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Improvement of Engine Exhaust Particle Sizer (EEPS) size distribution measurement – I. Algorithm and applications to compact-shape particles

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ABSTRACT

Comparisons between the Engine Exhaust Particle Sizer Spectrometer (EEPS) and scanning mobility particle sizers (SMPS) have shown that the EEPS underestimates size and concentration of particles $> \sim 75$ nm and that the discrepancies vary by particle type. This paper describes the development of a new EEPS instrument matrix to improve size distribution measurements for compact-shape particles. Both the operating principle and the mathematical model of the EEPS data inversion are described. Monodisperse and polydisperse sucrose, poly-α-olefin oil (PAO), and sodium chloride (NaCl) particles were used for calibration. A new instrument matrix was developed and implemented for data inversion. This study confirms the literature findings that the geometric mean diameter, geometric standard deviation, and total number concentration by EEPS with the default instrument matrix (referred to as IM-2004) agrees with SMPS within $\pm 20\%$ for compact-shape particles $< \sim 75$ nm. However, EEPS with IM-2004 underestimates geometric mean diameters by 20–40% for larger particles. The revised instrument matrix improves the size agreement with the SMPS to within $\pm 14\%$ across the entire size range.

1. Introduction

Particle size is an important parameter for determining particle origin and fate, physical and chemical properties, and environmental and health effects (U.S.EPA, 2004). Electrical mobility analysis (Flagan, 1998; McMurry, 2000), both voltage scanning and non-scanning types, is used to measure submicron particle size distributions (PSD). Voltage-scanning mobility sizers, represented by the scanning mobility particle sizer (SMPS), require > 30 s to measure a PSD (Wang & Flagan, 1990). Faster SMPSs (e.g., TSI Model 3938) allow < 10 s per scan (Erickson & Quant, 2011), but this is slower than aerosol changes for many processes. SMPSs are more suitable for measuring stable aerosols. Non-scanning mobility spectrometers employ multiple detectors to simultaneously measure mobility-separated particles and acquire PSDs at 0.1–1 s intervals (Biskos, Reavell & Collings, 2005; Johnson, Caldow, Pöcher, Mirme & Kittelson, 2004; Tammet, Mirme & Tamm, 2002). This fast

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Table 1
Summary of previous EEPS, SMPS, and CPC comparisons for compact-shape particles.

Citation	Instruments[a]	Aerosol type[b] [c]	Observation[c]
Zimmerman et al. (2015)	EEPS, RSMPS, and NSMPS (0.6/6 L/min)[d]	PSL, sucrose, and NH_4NO_3	Mode diameter for particle ≥ 80 nm: EEPS$=$SMPS$\times 0.58+25$
Zimmerman et al. (2014)	EEPS and CPC (2.5 nm)[e]	miniCAST compact soot ($d_g=22$ nm)	EEPS / CPC (C_N)$=\sim 1$
Kaminski et al. (2013)	EEPS and RSMPS (0.3/3 and 0.6/6 L/min)[d]	NaCl ($d_g=40$ nm)	EEPS agreed reasonably well with RSMPS: EEPS / RSMPS (d_g)$=1.05\pm 0.03$ EEPS / RSMPS (σ_g)$=0.95\pm 0.03$CPC EEPS / RSMPS (C_N)$=0.86\pm 0.07$
		DEHS ($d_g=250$–300 nm)	EEPS showed smaller mean diameter, narrower PSD, and higher concentration: EEPS / RSMPS (d_g)$=0.72\pm 0.04$ EEPS / RSMPS (σ_g)$=0.84\pm 0.04$ EEPS / RSMPS (C_N)$=1.18\pm 0.15$
Lee et al. (2013)	EEPS and RSMPS (0.4/4 L/min)[d]	NH_4NO_3, NH_4HSO_4, $(NH_4)_2SO_4$, and NaCl	Mode vs. diameter for particle ≥ 50 nm: EEPS$=$SMPS$\times 0.56+14.7$
Leskinen et al. (2012)	EEPS, CPC (2.5 nm)[e], and RSMPS (0.3/3 L/min)[d]	PSL (97 ± 3 nm)	EEPS showed smaller diameter and wider distribution: EEPS $d_g=88$ nm; $\sigma_g=1.5$ RSMPS $d_g=99$ nm; $\sigma_g=1.0$
		PSL (300 ± 6 nm)	EEPS showed much smaller diameter: EEPS $d_g=187$ nm; $\sigma_g=1.3$ RSMPS $d_g=299$ nm; $\sigma_g=1.1$
		$(NH_4)_2SO_4$ ($d_g=32$ nm)	EEPS agreed well with RSMPS and CPC: EEPS / RSMPS (d_g)$=1.06$ EEPS / RSMPS (σ_g)$=1.03$ EEPS / RSMPS (C_N)$=0.96$ EEPS / CPC (C_N)$=0.96$
Jeong and Evans (2009)	EEPS and NSMPS (0.6/6 L/min)[d]	NaCl ($d_g=50$ nm) and gold nanoparticle ($d_g=22$ nm)	EEPS agreed well with NSMPS: EEPS / NSMPS (d_g)$=1.0$ EEPS / NSMPS (C_N)$=0.89$–0.93
Asbach et al. (2009)	EEPS and RSMPS (0.3/3 L/min)[d]	PSL (100 nm)	EEPS peak diameter was smaller than the RSMPS: EEP $d_g=80$ nm; RSMPS $d_g=105$ nm
	EEPS and RSMPS (0.3/3 and 0.6/6 L/min)[d]	NaCl ($d_g=35$ nm)	EEPS showed reasonable agreement with RSMPS, with smaller diameter, broader distribution, and comparable concentration: EEPS / RSMPS (d_g)$=0.78$–0.91 EEPS / RSMPS (σ_g)$=1.11$–1.19 EEPS / RSMPS (C_N)$=1.05$–1.16

Notes:

[a] Instruments abbreviations: **CPC**: Condensation Particle Counter; **NSMPS**: Nano SMPS with a TSI Model 3085 nano DMA; **DMA**: Differential mobility analyzer; **RSMPS**: Regular SMPS with a TSI Model 3081 long DMA; **SMPS**: Scanning mobility particle sizer; **EEPS**: Engine Exhaust Particle Sizer.

[b] Aerosol Type abbreviations: $\mathbf{NH_4NO_3}$: Ammonium nitrate; **CAST**: Combustion Aerosol Standard soot generator; $\mathbf{(NH_4)_2SO_4}$: Ammonium sulfate; DEHS: Di-Ethyl-Hexyl-Sebacate; $\mathbf{NH_4HSO_4}$: Ammonium bisulfate; **PSL**: Polystyrene latex; **NaCl**: Sodium chloride.

[c] Other abbreviations: $\mathbf{d_g}$: Geometric mean diameter; $\boldsymbol{\sigma_g}$: Geometric standard deviation; and $\mathbf{C_N}$: Total particle number concentration.

[d] The number after SMPS indicates the aerosol/sheath flow rates.

[e] The diameter after the CPC indicates the 50% cutoff particle diameter.

response permits quantification of rapidly-changing PSDs, such as those from engine exhaust and nanoparticle manufacturing processes.

The Engine Exhaust Particle Sizer™ (EEPS; Model 3090, TSI Shoreview, MN) is a non-scanning mobility spectrometer (Johnson et al., 2004) based on the initial design of Tammet et al. (2002). It measures PSD in the mobility diameter range of 5.62–562 nm up to 10 times per second. The Fast Mobility Particle Sizer (FMPS; Model 3091, TSI Shoreview, MN) uses the same principle as the EEPS, with a one second time resolution. These two instruments are treated as the same in this paper. The EEPS has been used to measure PSDs for: 1) laboratory engine and vehicle emission characterization under steady state and transient conditions (Liu, Ford, Vasys, Chen & Johnson, 2007; Wang et al., 2006); 2) real-world emission measurements on test vehicles, at roadside stations, and in tunnels (Barrios, Domínguez-Sáez, Rubio & Pujadas, 2011; Zimmerman et al., 2014); 3) diesel particulate filter (DPF) performance characterizations (Bergmann, Kirchner, Vogt & Benter, 2009; Liu, Thurow, Caldow & Johnson, 2005; Zervas and Dorlhene, 2006); 4) PSD evolution in biomass burnings (Hosseini et al., 2010); and 5) ambient indoor and outdoor PSDs (Jeong & Evans, 2009; Zimmerman et al., 2014). Several studies have examined integrated PSDs from EEPS for potential application to engine exhaust emission regulation (Li et al., 2014; Liu et al., 2009).

Table 1 summarizes EEPS comparisons with SMPS and condensation particle counters (CPC) for compact-shape particles that are nearly spherical (e.g., sodium chloride [NaCl], Di-Ethyl-Hexyl-Sebacate [DEHS], ammonium sulfate [$(NH_4)_2SO_4$], gold nanoparticles, and miniCAST compact soot). The EEPS agrees with SMPS and/or CPC measurements for PSD and number concentrations for diameters $<\sim 50$ nm (Asbach et al., 2009; Jeong & Evans, 2009; Kaminski et al., 2013; Leskinen et al., 2012; Zimmerman et al., 2014). However, the EEPS reports smaller diameters for larger sizes ($>\sim 75$ nm) (Asbach et al.,