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Volatile particles measured by vapor-particle separator

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A B S T R A C T

Vapor-Particle Separator (VPS) is a new technology developed for characterization of the volatile fraction of particulate matter in a combustion aerosol population. VPS incorporates a novel metallic membrane and operates in a cross-flow filtration mode for separation of vapor and solid (i.e. non-volatile) particles. Demonstration of the VPS technology on aircraft engine-emitted particles has led to the improvement of the technology and increased confidence on the robustness of its field performance. In this study, the performance of the VPS was evaluated against the Particle Measurement Programme (PMP) volatile particle remover (VPR), a standardized device used in heavy duty diesel engines for separation and characterization of non-volatile particulate matter. Using tetracontane particles in the laboratory reveals that the VPS performed reasonably well in removing the volatile species. In the field conditions, a single-mode particle size distribution was found for emitted particles from a T63 turboshaft engine at both idle and cruise engine power conditions. Removal of the volatile T63 engine particles by the VPS was consistent with that of PMP VPR. In tests on an F117 turbofan engine, the size distribution at the idle (4% rated) engine power condition was found to be bimodal, with the first mode consisting of particles smaller than 10 nm, which are believed to be mostly semi-volatile particles, while the second mode of larger size was a mixture of semi-volatile and non-volatile particles. The distribution was single modal at the 33% rated engine power with no secondary mode observed. Overall, for particles emitted by both engines, the removal efficiency of the VPS appears to surpass that of the PMP VPR by 8-10%.

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1. Introduction

Combustion particles from aircraft engines are composed of condensable and non-volatile fractions (Cheng, Corporan, DeWitt & Landgraf, 2009), and all turbine engine particles are ultrafine (Cheng et al., 2008, 2009). Small size of particles enhances their ability to translocate if they are inhaled (Oberdörster & Utell, 2002). Numerous epidemiological studies have clearly shown a relationship between particulate matter (PM) concentrations and mortality rates. $PM_{2.5}$ or particles ≤ 2.5 μm in aerodynamic diameter is a criteria pollutant by the U.S. Environmental Protection Agency (EPA). The U.S. EPA and international environmental agencies continue to implement more stringent air quality standards. These standards and regulations will no doubt affect the transportation sector, including aviation industry that relies heavily on the use of fossil fuels. In the case of aviation, the regulation may slow the growth of commercial aviation worldwide and limit operations in U.S. military bases, especially those located within National Ambient Air Quality non-attainment areas.

More than 50% of the atmospheric PM mass is classified as secondary in many regions such as the Southeast U.S. Secondary PM is a result of the complex gas-to-particle transformation and mass transfer between the two phases. Molecules of higher molecular weight, including sulfur-based and organic compounds, are responsible for the formation of secondary PM (referred to as volatile PM – VPM) in the atmosphere. As the exhaust leaves the engine, it rapidly mixes with the ambient air and cools down, high molecular weight vapor molecules in the exhaust plume would condense onto the non-volatile fraction (or soot) (Ristimaki, Vaaraslahti, Lappi & Keskinen, 2007). Given a sufficient concentration, the vapors could nucleate into new particles through the condensation-nucleation processes (Ronkko et al., 2007) that would change the particle size distribution from a single mode distribution to possibly a bi-modal one of non-equal size. Representative sampling and accurate measurement of the volatile aircraft engine PM has been challenging as these are greatly influenced by the ambient conditions and composition of the engine exhaust. At the present, only soot or soot-like materials or non-volatile PM (primary PM) can be measured consistently in the particulate phase by modern aerosol instrument and sampling technology as demonstrated in the Particle Measurement Programme (PMP) (Giechaskiel, Dilara, Sandbach & Anderson, 2008; Mamakos, 2012; Zheng et al., 2012).

There exists no standard method for sampling and measurement of VPM. Currently, researchers remove aircraft volatile PM by using devices such as thermodenuder (Burtscher et al., 2001), catalytic stripping (Swanson & Kittelson, 2010; Mamakos, 2012), and Volatility Tandem Differential Mobility Analyzer (VTDMA) (Johnson, Ristovski & Morawska, 2004; Villani, Picard, Marchand & Laj, 2007). None of these enable one to observe engine particle dynamics, molecular transfer, or evaporation process under varying temperature conditions. For example, the thermodenuder and the catalytic stripper were intended for rapid removal of volatile components from soot particles, while VTDMA was to investigate volatilization and hygroscopicity of single ambient aerosol particles. Although highly detailed, the VTDMA is too slow to be suitable for aircraft VPM measurement. In addition, the concentrations of water vapor, unburned hydrocarbons, and particles in the engine exhaust are so high that the VTDMA would be overwhelmed.

For 30 years, thermodenuder of different variations has been a popular device designed to desorb volatile species for studies of “solid” ambient particles (Johnson et al., 2004; Newman, 1978; Cobourn, Husar & Husar, 1978; Slanina, Keuken & Schoonebeek, 1987; Sturges & Harrison, 1988; Wehner, Philippin & Wiedensohler, 2002; Fierz, Vernooij & Burtscher, 2007; Park, Kim, Choi & Hwang, 2008; Huffman, Ziemann, Jayne, Worsnop & Jimenez, 2008; Wu, Poulain, Wehner, Wiedensohler & Herrmann, 2009). Thermal stripping devices have also been used on diesel engine soot and aircraft emissions (Burtscher et al., 2001; Maricq, Chase, Podsiadlik & Vogt, 1999; Vaaraslhti, Virtanen, Ristimaki & Keskinen, 2004; Virtanen, Ristimaki, Vaaraslhti & Keskinen, 2004; Petzold et al., 2005; Mamakos, Ntziachristos & Samaras, 2006). Although volatile components are removed from the PM, the adsorbent used in these designs retain the volatile components. Once the adsorption capacity is exceeded, the volatiles could and have been found to re-condense on existing particles or form new ones (e.g., Swanson & Kittelson, 2010).

2. Description of vapor particle separator (VPS)

To improve measurement and characterization of aircraft VPM, a new technology called Vapor-Particle Separator (VPS) has been designed and tested at the Oak Ridge National Laboratory (ORNL) (Cheng & Allman, 2011). The VPS technology was tested against the PMP VPR (Giechaskiel et al., 2008; Mamakos, 2012; Zheng et al., 2012) using tetracontane particles and exhaust particles from turbine engines (T63 and F117 engines at the Wright-Patterson Air Force Base). The PMP VPR requirements have been modified to accommodate the smaller particles emitted by turbine engines relative to diesel engines. The VPS has met the total volatile particle removal requirements, but additional tests are needed to demonstrate compliance with size-dependent losses of non-volatile particles and other VPR requirements. These had not been established at the time the VPS was evaluated.

It is important to mention that the PMP VPR is not a standard for aircraft emission measurement, although it has been used as a standard protocol in diesel engine research and certification (Giechaskiel,Carriero, Martini & Andersson, 2009). Its use and the results reported in this paper are primarily for comparison with those of the VPS. Currently, there isn't a standard VPR for non-volatile PM measurements from aircraft turbine engines. The SAE E31 committee has established requirements for a compliant VPR in the draft of the nvPM Aerospace Recommended Practice (ARP) 6320. The ARP will be balloted by December 2016. If its approved, then the VPR as established in the ARP will be the standard.