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A fast integrated mobility spectrometer with wide dynamic size range: Theoretical analysis and numerical simulation

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ABSTRACT

A fast integrated mobility spectrometer with wide size range (WSR-FIMS) is described. The WSR-FIMS greatly enhances the dynamic size range of the original FIMS [Kulkarni, P., & Wang, J. (2006a). New fast integrated mobility spectrometer for real-time measurement of aerosol size distribution—I: Concept and theory. *Journal of Aerosol Science*, *37*, 1303—1325; Kulkarni, P., & Wang, J. (2006b). New fast integrated mobility spectrometer for real-time measurement of aerosol size distribution—II: Design, calibration, and performance characterization. *Journal of Aerosol Science*, *37*, 1326—1339] by employing a non-uniform electric field. The strength of this electric field varies over three orders of magnitude along the width of the separator, allowing particles of a much wider size range to be classified and measured simultaneously. A theoretical framework is developed to derive the transfer function, resolution, and transmission efficiency of the WSR-FIMS. Two representative operation configurations are simulated, and the results show the WSR-FIMS can simultaneously measure particles ranging from 10 to 1470 nm, therefore greatly reducing the measurement time from minutes required by scanning mobility particle sizer (SMPS) to 1 s or less. The WSR-FIMS also has a higher size resolution than typical SMPS over most of its measurement size range. For typical ambient aerosols, the simulations show that 1 s measurements using the WSR-FIMS provide good counting statistics.

1. Introduction

Real-time measurement of particle size distributions, especially in the nanometer size range, is important in many applications such as measurement of atmospheric aerosols and characterization of particles in combustion systems. Rapid measurements are often required to capture transient aerosol dynamics occurring on very small time scales, such as in high temperature environments or other nucleation-dominated systems. In other types of measurements, such as those onboard fast-moving platforms (e.g. research aircraft) aimed at characterizing spatial and temporal distributions of atmospheric aerosols, high time resolution is essential to capture the variations of aerosol properties over small spatial domain.

Previously existing instruments for sub-micrometer aerosol size distribution measurements are summarized briefly in Kulkarni and Wang (2006a). Currently, sub-micrometer aerosol size distributions are often measured using scanning mobility particle sizers (SMPS) and optical particle counters (OPC). The SMPS is a sequential measurement technique. Therefore, only particles within a narrow size range, which represent a small fraction of total particles introduced, are measured at one time. Obtaining the entire aerosol size distribution requires scanning the classifying voltage over a wide range, which typically takes about 1 min or more and is too slow for aircraft-based measurements (Wang and Flagan, 1989). The time required for scanning

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Nomenclature

Symbols

a	gap between electrodes
b	width of separator
b_0	width of virtually extended separator
b_1	distance over which voltage applied to the HV electrode increases exponentially
C	number of particle counts detected in a size bin
d_p	particle diameter
E_x, E_y	x and y components of the electric field inside separator
k	Boltzmann constant
l_s	length of separator
Pe_{mig}	migration Péclet number
Q_a, Q_{sh}, Q_t	aerosol, sheath, and total flowrates
q	electric charge carried by particles
R_{FWHW}	mobility resolution based on the full width at half maximum of mobility transfer function
R_{std}	mobility resolution based on the standard deviation of mobility transfer function
T	absolute temperature
t_c	counting time
U_x, U_y, U_z	x, y, and z components of particle velocity
u_x, u_y, u_z	x, y, and z components of flow velocity
V	voltage applied to high voltage electrode
V_{diff}	characteristic voltage below which particle diffusion becomes dominant of transfer function
x^*_{out}, y^*_{out}	x- and y-coordinates at the separator exit for particles introduced along central flow streamlines
y_{in}	particle y-coordinate at aerosol inlet
Z_p	particle electrical mobility
Z^*_p	instrument response mobility

Greek letters

Ψ	flow streamline function
Φ	electric flux function
β	ratio of aerosol flow rate to sheath flow rate
η	transmission efficiency of WSR-FIMS
η_{chg}	fraction of particles carrying one positive charge in a bipolar charger
μ	exponential constant of the varying voltage applied to HV electrode
σ_C	uncertainty in particle counts detected in a size bin

the classifying voltage can be reduced to 1–2 s by using a fast mixing-type CNC as the detector (Wang, McNeill, Collins, & Flagan, 2002). However, because only a small fraction of total particles is measured at a time, the sampling rate of the SMPS is insufficient for rapid measurements. As a result, despite the improvement in measurement speed by using a fast-response detector, measurements in clean environments are often compromised by the time required to obtain statistically significant numbers. Other electrical mobility-based instruments, such as the electrical aerosol spectrometer (EAS, Mirme et al., 1984; Mirme, 1994; Tammet, Mirme, & Tamm, 1998; Tammet, Mirme, & Tamm, 2002), engine exhaust particle sizer (EEPS, Johnson, Caldow, Pocher, Mirme, & Kittelson, 2004), and differential mobility spectrometer (DMS, Biskos, Reavell, & Collings, 2005), measure particles of different mobilities simultaneously using an array of integrated electrometers, and are capable of sub-second measurements of aerosol size distributions. However, compared to CPCs that detect individual particles optically, electrometers have low sensitivity. Applications of these instruments are therefore limited to aerosols with high number concentrations, such as engine exhausts. Besides low sensitivity, EAS, EEPS, and DMS also have considerably lower size resolution than SMPS.

The other type of instruments frequently used to measure sub-micrometer aerosol size distributions is OPC, which measures particle sizes based on the intensity of light scattered by the particles. OPC offers fast measurement speed and better counting statistics than does SMPS, but its measurement range is usually limited to particles with diameters greater than 100 nm (note all particle size are given in particle diameter in this study). In addition, particle physical properties such as shape, refractive index, and morphology have strong influences on derived particle sizes, and are often unavailable. Even for the ideal case of homogeneous spherical aerosol particles, the uncertainty in refractive index often leads to significant uncertainties in derived size distributions (Hering and McMurry, 1991).

A fast integrated mobility spectrometer (FIMS) was previously developed by Kulkarni and Wang (2006a, 2006b). The data inversion technique for FIMS measurement was developed (Olfert, Kulkarni, & Wang, 2008), and the performance of the FIMS was characterized (Kulkarni and Wang, 2006b; Olfert and Wang, 2009). By simultaneously measuring particles of different sizes/mobilities, the FIMS provides size spectra of sub-micrometer aerosol within 1 s, nearly 100 times faster than traditional