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New fast integrated mobility spectrometer for real-time measurement of aerosol size distribution: II. Design, calibration, and performance characterization☆

Pramod Kulkarni, Jian Wang*

Brookhaven National Laboratory, Building 815E, Upton, NY 11973-5000, USA

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Abstract

A Fast Integrated Mobility Spectrometer (FIMS) has been developed for sub-second aerosol size distribution measurements based on the description presented in the preceding paper (Paper I). The performance of FIMS was characterized using DMA classified aerosols in the size range 15–170 nm. An excellent agreement was observed between the mean particle diameter measured by FIMS and the DMA centroid diameter. Comparison of particle concentrations measured by FIMS and a Condensation Particle Counter (CPC) shows that counting efficiency of FIMS is 100% for particles larger than 20 nm, and higher than that of the CPC for particles with diameters less than 15 nm. Experimentally determined FIMS mobility resolution ranged from 5 to 14 for particle diameters between 22 to 170 nm, and agreed with theoretical predictions made using FIMS transfer theory, though there was some deviation observed at particle sizes that correspond to high theoretical mobility resolution.

Keywords: Aerosol size distribution measurements; High time resolution; Electric mobility; Transfer function; Counting efficiency; Particle diffusion; Mobility resolution

1. Introduction

A Fast Integrated Mobility Spectrometer (FIMS) for real-time measurement of sub-micrometer aerosol size distributions (15–1000 nm) has been developed based on the description presented in the preceding paper (Paper I). The FIMS first separates aerosol particles based on their electrical mobility in a uniform electric field generated by a parallel plate geometry, and subsequently grows them into super-micrometer droplets in a supersaturation environment. The detector—a high speed camera—records the mobility-dependent particle positions and counts, which are then used to derive particle electrical mobility and concentration. By detecting particle of different sizes simultaneously, the FIMS eliminates the need for voltage scanning required in traditional scanning mobility techniques, and ensures

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* Corresponding author. Tel.: +1 631 344 7920; fax: +1 631 344 2887.
E-mail address: jian@bnl.gov (J. Wang).

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significant increases in both measurement speed and counting statistics. This paper describes design and performance characterization of a prototype FIMS based on the analysis presented in Paper I.

Standard calibration techniques, pertinent to characterization of FIMS, are briefly reviewed below. Although there are many methods, the cylindrical DMA has been extensively used to generate monodisperse aerosols for instrument calibrations. Agarwal and Sem (1978) described calibration of a DMA using monodisperse particles that were classified from a polydisperse aerosol with a second DMA. In their method, two DMAs are used in a sequence such that the 'quasi-monodisperse' aerosol from the first DMA is input to the second DMA for calibration. This method, which is often referred to as Tandem DMA (TDMA) technique (Rader & McMurry, 1986), has been extensively used to determine the DMA transfer function and to study the broadening of the transfer function due to Brownian diffusion of small particles. Kousaka, Okuyama, Adachi, and Mimura (1986) investigated, both theoretically and experimentally, the diffusional broadening of DMA transfer function. Stolzenburg (1988) performed detailed analysis of particle Brownian diffusion in a cylindrical DMA and derived an analytical expression for DMA transfer function that accounts for both migration and Brownian diffusion. He showed that the diffusional broadening of the DMA transfer function is characterized by a spread factor (σ) that represents non-dimensional variance in the particle stream function. He also experimentally measured the spread factor using the TDMA method and showed that the measured spread factor agreed with the theoretical value at aerosol to sheath flow ratio (β) of 0.1, but was slightly higher than the predicted value at $\beta = 0.05$. Zhang and Flagan (1996) extended the Stolzenburg's model to derive the transfer function of their radial DMA. They also measured the spread factor using TDMA technique, and found the measured σ was higher than the theoretical prediction. Zhang and Flagan (1996) concluded that the discrepancy was possibly due to non-idealities in flow and electrical fields inside the radial DMA.

Following the convention in spectroscopic literature, Zhang and Flagan (1996) proposed that the performance of DMAs could be characterized in terms of mobility resolution, which is defined as the ratio of the mobility at the peak of the transfer function to the full width at half the peak height of transfer function. Thus, mobility resolution characterizes the relative uncertainty in measured mobility. Their experimental results showed that the resolution of radial DMA approached the theoretical limit at small Peclet numbers, but fell below the theoretical value in the large Peclet number limit, suggesting that the cause for this deviation could be attributed to the flow distortion at the aerosol entrance. Stolzenburg's (1988) study of cylindrical DMA also showed similar deviation, though smaller in magnitude, at high flow rates—possibly resulting from entrance flow arrangement.

In this paper, we report detailed calibration and characterization of a prototype FIMS. Using a technique similar to TDMA, the diffusion broadening of the FIMS transfer function has been characterized by operating a cylindrical DMA and FIMS in series. The response of FIMS to the monodisperse aerosol classified by the DMA can be theoretically predicted using the FIMS transfer function derived in Paper I. The spread factor (σ) in the FIMS transfer function was derived by fitting the theoretical model to measured FIMS response. The derived spread factor and the FIMS resolution calculated using the experimentally derived σ are compared to theoretical values, and the possible reasons for observed discrepancies are discussed.

2. Experimental

2.1. Instrument design

The schematic cross section of FIMS is shown in Fig. 1. The design of the prototype was based on analyses presented in Paper I. The entire parallel plate geometry is divided into four detachable sections—(i) entrance, (ii) separator, (iii) condenser, and (iv) detector, and were designed such that when all sections are put together in a sequence, a rectangular channel with a clear cross-sectional area of 1 cm × 10 cm is formed in x–z plane. Individual section can be disassembled for maintenance purposes without losing mechanical precision. The key physical dimensions of the prototype FIMS are same as those of Units 2–4 presented in Paper I. Particle-free sheath air, saturated with n-butanol enters the channel through ports located at the top of entrance section. The sheath flow then passes through a fine screen that evenly distributes the flow, and provides a uniform flow field at the entrance. The aerosol flow enters the main channel tangentially through a 1 mm wide slit. The slit spans over the entire width of 10 cm in the z-direction. Length of the entrance section is maintained sufficiently long to ensure a fully developed sheath flow at the aerosol entrance. The two embedded steel plate-electrodes create a uniform electric field in the flow passage and are insulated from the rest of the