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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/m^3 to 1865 kg/m^3 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.

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 (Burtscher, 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, & Dumitrean,, 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 $\sim 1000\ \mathrm{kg/m^3}$ 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 $710\ \mathrm{kg/m^3}$ to $840\ \mathrm{kg/m^3}$ 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 (~ 0.7 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