Fractal aggregates

Objects with infinite dilation (self-similarity) symmetry are called fractal. Real objects are also termed fractal if they show self-similarity over the scale of their size. Soot particles often display self-similarity on different length scales, and are therefore often described by a fractal scaling law relating aggregate size and number of primary particles to describe their morphology ([Schmidt-Ott, 1988](#)).

Equation (1) defines a relationship for fractal aggregates ([Sorensen, 2011](#)) consisting of spherical primary particles. It relates the number of primary particles (N_{pp}) to the radius of gyration (d_g) normalized to the diameter of the primary particles (d_{pp}). This implies self-similarity of the agglomerates over a certain range for N_{pp} .

$$N_{pp} = k (d_g/d_{pp})^{D_f} \quad (1)$$

where D_f is the fractal dimension and k is a scaling prefactor.

Assuming the electrical mobility size scales with N_{pp} , it can analogously be written:

$$N_{pp} \sim d_m^{D_m} \quad (2)$$

In which d_m is the electrical mobility diameter and D_m is the mass–mobility scaling exponent.

As the primary particles are formed in the same environment, their size and density can be assumed constant ([Schmidt-Ott, Baltensperger, Gägeler, & Jost, 1990](#)), the particle mass (m_p) is then directly proportional to N_{pp} :

$$m_p = C * d_m^\varepsilon \quad (3)$$

C is a constant with units [kg/m^ε], and is called the mass–mobility prefactor. ε is the mass–mobility exponent, which is related to the arrangement of the primary particles within the agglomerate such that $\varepsilon=1$ and 3 correspond to an infinite long straight chain-like structure and a compact sphere-like structure, respectively ([Friedlander, 2000](#)).

When reporting densities of fractal aggregates, the effective density is a convenient quantity because it can be determined experimentally. Knowledge of d_m and the corresponding mass yields the effective density ρ_{eff} ([DeCarlo et al., 2004](#)):

$$\rho_{eff} = \frac{m_p}{d_m^3} = \frac{C * d_m^\varepsilon}{d_m^3} = C' * d_m^{\varepsilon-3} \quad (4)$$

C and C' are related such that:

$$C' = C * \frac{6}{\pi} \quad (5)$$

where C' is a constant with the same units as C [kg/m^ε]. It is called the density–mobility prefactor. Hereafter, we always refer to the mass–mobility prefactor C .

3. Experimental methods

The Aviation Particle Regulatory Instrumentation Demonstration Experiment 5 (A-PRIDE 5) was conducted in the aircraft engine test cell at SR Technics, Zurich airport. We present data collected from 3rd to 24th of August 2013 during the dedicated measurement tests.

3.1. Measurement procedure

A dedicated measurement run consisted of a warm-up (WU) procedure typically comprising four thrust levels including ground idle (GI) followed by a sequence of up to 12 thrust levels on a decreasing power curve ([Table 1](#)). Prior to each measurement run, the engine must perform a warm up procedure consisting of a sequence of ascending thrust levels. The purpose was to heat up the probe by stabilizing the engine at these values for about 5 min. The engine test points were set using the combustor inlet temperature T3. T3 was used to predict the thrust at sea level (static thrust the engine would produce at 1 atm ambient pressure and 15 °C) and can therefore exceed 100%. Here, we report this predicted thrust. Because the ambient temperature and pressure varied between engine runs, the actual thrust produced by the engine varied at constant T3. Note that different definitions of thrust exist which are reported in other publications referenced later herein.

Table 1

Overview of test points, predicted thrust levels and number of measurements per selected mobility size conducted. Ground idle (GI) and warm ups (WU) are conducted in addition to the desired test points.

Test point	Thrust level [%]	Number of measurements per thrust level at the selected mobility size [nm] (columns) and engine thrust (rows)									
		20	30	40	50	60	75	90	100	125	150
GI	2.5 ± 0.5	1	4	1	3	1	3	1	–	–	–
WU7	7 ± 1	1	1	–	2	–	2	–	1	–	–
WU65	66 ± 2	1	4	1	6	1	3	1	3	–	–
WU85	84 ± 2	1	3	–	4	1	3	–	2	1	–
0	118 ± 6	–	3	2	–	1	2	–	2	–	2
1	104.5 ± 6	3	9	4	12	6	6	2	10	2	10
2	99.5 ± 4	1	2	4	4	–	–	–	2	1	6
3	94 ± 6	4	13	8	10	4	5	2	8	8	7
4	85 ± 1	1	3	1	3	1	2	2	3	1	5
5	67 ± 1	3	10	13	9	4	6	2	8	3	5
6	33 ± 2	3	6	4	9	2	7	1	7	–	–
7	26 ± 1	–	2	3	8	1	2	–	–	–	–
8	22 ± 1	–	1	2	8	1	1	–	–	–	–
9	7 ± 1	–	1	3	8	2	1	–	–	–	–
10	6 ± 1	–	3	3	18	–	1	–	–	–	–
11	3 ± 1	–	4	3	17	2	2	–	–	–	–

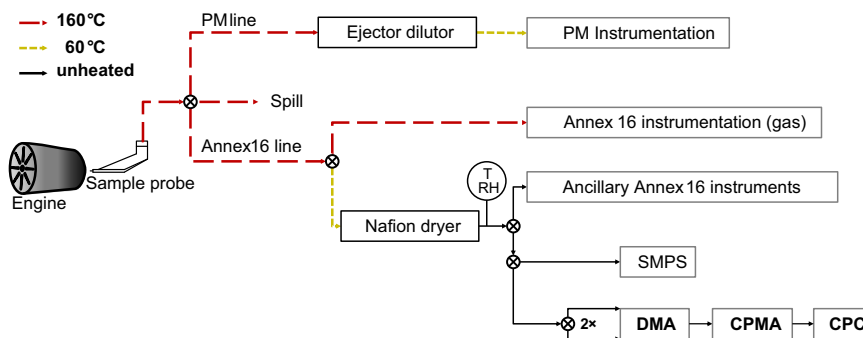


Fig. 1. Schematic of the experimental set-up during A-PRIDE 5. The effective density measurements were performed using the two identical DMA–CPMA–CPC systems.

[Durdina et al. \(2014\)](#) and [Lobo et al. \(2015\)](#) used a definition of thrust that corresponds to a thrust corrected to International Standard Atmosphere (ISA) conditions at sea level ($p=101,325$ Pa, $T=288.15$ K) whereas [Johnson et al. \(2015\)](#) used the uncorrected measured thrust in the test cell.

The observed ranges for each engine thrust level are given in [Table 1](#). At each thrust level a number of mass scans were performed at different particle mobility sizes (see [Section 3.3](#)). The number of test points measured varied from day to day because the engine test cycles varied in duration and thrust settings. In addition to the dedicated measurement runs, measurements were taken during post-maintenance engine runs of customer engines.

3.2. Sampling system

[Figure 1](#) shows a schematic of the experimental set-up during the campaign. The used standardized sampling system conforms to the emission certification regulations captured by the “Society of Automotive Engineers, Aerospace Information Report 6241” ([SAE, 2013](#)). Exhaust was sampled by either of two 8 mm ID sample probe at a distance of ~ 0.7 m behind the engine and then distributed to the different instruments. The probe inlet was oriented to sample parallel to the exhaust stream. The probe was vertically movable to adapt to different types of engines. In addition to the earlier used single point probe, a multipoint probe was introduced on the 17th of August. It consisted of 24 selectable sampling nozzle positions in a cruciform pattern. Twelve of them were used to provide a representative sample directly at the engine exit plane according to the emissions certification requirements ([ICAO, 2008](#)). The sampled engine exhaust was drawn through tubing heated to 160°C in order to prevent condensation and/or evolution of secondary organic aerosol in the sampling system.

The sampling system consisted of two main measurement lines: the PM line and the Annex 16 line. The PM line was diluted with synthetic air (grade 5.0) by a factor of ten using a Dekati ejector dilutor (Dekati, Model DI 1000, Dekati Ltd., Kangasala, Finland) and was kept at 60°C . This line was primarily used to measure non-volatile PM number and mass. “Annex 16” refers to the standard: “International Civil Aviation Organization Annex 16: Environmental Protection, vol. 2 –

Aircraft Engine Emissions” (ICAO Annex 16 VOL II; ICAO, 2008), which prescribes standards and procedures for the certification of aircraft emissions. The undiluted Annex 16 line was heated to 160 °C and was primarily used for measurements of gaseous emissions.

For our measurements, a split was installed in the Annex 16 line leading into a 60 °C heated line. The advantages of measuring on the Annex 16 line were a stronger signal due to a higher particle concentration as well as being unaffected by changes in the dilution ratio in the PM line during some experiments. Downstream of the Nafion dryer (Perma Pure, Model PD-100T-24(MSS), Perma Pure LLC, Toms River, USA) the flow was no longer heated. The conditions for nucleation were monitored by measuring temperature (T) and relative humidity (RH) downstream of the dryer.

The flow was then distributed into ancillary Annex 16 instruments, into a Scanning Mobility Particle Sizer (SMPS, TSI, Model 3936, TSI Inc., St. Paul, USA) system, and into the two identical Differential Mobility Analyzer (DMA; TSI, Model 3081, TSI Inc., St. Paul, USA)–Centrifugal Particle Mass Analyzer (CPMA; Cambustion Ltd., Cambridge, UK)–Condensation Particle Counter (CPC; TSI, Model 3776; TSI Inc., St. Paul, USA) systems. The two DMA-CPMA-CPC systems described below sampled from the Annex 16 line except for the two first dedicated measurement days.

3.3. DMA-CPMA-CPC systems

Performing one DMA-CPMA-CPC scan at a fixed particle size and aircraft engine thrust eventuating in one mass distribution takes between 4 and 7 min. The exact duration depends on the resolution of the scan and the average mass of the single particles under investigation. Due to time restrictions on the engine runtime and scarcity of repetitions, it was only possible to scan a limited number of sizes (see Table 1). In order to record a more comprehensive data set, two DMA-CPMA-CPC systems were set up in parallel. During the entire campaign, the monitored T and RH downstream of the dryer ranged from 22 °C to 28 °C and 20% to 38%, respectively. This results in a maximum dew point temperature below 12 °C when taking the extreme values, so that condensation of liquid water is unlikely to have taken place.

The DMA was used to select particles of a desired electrical mobility size. The sheath and the aerosol flow rates were set to 12.0 l/min and 1.5 l/min, respectively. The DMA was part of an electrostatic classifier model 3080 (TSI Inc., Shoreview, USA). Before the particles entered the systems they were treated with an aerosol neutralizer (model 3077, TSI Inc., Shoreview, USA) to apply a known charge distribution to the particles (Wiedensohler, 1988). This ensures an accurate measurement when using instruments operating with an electrostatic principle, as it is the case for the DMA and the CPMA.

The CPMA classifies particles according to their mass to-charge-ratio (Cambustion, Cambridge, UK; Olfert & Collings, 2005; Olfert, Symonds, & Collings, 2007). Within the CPMA, the particles pass between two rotating concentric cylinders with an applied voltage. Only particles in a narrow mass-to-charge ratio range are transferred through the instrument. The particle concentration downstream of the CPMA was recorded by a CPC at a flow rate of 1.5 l/min using an external pump.

3.4. Measurement uncertainty

From our measurements we obtained standard deviations for the size- and thrust-selected measured mass of maximum 16.6% for particles ≤ 40 nm and 11.0% for particles > 40 nm. An exception was the data point of lowest thrust level (3%) and $d_m=40$ nm that showed an exceptionally high standard deviation of 23.6% and was therefore excluded from further analysis. Reasons could be the variations of thrust ($3 \pm 1\%$) when setting this test point and the possible changes in the size distribution (see Fig. 2). The number of measurements performed for the same particle size and at the same thrust level

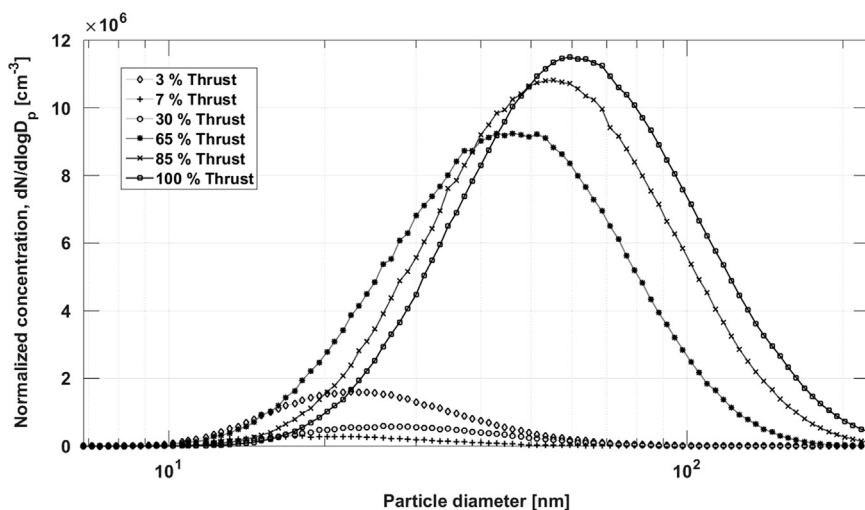


Fig. 2. Typical PM distributions measured on the 28th of August using an SMPS system on the Annex 16 line after the Nafion dryer.

varied from one to nine. If less than three mass scans were performed for a given size and thrust, the above mentioned maximum standard deviation was applied to these data points as well. The data between individual test days vary mainly due to different ambient conditions affecting the engine operation.

3.5. Effective density and mass–mobility exponent calculation

The effective density was calculated from the selected mobility size and the respective measured particle mass using the mass–mobility relationship shown in Eq. (4). The mass was determined as the mode of a lognormal function fitted to the mass distributions recorded by the CPMA. The particle mass was averaged for the same particle size and engine test conditions. The averaged mass was then fitted for each test point using Eq. (3). This was done using units such that the values (mass and mobility size) were close to one in order to avoid reaching limitations of the fitting program. The fitting procedure was then repeated in SI units holding the beforehand derived ε constant. It was not possible to derive ε for thrust levels consisting of three or less different sizes measured because of the few number of data points available for fitting. The precision in terms of effective density of the DMA–CPMA–CPC system itself was determined to be $\pm 9.4\%$ (Johnson, Symonds, & Olfert, 2013).

4. Results and discussion

4.1. Mass–mobility relationship

Figure 2 shows exemplary size distributions measured on the 28th of August representative for the effective density measurements conducted after the Nafion dryer during A-PRIDE 5. The particle size distributions were lognormal for all test points. The geometric mean diameter (GMD) had a local maximum of ~ 20 nm at engine idle and then monotonically increased with thrust reaching 60 nm at maximum thrust. The particle number concentration followed the same trend showing a local maximum at idle, a minimum at 7% thrust and then an increase with increasing thrust. The broadening of the size distribution and the increase in particle concentration therefore allowed to select a wider range of particle size at higher thrust levels. At thrust levels below 30% the investigated size range spanned mobility sizes from approximately 30 nm to 75 nm in diameter whereas for higher thrusts the range spanned from 20 nm to 150 nm in diameter.

The mass–mobility relationship for the CFM56-7B26/3 engine at 3%, 7%, 22%, 33%, 67%, 95% and 105% thrust is shown in Fig. 3. The x- and y-axis show the selected mobility size and measured mass, respectively. The error bars represent the standard deviation derived from the modal mass measurements at constant DMA and thrust conditions (see Section 3.4). The data points are grouped into boxes each showing the measured masses for a certain d_m at different thrust. They are depicted with a slight offset in x-direction such that the thrust in one box increases from left to right. The mass at a certain size is generally increasing with increasing thrust. This implies a more compact arrangement of the primary particles that is also supported by values of the mass mobility exponents discussed below or a bigger primary particle size.

The measured particle mass ranged from 5.5×10^{-3} fg to 1.4 fg for particles with $d_m = 20$ nm and 150 nm, respectively. With increasing width of the size distribution the applied power law fit generally improves with respect to the 95% confidence interval of the coefficients C and ε .

Figure 4 summarizes the mass mobility exponents obtained for the dedicated runs (full circles) and for warm up (empty circles). The mass mobility exponent was found to be significantly lower at low thrust than at high thrust. At thrust levels below 30% it ranged between 1.85 and 2.32 and at thrust levels between 67% and 120% it ranged from 2.57 to 2.79. At 105% thrust, the measurements performed on particles smaller than 30 nm exceptionally showed a decrease in effective density (see Section 4.2) compared to the value measured at 30 nm and were therefore not taken into account for the calculation of ε . This behavior was also observed by Johnson et al. (2015) and needs further investigation.

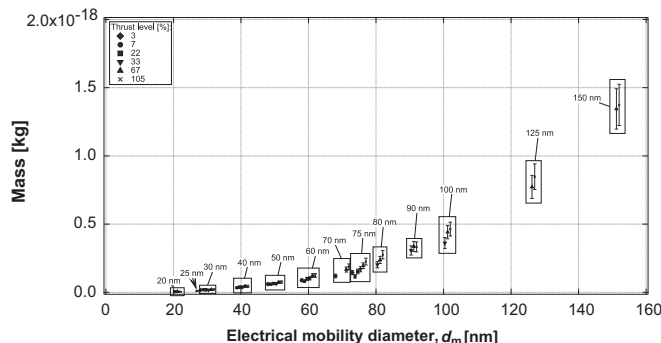


Fig. 3. Electrical mobility diameter (d_m) vs. mass (m) from PM exhaust from a CFM56-7B26/3 engine. The data points are grouped into boxes each showing the measured masses for a certain d_m at different thrust. They are depicted with a slight offset in x-direction such that the thrust in one box increases from left to right.

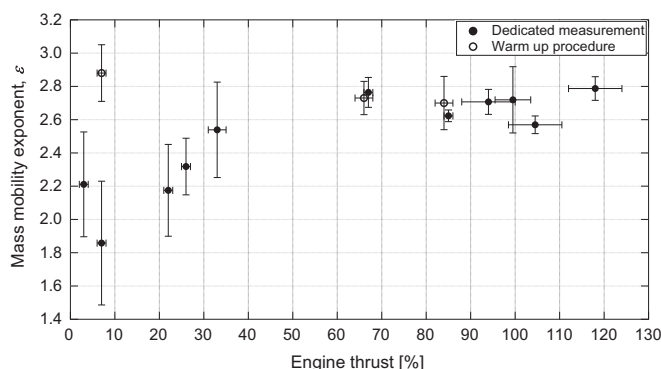


Fig. 4. Mass mobility exponents (ϵ) at the different thrust levels derived during dedicated measurements (full circles) and warm up procedures (empty circles).

The general increase of the uncertainty in ϵ with decreasing thrust is assigned to the decrease in number of selected sizes and decreasing size range. The relative high value of ϵ (> 2.50) for thrust higher than 60% indicates that the particles have a more spherical shape and are less fractal than observed in other combustion sources. Olfert et al. (2007) determined mass mobility exponents from a diesel oxidation catalyst using a similar DMA–CPMA–CPC system. The values ranged from 2.22 to 2.48 at engine loads where the sulfate level was low enough to neglect condensation onto the particles. Park, Cao, Kittelson, & McMurry (2003) found values ranging from 2.33 to 2.41 at different loads for a diesel engine (John Deere 4045, 4 cylinders, 4.5 L, 75 kW). Table 2 summarizes this study's mass mobility exponents and mass mobility prefactors derived at the different engine loads and corresponding size ranges.

Due to the set-up of two parallel DMA–CPMA–CPC systems, it was possible to perform enough mass scans to derive the mass-mobility relationship at 7%, 66% and 85% thrust during warm up. Except for 7% thrust during warm up, the particles show very similar ϵ during the warm up as compared to the dedicated runs. This indicates similar particle morphology and comparable combustion process. The difference in ϵ at 7% thrust during warm up and ϵ at 7% during the dedicated runs can be explained by the fact that the temperature inside of the engine influences the combustion process. This temperature was still near ambient conditions just after the cold start when the warm up procedure was initiated.

4.2. Effective densities

Figure 5 shows that the effective density decreases with increasing particle size. The decrease of effective density with mobility size was observed for all measured thrust levels. Hence, these particles can be considered to follow the concepts of fractal aggregates. For particles with $d_m = 30$ nm, the effective density ranged from 1075 kg/m^3 to 1490 kg/m^3 , with the exception of the high value of $1865 \pm 291 \text{ kg/m}^3$ at 118% thrust. At $d_m = 75$ nm, measurements spanning the whole thrust range were conducted and ρ_{eff} ranged from 530 kg/m^3 to 1020 kg/m^3 . With increasing thrust the effective densities generally increase for all selected sizes due to changes in the combustion process. Excluding 118% thrust, this increase in effective density is smaller for smaller d_m . For particles larger than 100 nm only measurements at thrusts levels $\geq 67\%$ were possible and ρ_{eff} approaches $\sim 800 \text{ kg/m}^3$ for $d_m = 150$ nm.

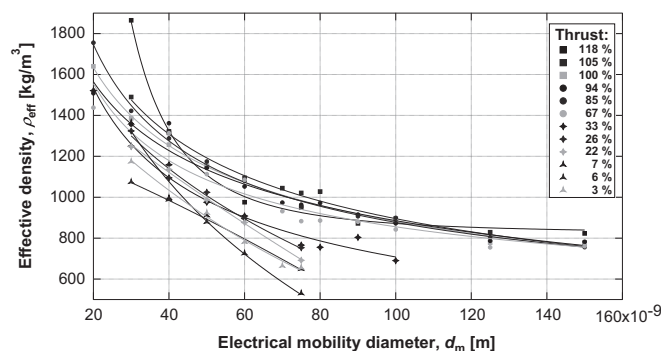
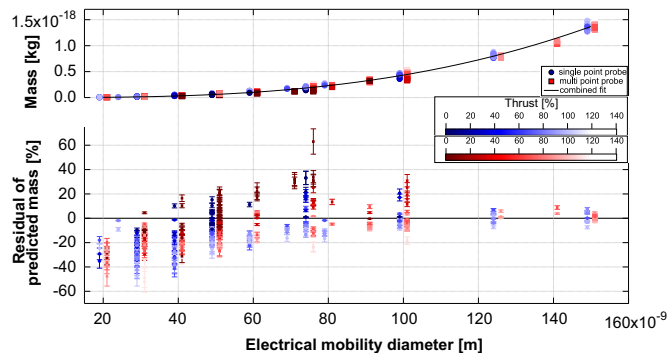
The mass distributions used to determine the mass of the size selected particles show a single mode for particles with a $d_m \geq 30$ nm. For particles < 30 nm, the distributions are not always unimodal. In this case, it is assumed that the selected mobility size was close to the size of the primary particles and the number of primary particles was close to the limit of one single primary particle. For a diesel engine, the measured d_{pp} ranged from 24 nm to 28 nm with a standard deviation of $\sim 25\%$ (Rissler et al., 2013), i.e. were observed with a similar value within the uncertainty range. Furthermore, the possible increase in aircraft engine primary particle size with increasing engine thrust is consistent with similar studies on combustion engine exhaust particles. Mathis et al. (2005) found values for d_{pp} of a heavy-duty diesel engine to vary between 17.5 nm and 32.5 nm depending on engine power and injection pressure with larger d_{pp} at high engine load.

The effective density is equal to the material density if the number of primary particles reaches the limit of one. If at 118% thrust the primary particle size was reached at $d_m = 30$ nm, the material density of the particles investigated in this study would correspond to $1865 \pm 291 \text{ kg/m}^3$. Within its uncertainty, this value is consistent with the density of $1700 \pm 70 \text{ kg/m}^3$ found by Park, Kittelson, Zachariah, & McMurry (2004) for preheated (in order to avoid condensation of organics) diesel soot particles. In addition, a primary particle size of 30 nm is consistent with the measurements of Vander Wal, Bryg, & Huang (2014), where primary particles larger than 25 nm were observed at 85% thrust for a different aircraft engine, namely a CFM-56-3 aircraft engine. Despite the effort taken to avoid condensation of volatile and semi-volatile species by heating and drying the sample during A-PRIDE 5, an influence thereof on the measured effective density cannot completely be excluded because no corresponding measurements were performed.

Since the effective densities obtained at different thrust levels do not converge to one single mobility size, it is possible that the primary particle size changes with changing thrust. By extrapolating the fits towards smaller sizes, the above

Table 2Coefficients ε and C (see Eq. (3)), and the corresponding valid size range at different thrust levels.

Thrust level [%]	ε	C [kg/m ³]	size range [nm]
3	2.21 ± 0.32	$810 \cdot 10^{-6} \pm 41 \cdot 10^{-6}$	30–75
7	1.86 ± 0.37	$20.7 \cdot 10^{-6} \pm 0.2 \cdot 10^{-6}$	30–75
22	2.18 ± 0.28	$400 \cdot 10^{-6} \pm 30 \cdot 10^{-6}$	30–75
26	2.32 ± 0.17	$5.48 \cdot 10^{-3} \pm 0.20 \cdot 10^{-3}$	30–75
33	2.54 ± 0.29	$220 \cdot 10^{-3} \pm 10 \cdot 10^{-3}$	20–100
67	2.76 ± 0.09	7.28 ± 0.13	20–150
85	2.62 ± 0.04	1.06 ± 0.007	20–150
94	2.71 ± 0.08	4.06 ± 0.059	20–150
99.5	2.72 ± 0.20	4.86 ± 0.13	20–150
104.5	2.57 ± 0.08	0.46 ± 0.008	30–150
118	2.79 ± 0.07	15.17 ± 0.18	30–150
Warmup: Thrust level [%]			
7	2.88 ± 0.17	57.12 ± 1.52	20–100
66	2.73 ± 0.10	5.16 ± 0.10	20–140
84	2.70 ± 0.16	3.32 ± 0.083	20–140

**Fig. 5.** Effective densities of PM exhaust from a CFM56-7B26/3 engine for the measured sizes and applied thrust.**Fig. 6.** Comparison of the two sample probes. The x-axis shows the particle mobility diameter [m] with a positive and negative offset for the multi- (red) and single-point (blue) probe, respectively. The upper panel shows the measured masses [kg]. The lower panel shows the residuals from the measured masses to an overall best fit. The thrust [%] is depicted by the intensity of the color.

assumed material density would be reached at smaller sizes for lower thrusts. Thus, our data imply that the primary particle size decreases with decreasing thrust. Consistent with this hypothesis, [Vander Wal et al. \(2014\)](#) have also observed smaller primary particle sizes at lower thrust conditions for aircraft-turbine soot. Moreover, this hypothesis is confirmed by findings of [Liati et al. \(2014\)](#) who analyzed TEM pictures of aircraft engine exhaust particles sampled during the same A-PRIDE 5 campaign. The primary particle size was found to increase from 13 ± 3 nm at low thrust (7%) to 24 ± 9 nm at high thrust (100%) conditions using the same definition of thrust as presented in this study. The authors attributed the increase in size with increasing thrust to a decrease in air-to-fuel ratio and a shorter residence time of the combustion products within the combustor; both processes probably lead to a reduction of the soot oxidation rate and thus to larger primary particle sizes. Changes in the combustion temperature within the engine may also have played a role. It is worth noting that [Dastanpour](#)

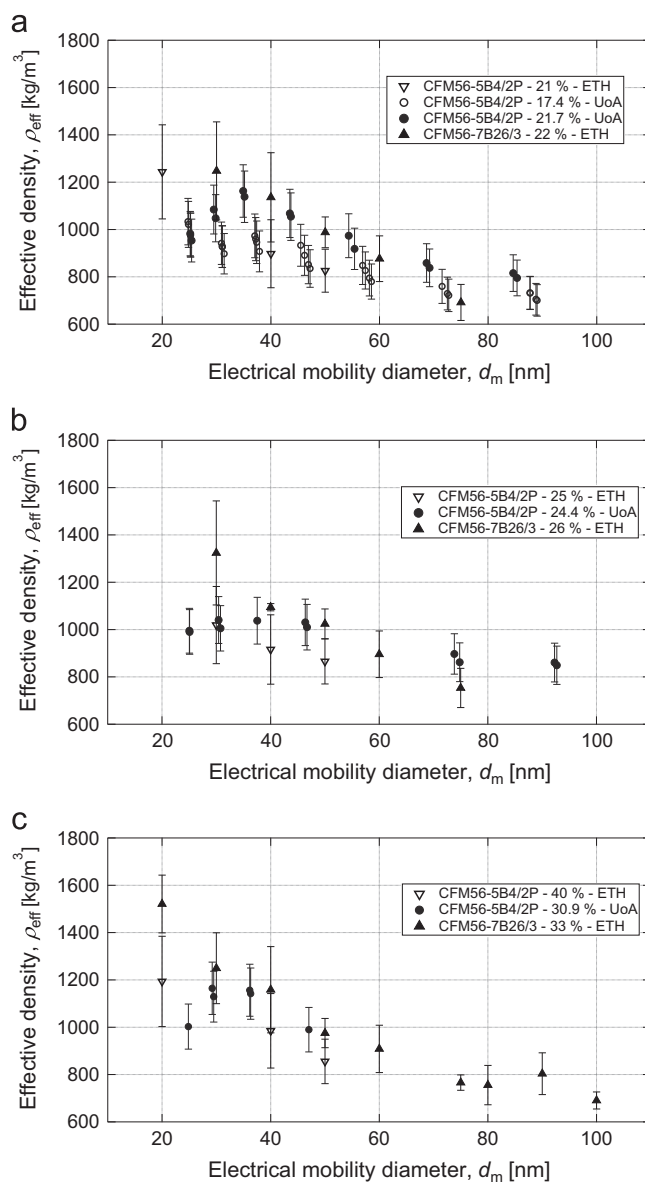


Fig. 7. Comparison of effective densities derived by our measurements (triangles) from a CFM56-7B26/3 (full) and a CFM56-5B4/2P (open) engine to literature values measured by [Johnson et al. \(2015\)](#) (circles) from a CFM56-5B4/2P engine at similar thrust levels.

and [Rogak \(2014\)](#) have observed that soot aerosols tend to be external mixtures of soot aggregates, with smaller aggregates containing smaller primary particles and vice versa. In the present sample, such an effect would have to be secondary to thrust effects for the trends observed herein and by [Liati et al. \(2014\)](#) to be true.

We also calculated effective densities for particles < 30 nm at thrust levels above 100% but these effective densities did not follow the fractal nature observed for the larger particles and the uncertainty range was exceptionally high and were therefore excluded from analysis.

4.3. Comparison of the single vs. multi-point probe

[Figure 6](#) shows a comparison of the two probes. Depicted are the residuals of the measured masses predicted from the overall best fit to Eq. (3) and using all valid mass measurements. Residuals represent the error of a measured data point to the mathematically derived value using a fit function. The thrust range is colored in blue and red for the single point and the multi-point probe, respectively. To visually separate the measurements from the two probes, the data points from the single and multi-point probe have been arranged with a negative and positive offset from the actual value on the x-axis. Due to the lack of measurements of particles having the same size and thrust conditions when comparing both probes, only few

overlapping data points exist. The residuals are within $\pm 40\%$ for the majority of measurements. The residuals generally increase with decreasing thrust for a given d_m . Hence, residuals would be smaller if only data from one thrust level was fitted. That is, the thrust-dependent mass-mobility relationships discussed in [Section 4.1](#) provide a more accurate mass prediction than this overall fit.

No systematic difference in terms of particle size and corresponding mass can be found between the single- and the multi-point probe. Consequently, data from both the probes were combined for the effective density analysis as presented above.

In a similar way, size selected particle masses measured from the Annex 16 line were compared with those measured from the PM line (cf. [Fig. 1](#)). No significant or systematic differences were revealed. This indicates that the particles experienced negligible restructuring and/or condensation of secondary material in either of the sampling systems after emission. If this had been the case, significant differences would have been expected to arise due to the different temperatures in the two sampling lines. As a consequence of these results, the comparison of two engines as discussed in the next section includes all measurements, regardless of sampling probe or sampling line.

4.4. Comparison to the CFM56-5B4/2P engine

In addition to the measurements conducted on the CFM56-7B26/3 engine during A-PRIDE 5, we performed 22 DMA-CPMA-CPC scans for a CFM56-5B4/2P engine at 3 different thrust levels in the range of 21–40% during A-PRIDE 4 in November 2012. Corresponding size distributions for the same CFM56-5B4/2P engine can be found in [Lobo et al. \(2015\)](#) that shows that the emitted particles are generally smaller. This engine has a unique dual annular combustor with two rings of fuel injection points designed for low NO_x emissions. The CFM56-7B26/3 has a commonly used single annular combustor. Both engines are turbofan engines and do not mix the air from the engine core with bypass air before the exhaust duct. [Johnson et al. \(2015\)](#) performed effective density measurements on the same CFM56-5B4/2P engine at the same SR-Technics facility during SAMPLE III.2 in April/May 2012 ([EASA, 2012](#)). The measurements were also conducted using a CPMA, sampling from both, the PM line and the undiluted Annex 16 line. In this section, we compare these two data sets for overlapping thrust levels. However, Johnson et al. used actual measured test cell thrust for which the corresponding combustor inlet temperature linked sea level thrust for Zurich can be up to 15% higher depending on the different ambient conditions.

[Figure 7](#) shows this study's measurements (triangles) for both engines in addition to the University of Alberta (UoA) data from [Johnson et al. \(2015\)](#) (circles). The data are grouped into three thrust categories: $21 \pm 1\%$, $25 \pm 1\%$ and $35 \pm 5\%$ thrust (a, b and c). [Figure 7a](#) includes an additional UoA measurement performed at 17.4% thrust (empty circles). UoA used a CPMA and a modified Differential Mobility Spectrometer (mDMS) system to derive effective densities ([Johnson et al., 2015](#)). The CPMA preselected particles with a certain mass-to-charge ratio. The mobility size distributions of the preselected particles were then obtained from the mDMS. Data was recorded from both lines with and without a Catalytic Stripper (CS). The CS was used to remove the gas-phase and semi-volatile fraction of the soot particles. In contrast to our findings, Johnson et al. observed a significant difference in the effective density measured from the diluted and the Annex 16 line. Therefore, we compare our data only to data recorded at the Annex 16 line without a CS.

Comparison of the two CFM56-5B4/2P engines (circles and open triangles) reveals that the UoA data is generally higher but within the uncertainty range. The most striking difference is that except for the lowest thrust shown in [Fig. 7a](#), the measured UoA-effective densities show maxima for particle sizes between 30 nm and 40 nm whereas our data depict a steady increase towards smaller sizes. Possible reasons for these differences could be different experimental set-ups as outlined above, the different ambient measurement conditions, or differences in the engine/combustion process. The UoA data were recorded in April/May, whereas our measurements took place in the month of August (A-PRIDE 5) and November (A-PRIDE 4). The ambient temperature and pressure can influence the combustion process and thereby particle formation. As a consequence, the season when the experiment took place might have to be considered as well for the interpretation of the results. However, due to the lack of data from different seasons no conclusions are drawn regarding the effect of ambient T and RH on particle effective densities. Additional reasons for the observed differences could be due to different measurement techniques and engine wear.

The comparison of the CFM56-7B26/3 to the CFM56-5B4/2P engine in [Fig. 7a](#) and b indicates that the CFM56-5B4/2P engine yielded lower effective densities than the CFM56-7B26/3 engine for particles < 40 nm. We assume that these differences are attributed to the different combustor systems described above that likely produce different primary particle sizes as well that could affect the measured effective density.

To infer similar information from the data presented in [Fig. 7c](#) is less appropriate since herein, non-overlapping thrust levels of 40% and 33% are compared. The effective density however, was shown to increase with increasing thrust. Consequently, the effective density of particles from the CFM56-7B26/3 engine is likely to be higher if it would have been measured at the same 40% thrust level rather than at 33%. For particles with a mobility diameter ≥ 40 nm, the effective density of particles from both engines lies within the uncertainty range. The change in effective density with mobility size is smaller for the CFM56-5B4/2P engine for all thrust levels.

[Johnson et al. \(2015\)](#) calculated a mass-mobility exponent for the measurements at 17.4% of 2.72 and 2.75 as shown in [Fig. 7a](#). At the closest thrust level of our measurements of 22%, the mass-mobility exponent for particles from the CFM56-7B26/3 engine was only 2.18 ± 0.28 . This indicates that the particles from the CFM56-5B4/2P engine were more spherical in

5. Summary

A comparison of two engines revealed that for particles with $d_m > 40$ nm the effective densities from the CFM56-7B26/3 and the CFM56-5B4/2P are within the uncertainty range. For smaller particles the CFM56-5B4/2P engine showed lower effective densities than the CFM56-7B26/3 engine. The values for the mass-mobility exponents at thrust levels higher than 60% (2.54–2.79) from a CFM56-7B26/3 were similar to literature values of ~ 2.74 measured from a CFM56-5B4/2P at 10% thrust. A new sampling probe introduced during A-PRIDE 5 did not show a systematic difference between the two sampling probes with regard to our density measurement.

From an atmospheric science perspective the presented values as well as a possibly improved knowledge of the ageing in terms of conversion speed and rate could be applied in climate models. The values found in this study could be used as a starting point to investigate atmospheric ageing of turbine emission particles from the source. The ageing then influences the particle scattering and absorption properties which are important for the Earth's radiation budget.

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References

- Bond, T.C., Doherty, S.J., Fahey, D.W., Forster, P.M., Bernsten, T., & DeAngelo, B.J., et al. (2013). Bounding the role of black carbon in the climate system: A scientific assessment. *Journal of Geophysical Research: Atmospheres* <http://dx.doi.org/10.1002/jgrd.50171> n/a–n/a.
- Boucher, O., Randall, D., Artaxo, P., Bretherton, C., Feingold, G., & Forster, P., et al. (2013). Clouds and aerosols. In T.F. Stocker, D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex, & P.M. Midgley (Eds.), *Climate Change 2013: The physical science basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge University Press: Cambridge, UK; New York, NY, USA.
- Burtscher, H. (2005). Physical characterization of particulate emissions from diesel engines: A review. *Journal of Aerosol Science*, 36(7), 896–932, <http://dx.doi.org/10.1016/j.jaerosci.2004.12.001>.
- Cape, J.N., Coyle, M., & Dumitrescu, P. (2012). The atmospheric lifetime of black carbon. *Atmospheric Environment*, 59, 256–263, <http://dx.doi.org/10.1016/j.atmosenv.2012.05.030>.
- Cheng, M.-D., Corporan, E., DeWitt, M.J., Spicer, C.W., Holdren, M.W., & Cowen, K.A., et al. (2008). Probing emissions of military cargo aircraft: Description of a joint field measurement strategic environmental research and development program. *Journal of the Air & Waste Management Association*, 58(6), 787–796, <http://dx.doi.org/10.3155/1047-3289.58.6.787>.
- Dastanpour, R., & Rogak, S.N. (2014). Observations of a correlation between primary particle and aggregate size for soot particles. *Aerosol Science and Technology*, 48(10), 1043–1049, <http://dx.doi.org/10.1080/02786826.2014.955565>.
- DeCarlo, P.F., Slowik, J.G., Worsnop, D.R., Davidovits, P., & Jimenez, J.L. (2004). Particle morphology and density characterization by combined mobility and aerodynamic diameter measurements. Part 1: Theory. *Aerosol Science and Technology*, 38(12), 1185–1205, <http://dx.doi.org/10.1080/027868290903907>.
- Durdina, L., Brem, B.T., Abegglen, M., Lobo, P., Rindlisbacher, T., & Thomson, K.A., et al. (2014). Determination of PM mass emissions from an aircraft turbine engine using particle effective density. *Atmospheric Environment*, 99, 500–507, <http://dx.doi.org/10.1016/j.atmosenv.2014.10.018>.
- EASA, 2012. SAMPLE III: Contribution to aircraft engine PM certification requirement and standard; Second specific contract – final report.
- Friedlander, S.K. (2000). *Smoke, dust, and haze: Fundamentals of aerosol dynamics* 2nd ed.). Oxford University Press: USA.
- Ghazal, R., & Olfert, J.S. (2013). Coating mass dependence of soot aggregate restructuring due to coatings of oleic acid and dioctyl sebacate. *Aerosol Science and Technology*, 47(2), 192–200, <http://dx.doi.org/10.1080/02786826.2012.741273>.
- ICAO, 2008. Annex 16 to the convention on international civil aviation: Environmental protection (Vol. II). *Aircraft engine emissions*.
- ICAO, 2013. *Aviation and climate change*. Environmental report.

- Johnson, T.J., Olfert, J.S., Symonds, J.P.R., Johnson, M., Rindlisbacher, T., & Swanson, J.J., et al. (2015). Effective density and mass–mobility exponent of aircraft turbine particulate matter. *Journal of Propulsion and Power*, 31(2), 573–582 doi: 10.2514/1.B35367.
- Johnson, T.J., Symonds, J.P.R., & Olfert, J.S. (2013). Mass–mobility measurements using a centrifugal particle mass analyzer and differential mobility spectrometer. *Aerosol Science and Technology*, 47(11), 1215–1225, <http://dx.doi.org/10.1080/02786826.2013.830692>.
- Khalizov, A.F., Xue, H., Wang, L., Zheng, J., & Zhang, R. (2009). Enhanced light absorption and scattering by carbon soot aerosol internally mixed with sulfuric acid. *The Journal of Physical Chemistry A*, 113(6), 1066–1074, <http://dx.doi.org/10.1021/jp807531n>.
- Kiselev, A., Wennrich, C., Stratmann, F., Wex, H., Henning, S., & Mentel, T.F., et al. (2010). Morphological characterization of soot aerosol particles during LACIS Experiment in November (LEXNo). *Journal of Geophysical Research: Atmospheres*, 115(D11) <http://dx.doi.org/10.1029/2009JD012635> n/a–n/a.
- Liati, A., Brem, B.T., Durdina, L., Vögtli, M., Arroyo Rojas Dasilva, Y., & Dimopoulos Eggenschwiler, P., et al. (2014). Electron microscopic study of soot particulate matter emissions from aircraft turbine engines. *Environmental Science & Technology*, 48(18), 10975–10983, <http://dx.doi.org/10.1021/es501809b>.
- Lighty, J.S., Veranth, J.M., & Sarofim, A.F. (2000). Combustion aerosols: Factors governing their size and composition and implications to human health. *Journal of the Air & Waste Management Association*, 50(9), 1565–1618, <http://dx.doi.org/10.1080/10473289.2000.10464197>.
- Lobo, P., Durdina, L., Smallwood, G.J., Rindlisbacher, T., Siegerist, F., & Black, E.A., et al. (2015). Measurement of aircraft engine non-volatile PM emissions: Results of the aviation – Particle Regulatory Instrument Demonstration Experiment (A-PRIDE) 4 campaign. *Aerosol Science and Technology* <http://dx.doi.org/10.1080/02786826.2015.1047012> 00–00.
- Ma, X., Zangmeister, C.D., Gigault, J., Mulholland, G.W., & Zachariah, M.R. (2013). Soot aggregate restructuring during water processing. *Journal of Aerosol Science*, 66, 209–219, <http://dx.doi.org/10.1016/j.jaerosci.2013.08.001>.
- Maricq, M.M. (2007). Coagulation dynamics of fractal-like soot aggregates. *Journal of Aerosol Science*, 38(2), 141–156, <http://dx.doi.org/10.1016/j.jaerosci.2006.11.004>.
- Maricq, M.M., & Xu, N. (2004). The effective density and fractal dimension of soot particles from premixed flames and motor vehicle exhaust. *Journal of Aerosol Science*, 35(10), 1251–1274, <http://dx.doi.org/10.1016/j.jaerosci.2004.05.002>.
- Mathis, U., Mohr, M., Kaegi, R., Bertola, A., & Boulouchos, K. (2005a). Influence of diesel engine combustion parameters on primary soot particle diameter. *Environmental Science & Technology*, 39(6), 1887–1892, <http://dx.doi.org/10.1021/es049578p>.
- Mazaheri, M., Bostrom, T.E., Johnson, G.R., & Morawska, L. (2013). Composition and morphology of particle emissions from in-use aircraft during takeoff and landing. *Environmental Science & Technology*, 47(10), 5235–5242, <http://dx.doi.org/10.1021/es3046058>.
- Miljevic, B., Surawski, N.C., Bostrom, T., & Ristovski, Z.D. (2012). Restructuring of carbonaceous particles upon exposure to organic and water vapours. *Journal of Aerosol Science*, 47, 48–57, <http://dx.doi.org/10.1016/j.jaerosci.2011.12.005>.
- Myhre, G., Shindell, D., Bréon, F.-M., Collins, W., Fuglestad, J., & Huang, J., et al. (2013). Anthropogenic and natural radiative forcing. In T.F. Stocker, D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex, & P.M. Midgley (Eds.), *Climate change 2013: The physical science basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge University Press: Cambridge, UK; New York, NY, USA.
- Olfert, J.S., & Collings, N. (2005). New method for particle mass classification—The Couette centrifugal particle mass analyzer. *Journal of Aerosol Science*, 36(11), 1338–1352, <http://dx.doi.org/10.1016/j.jaerosci.2005.03.006>.
- Olfert, J.S., Symonds, J.P.R., & Collings, N. (2007). The effective density and fractal dimension of particles emitted from a light-duty diesel vehicle with a diesel oxidation catalyst. *Journal of Aerosol Science*, 38(1), 69–82, <http://dx.doi.org/10.1016/j.jaerosci.2006.10.002>.
- Onasch, T.B., Jayne, J.T., Herndon, S., Worsnop, D.R., Mlake-Lye, R.C., & Mortimer, I.P., et al. (2009). Chemical properties of aircraft engine particulate exhaust emissions. *Journal of Propulsion and Power*, 25(5), 1121–1137, <http://dx.doi.org/10.2514/1.36371>.
- Park, K., Cao, F., Kittelson, D.B., & McMurry, P.H. (2003). Relationship between particle mass and mobility for diesel exhaust particles. *Environmental Science & Technology*, 37(3), 577–583, <http://dx.doi.org/10.1021/es025960v>.
- Park, K., Kittelson, D.B., Zachariah, M.R., & McMurry, P.H. (2004). Measurement of inherent material density of nanoparticle agglomerates. *Journal of Nanoparticle Research*, 6(2), 267–272, <http://dx.doi.org/10.1023/B:NANO.0000034657.71309.e6>.
- Petzold, A., Fiebig, M., Fritzsche, L., Stein, C., Schumann, U., & Wilson, C.W., et al. (2005). Particle emissions from aircraft engines – A survey of the European project PartEmiss. *Meteorologische Zeitschrift*, 14(4), 465–476, <http://dx.doi.org/10.1127/0941-2948/2005/0054>.
- Petzold, A., Ogren, J.A., Fiebig, M., Laj, P., Li, S.-M., & Baltensperger, U., et al. (2013). Recommendations for reporting “black carbon” measurements. *Atmospheric Chemistry and Physics*, 13(16), 8365–8379, <http://dx.doi.org/10.5194/acp-13-8365-2013>.
- Popovich, O.B., & Starik, A.M. (2007). Aircraft-generated soot aerosols: Physicochemical properties and effects of emission into the atmosphere. *Izvestiya, Atmospheric and Oceanic Physics*, 43(2), 125–141, <http://dx.doi.org/10.1134/S0001433807020016>.
- Ris, C. (2008). U.S. EPA Health assessment for diesel engine exhaust: A review. research-article. Retrieved 09.05.14, from <http://informahealthcare.com/doi/abs/10.1080/08958370701497960>.
- Rissler, J., Messing, M.E., Malik, A.I., Nilsson, P.T., Nordin, E.Z., & Bohgard, M., et al. (2013). Effective density characterization of soot agglomerates from various sources and comparison to aggregation theory. *Aerosol Science and Technology*, 47(7), 792–805, <http://dx.doi.org/10.1080/02786826.2013.791381>.
- Rogers, F., Arnott, P., Zielinska, B., Sagebiel, J., Kelly, K.E., & Wagner, D., et al. (2005). Real-time measurements of jet aircraft engine exhaust. *Journal of the Air & Waste Management Association*, 55(5), 583–593, <http://dx.doi.org/10.1080/10473289.2005.10464651>.
- SAE (2013). *Aerospace Information Report 6241: Procedure for the continuous sampling and measurement of non-volatile particle emissions from aircraft turbine engines*.
- Schmidt-Ott, A. (1988). New approaches to in situ characterization of ultrafine agglomerates. *Journal of Aerosol Science*, 19(5), 553–563, [http://dx.doi.org/10.1016/0021-8502\(88\)90207-8](http://dx.doi.org/10.1016/0021-8502(88)90207-8).
- Schmidt-Ott, A., Baltensperger, U., Gäggeler, H., & Jost, D. (1990). Scaling behaviour of physical parameters describing agglomerates. *Journal of Aerosol Science*, 21(6), 711–717, [http://dx.doi.org/10.1016/0021-8502\(90\)90037-X](http://dx.doi.org/10.1016/0021-8502(90)90037-X).
- Shapiro, M., Vainshtein, P., Dutcher, D., Emery, M., Stolzenburg, M., & Kittelson, D.B., et al. (2012). Characterization of agglomerates by simultaneous measurement of mobility, vacuum aerodynamic diameter and mass. *Journal of Aerosol Science*, 44, 24–45, <http://dx.doi.org/10.1016/j.jaerosci.2011.08.004>.
- Sorensen, C.M. (2001). Light scattering, M.R., by fractal aggregates: A review. *Aerosol Science and Technology*, 35(2), 648–687, <http://dx.doi.org/10.1080/02786820117868>.
- Sorensen, C.M. (2011). The mobility of fractal aggregates: A review. *Aerosol Science and Technology*, 45(7), 765–779, <http://dx.doi.org/10.1080/02786826.2011.560909>.
- Timko, M.T., Yu, Z., Onasch, T.B., Wong, H.-W., Mlake-Lye, R.C., & Beyersdorf, A.J., et al. (2010). Particulate emissions of gas turbine engine combustion of a Fischer–Tropsch synthetic fuel. *Energy & Fuels*, 24(11), 5883–5896, <http://dx.doi.org/10.1021/ef100727t>.
- Vander Wal, R.L., Bryg, V.M., & Huang, C.-H. (2014). Aircraft engine particulate matter: Macro- micro- and nanostructure by HRTEM and chemistry by XPS. *Combustion and Flame*, 161(2), 602–611, <http://dx.doi.org/10.1016/j.combustflame.2013.09.003>.
- Wiedensohler, A. (1988). An approximation of the bipolar charge distribution for particles in the submicron size range. *Journal of Aerosol Science*, 19(3), 387–389, [http://dx.doi.org/10.1016/0021-8502\(88\)90278-9](http://dx.doi.org/10.1016/0021-8502(88)90278-9).
- Wierzbicka, A., Nilsson, P.T., Rissler, J., Sallsten, G., Xu, Y., & Pagels, J.H., et al. (2014). Detailed diesel exhaust characteristics including particle surface area and lung deposited dose for better understanding of health effects in human chamber exposure studies. *Atmospheric Environment*, 86, 212–219, <http://dx.doi.org/10.1016/j.atmosenv.2013.11.025>.

- Williams, P.I., Allan, J.D., Lobo, P., Coe, H., Christie, S., & Wilson, C., et al. (2012). Impact of alternative fuels on emissions characteristics of a gas turbine engine – Part 2: Volatile and semivolatile particulate matter emissions. *Environmental Science & Technology*, 46(19), 10812–10819, <http://dx.doi.org/10.1021/es301899s>.
- Zhang, R., Khalizov, A.F., Pagels, J., Zhang, D., Xue, H., & McMurry, P.H. (2008). Variability in morphology, hygroscopicity, and optical properties of soot aerosols during atmospheric processing. *Proceedings of the National Academy of Sciences*, 105(30), 10291–10296, <http://dx.doi.org/10.1073/pnas.0804860105>.