A Miniature Cylindrical Differential Mobility Analyzer for sub-3 nm Particle Sizing

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Abstract

Effective particle sizing is one of the limitations in measuring sub-3 nm aerosol. In this study we developed a miniature cylindrical differential mobility analyzer (mini-cyDMA) for sub-3 nm particle sizing. The construction of the miniature cylindrical DMA, stemmed from the cost-effective DMA (cDMA) developed by Mei et al. (2011), enables it to be operated at higher sheath flowrate than the cDMA. To keep the sheath flow laminar in the DMA classification region for the flowrate up to 30 liters per minute (lpm) for better matching the flowrate required by the aerosol detector while having a good sizing resolution, the DMA components such as the inlet for sheath flow, nylon screen for flow laminarization, and the chambers for polydisperse aerosol flow inlet and excess flow exit were re-designed in the mini-cyDMA. Transfer function of the mini- cyDMA was evaluated using tetra-alkyl ammonium cations with electrical mobility diameters of 1.16 nm, 1.47 nm and 1.78 nm, respectively. A data inversion routine based on an empirical diffusive transfer function was used to obtain the transfer function of the mini- cyDMA. When classifying 1.47 nm particles at the aerosol-to-sheath flow ratio of 2.5/25 lpm, the penetration efficiency and the sizing resolution of the mini- cyDMA are 0.21 and 5.7, respectively. The mini- cyDMA was deployed to characterize newly-formed atmospheric particles and flame-generated nascent soot particles.

Key Words: cylindrical differential mobility analyzer (DMA); sub-3 nm particles; transfer function; new particle formation; soot particle

1. Introduction

Differential mobility analyzer (DMA) is widely used for classifying and sizing sub-micrometer particles (Knuston & Whitby, 1975; Liu & Pui, 1974; McMurry, 2000). Understanding aerosol nucleation mechanisms calls for the measurement of sub-3nm particles (Kulmala et al., 2012; McMurry et al., 2011). The development of diethylene glycol ultrafine condensation particle counter (DEG-UCPC, Iida et al., 2009) has made it feasible to measure the size distributions of sub-3 nm particles via the DEG-based scanning mobility particle spectrometer (SMPS) system (Jiang et al., 2011a). Recently, this system was made commercially available by TSI Incorporation (model 3938E77). However, the performance of the DEG-SMPS can be further improved by having a DMA with better performance when sizing sub-3 nm particles (Jiang et al., 2011b; Stolzenburg & McMurry, 2008). The penetration efficiency and the resolution of a DMA for sub-3 nm particles are expected to deteriorate because of the high diffusivity of these particles (Stolzenburg & McMurry, 2008). A DMA designed to size sub-3 nm particles at a moderate sheath flowrate (i.e., 20~30 liters per minute, lpm) will better fit into the DEG-SMPS while keeping its overall package compact and consuming less energy for field studies.

Several DMAs for sizing particles in the 1-3 nm size range have been developed. One example is the high-resolution DMAs developed by Fernández de la Mora's group (e.g., de Juan & Fernández de la Mora, 1998; Rosser & Fernández de la Mora, 2005). Among them, the half-mini DMA (Fernández de la Mora & Kozlowski, 2013) is readily available from NanoEngineering Corporation and has been used by different groups to generate standard ions or particles for instrument calibration. Another Vienna type DMA for high-resolution mobility measurement of 1-5 nm particles is the UDMA (Steiner et al., 2010). However, these DMAs are designed to operate at high sheath flowrate (typically several hundreds to thousands lpm) rather than matching the flowrate required by the DEG-UCPC. In addition, large sheath flow

recirculation system (including high volume filters and air mover) are required to operate those DMAs, making it troublesome for field measurement. Limited information on the penetration efficiency of these DMAs leads to difficulties for quantitative measurement of aerosol size distributions (Kangasluoma et al., 2016).

The nano radial DMA (nano-RDMA), whose recommended sheath flowrate is 6 lpm, is a low-flow DMA (Brunelli et al., 2009). Though its penetration efficiency for sub-3 nm particles at the sheath flowrate of 10 lpm is better compared to other conventional DMAs (Jiang et al., 2011b), its measured transfer functions deviate from the theoretical ones at 10 lpm or higher sheath flowrates. The radical opposed migration ion and aerosol classifier (ROMIAC) is also capable of sizing 1-3 nm particles (Mui et al., 2013). Different from the conventional design of DMAs, particle and sheath flows transport in the directions perpendicular to each other and particles migrate against the sheath flow in the classification region. When operating ROMIAC at the aerosol-to-sheath flow ratio of 1.7/34.3 lpm, the sizing resolution of ions with collisional cross-sections of 200-2000 Å² was reported to be ~20. However, its penetration efficiency has not been reported.

The cylindrical nanoDMA (TSI Incorporation, Model 3085, Chen et al., 1998) was calibrated and temporarily used for sub-3 nm aerosol sizing (Jiang et al., 2011a; 2011b; 2011c). However, its sizing resolution for sub-3 nm particles are relatively poor, i.e., 3.90 at the aerosol-to-sheath flow ratio of 2/20 lpm when classifying 1.47 nm particles. In addition, the applied voltage on the TSI nanoDMA when classifying sub-3 nm particles is small (e.g., 34 V for 3 nm particles and 4 V for 1 nm particles, respectively, at the sheath flowrate of 20 lpm) that leads to considerable uncertainties when subjected to small voltage shift. In the commercial version of the DEG-SMPS (TSI Incorporation, model 3938E77), a nanoDMA with shortened classification length was used. Its penetration efficiency and transfer function have not been reported.

The objective of this study was to develop a miniature cylindrical DMA (mini-cyDMA) with a moderate sheath flowrate to size particles in the 1-3 nm size range. Its transfer function and penetration efficiencies were calibrated using ions of 1.16, 1.47, and 1.70 nm. Finally, the mini- cyDMA was deployed to measure newly formed particles in the atmosphere and nascent soot particles formed in flames.

2. Construction of the mini- cyDMA

The design of the miniature cyDMA stemmed from the cost-effective DMA (cDMA) developed by Mei et al. (2011). The upper limit of sheath flowrate for cDMA is ~10 lpm. Our design objective of the mini- cyDMA is to operate it at 20-30 lpm. Figure 1 shows all the modifications made to the original cDMA in order to make it operate at 20-30 lpm sheath flowrate. Computation fluid dynamics simulation was applied to help with the design, while sizes of key components (e.g., circular slit of aerosol inlet) were determined experimentally. The sizing region is composed of an inner cylinder with an outer diameter, d_1 , of 7 mm and an outer cylinder with an inner diameter, d_2 , of 20 mm. The classification length, measured from the polydisperse aerosol inlet to the classified aerosol outlet, is 14.7 mm. The Reynolds number is ~1500 when the mini- cyDMA operates at the aerosol-to-sheath flow ratio of 3/30 lpm. Given the operational voltage of 20 V to 5000 V, the corresponding classified particle size range is 1.59-26.2 nm, 1.03-16.7 nm, and 0.84-13.5 nm at sheath flowrate of 10, 20, and 30 lpm, respectively. Compared to the original cDMA, the mini- cyDMA is expected to have higher penetration efficiency and sizing resolution for 1-3 nm particles.

Instead of injecting polydisperse aerosol from two opposite positioned inlet tubes in the cDMA, polydisperse aerosol in the mini- cyDMA is tangentially injected into the polydisperse aerosol chamber for rapid flow distribution. The polydisperse aerosol chamber in the mini- cyDMA was enlarged to damp out the potential tangential flow direction prior to entering the sizing region of the mini- cyDMA. The circular slit for

entering the DMA sizing region was also reduced to ensure polydisperse aerosol evenly distributed in the polydisperse aerosol chamber. Classified aerosol is extracted from the classified aerosol flow channel located in the inner cylinder. The classified aerosol flow channel consists of two sections (i.e., one at high voltage and the other at electrical ground) separated by an insulated section. Since the effective way to minimize particle electrostatic loss when transporting from high voltage to ground sections of the flow channel (Bezantakos et al., 2015; Tammet, 2015; Franchin et al., 2016) is not available, we simply reduce the length of the insulation section to reduce the time needed for classified particles to pass through.

To enable the higher sheath flowrate operation of the mini- cyDMA (compared with that of the cDMA), the simple cylindrical sheath flow channel used in the cDMA was replaced with a 15° trumpet-shaped flow channel followed by a 45° tapered funnel-shaped channel in the mini- cyDMA. Three layers of 305 nylon screens were installed in the funnel-shaped channel to keep the flow laminar after passing them. The excess flow chamber was also enlarged to ensure an even distribution of excess flow prior to exiting the mini- cyDMA.

3. Experimental setup and data inversion

Molecular ions were generated to calibrate the transfer functions of the mini- cyDMA. As shown in Figure 2, electrospray was used to produce cations of TPAI (tetra-propyl ammonium iodide, $N[C_3H_7]_4I$), THAB (tetra-heptyl ammonium bromide, $N[C_7H_{15}]_4Br$) and TDDAB (tetra-dodecyl ammonium bromide, $N[C_{12}H_{25}]_4Br$), which were dissolved in methanol of chromatographic grade. These organic salts and solvent were all purchased from Sigma Aldrich. Filtered compressed air acted as carrier gas in the setup to transport produced ions. A high resolution short-thin type half-mini DMA (Fernández de la Mora & Kozlowski, 2013) was used to select monodisperse ions. The electrical mobility diameters of classified TPAI, THAB and TDDAB monomers

were 1.16 nm, 1.47 nm, and 1.70 nm, respectively. An example of THAB cation size distribution and peaks corresponding to specific chemical composition are presented in Figure S1 (in the supplementary material). Only monomers were used for calibration to avoid any potential influence of multi-charged cations (Attoui et al., 2013). Sheath flowrate of the half-mini DMA was ~ 450 lpm, and the voltage-to-size relationship was calibrated before each experiment. Details about this ion standard can be found in Ude & Fernández de la Mora (2005). Temperature and pressure in the half-mini DMA were assumed to be 300 K and 0.99 kPa, respectively. While the blower was installed at the upstream of the half-mini DMA to inject the sheath flow, the relative pressure in the half-mini DMA was actually below the ambient (because of high gas velocity). Uncertainty resulted from the variation of temperature and pressure was estimated to be less than 3%.

Two Faraday cage electrometers (FCEs) were used as particle concentration detectors upstream and downstream of the mini- cyDMA. The one used at the DMA upstream was a home-made FCE and the other used at the DMA downstream was a TSI 3068B. Concerning the potential zero drift of both FCEs, raw counts of the two FCEs were linearly correlated before and after each measurement. Ions selected by the half-mini DMA were used for this correlation testing. An example of the found correlation is shown in Figure S2. The raw counts of two FCEs were in linear relationship with the coefficient of determination, R^2 , of 0.9998.

When calibrating the mini- cyDMA, the voltage of the half-mini DMA was fixed while the voltage of the mini- cyDMA was increased linearly. The voltage increase on the mini- cyDMA was sufficient slow to guarantee a pseudo-steady state for ions to migrate through the mini- cyDMA and downstream FCE. Each scan cycle (including both upscan and downscan) took 15 minutes. As shown in Figure S3, good agreement was found between the transfer functions obtained from both the stepping mode (one

minute for each voltage step) and the linear scanning mode operation of the mini-cyDMA.

A data inversion routine based on empirical diffusive transfer function was used to obtain the transfer functions of the mini- cyDMA (Flagan, 1999; Jiang et al., 2011b; Knuston & Whitby, 1975; Stolzenburg & McMurry, 2008). The detail on this data inversion method can be found in Jiang et al. (2011b). The penetration efficiency, η_{pene} , is defined as the efficiency that particles can get through the entrance and exit slits of DMA sizing region, and Ω is the DMA transfer function. Theoretically, Ω is a function of electrical mobility Z and central electrical mobility Z^* of particles. Hence the transmission efficiency N_2/N_1 , i.e., ratio of downstream and upstream electrometer readings, can be written as,

$$N_2/N_1 = \eta_{pene}(d_z) \cdot \Omega[Z(d_z), Z^*(V)] \quad [1]$$

where particle electrical mobility Z is only determined by particle electrical mobility diameter, d_z . Classified particle mobility, Z^* , is determined by central DMA voltage, V , aerosol-to-sheath flow ratio, Q_a/Q_c , and the geometrical factors of DMA.

Diffusive transfer function can be written as (Stolzenburg & McMurry, 2008),

$$\Omega = \frac{\sigma}{\sqrt{2}\beta(1-\delta)} \left[\varepsilon \left(\frac{\tilde{Z} - (1+\beta)}{\sqrt{2}\sigma} \right) + \varepsilon \left(\frac{\tilde{Z} - (1-\beta)}{\sqrt{2}\sigma} \right) - \varepsilon \left(\frac{\tilde{Z} - (1+\beta\delta)}{\sqrt{2}\sigma} \right) - \varepsilon \left(\frac{\tilde{Z} - (1-\beta\delta)}{\sqrt{2}\sigma} \right) \right] \quad [2]$$

where $\tilde{Z}$ is the dimensionless mobility defined as Z/Z^* , and σ is diffusion parameter. A multiplicative broadening factor f_σ is introduced to quantify the difference between σ and the theoretical diffusion parameter σ_{theo} as,

$$f_{\sigma} = \sigma / \sigma_{theo} \quad [3]$$

The other parameter to quantify the effect of transfer function broadening is sizing resolution, defined as the ratio of classified electrical mobility Z^* to the transfer function width at the half height, ΔZ , i.e.,

$$R = Z^* / \Delta Z \quad [4]$$

When inverting the transfer function of the mini- cyDMA, corrected concentration ratios of two FCEs , i.e., N_2/N_1 , were calculated, and then three parameters determining a DMA transfer function, i.e., the classified electrical mobility Z^* , multiplicative broadening factor, f_{σ} , and penetration efficiency, η_{pene} , were fitted by the least square method. Note that theoretical diffusive transfer functions of the mini-cyDMA were obtained by replacing σ with σ_{theo} , as illustrated by an example in Figure S3.

An effective diffusion length, L_{eff} , was used to calculate η_{pene} by assuming that particle loss in a DMA can be simulated as diffusion loss in a tube (Jiang et al., 2011b; Karlsson & Martinsson, 2003; Reineking & Porstendörfer, 1986). The penetration efficiency through a tube can be calculated as (Cheng, 2011),

$$\eta_{pene} = 0.819e^{-3.66\mu} + 0.0975e^{-22.3\mu} + 0.0325e^{-57.0\mu} + 0.0154e^{-107.6\mu} \quad (\text{for } \mu > 0.02)$$

[5]

$$\eta_{pene} = 1.0 - 2.56\mu^{2/3} + 1.2\mu + 0.1767\mu^{4/3} \quad (\text{for } \mu \leq 0.02) \quad [6]$$

where μ is the dimensionless deposition factor defined as,

$$\mu = \frac{\pi D L_{eff}}{Q} \quad [7]$$

D is the diffusion coefficient of particles of a given diameter, and Q is the flowrate through the virtual cylindrical tube, usually referring to aerosol flowrate.

4. Results and discussion

4.1 Identification of flow laminarizer for the mini- cyDMA

Two flow laminarizers (i.e., ultrafine aluminum honeycomb and nylon screens) were tested. The aluminum honeycomb column is consisted of hexagonal cells with the side length of 0.5 mm and the height of 10 mm. Two different nylon screens were tested: one is in 305 mesh with the opening of 35% and the other is in 420 mesh with the opening of 15%. These nylon screens were tested at an aerosol-to-sheath flow ratio of 2.5/25 lpm and the ultrafine aluminum honeycomb column at the ratio of 1.5/15 lpm. THA^+ cations of 1.47 nm were used for calibration. As shown in figure 3, nylon screen of 420 mesh has less extra broadening and thus higher sizing resolution (with a f_σ value of 1.10 at 2/20 lpm) compared to ultrafine aluminum honeycomb (with a f_σ value of 2.72 at 1.5/15 lpm). The performance of aluminum honeycomb column was caused by its unsatisfactory cell uniformity and insufficient column height. No obvious change in the DMA transfer function was observed in the cases with multiple layers of nylon screens. It is possible that sheath flow became laminar after it passes nylon screens and the broadening of DMA transfer function might be resulted from the imperfection in the flow channel of the tested mini- cyDMA. 305-meshed nylon screens in three layers were then selected for the mini- cyDMA as the flow laminarizer because of its 35% opening.

4.2 Performance of the mini- cyDMA

Shown in Figure 4(a) are the particle sizing resolution and penetration efficiency of the mini- cyDMA when classifying 1.47 nm ions. As the sheath flowrate was increased from 10 lpm to 25 lpm (while keeping the constant aerosol-to-sheath flow

ratio of 0.1), the sizing resolution of the mini- cyDMA was improved. At the same time, the value of multiplicative broadening factor, f_σ , also increased, indicating an increase in deviation from the ideal sizing resolution. At the sheath flowrate of 30 lpm, f_σ increased to 1.90 while the sizing resolution decreased to 4.75 (from 5.70 at the sheath flowrate of 25 lpm). η_{pene} gradually increased with an increase in the sheath flowrate, while appeared to be nearly stable when the sheath flowrate was between 15 lpm and 25 lpm. The above observation could be due to undamped tangential velocity of aerosol stream entering the DMA sizing region, resulting from the tangential injection of aerosol stream at the flowrate of 3 lpm and the flow disturbance in the sizing region when operated at the sheath flowrate of 30 lpm. To test the influence of undamped tangential aerosol flow velocity, two metal screens were temporarily placed in the polydisperse aerosol chamber of the mini- cyDMA. Nearly perfect agreement between the measured transfer function and the ideal one with a f_σ value of 1.06 (shown in Fig. S4) was obtained. Unfortunately, the particle penetration of the mini- cyDMA decreased from 0.211 for the case without metal screens to 0.075 for the case with metal screens. Thus, the working sheath flowrate of the mini- cyDMA in its present arrangement without metal screens is recommended to be the range of 10 to 25 lpm.

Figure 4(b) illustrates measured penetration efficiencies of the mini- cyDMA versus calculated ones (with a suggested effective diffusion length L_{eff} of 1.50 m at the aerosol-to-sheath flowrate of 2/20 lpm and 1.81 m at 2.5/25 lpm). Note that the use of L_{eff} to represent various particle losses in a DMA was just for simplicity. For the mini- cyDMA, no constant L_{eff} exists for all tested flowrates (10~30 lpm). For both the cDMA and the mini- cyDMA, we found that it is not feasible to find a single effective length to estimate particle loss for various flowrates and various particle sizes. Electrostatic loss from high voltage to ground sections of the flow channel and tangential mixing at aerosol inlet slit may contribute. Nonetheless, L_{eff} value can be provided for given flowrates and particles in a certain size range.

4.3 Comparison with other DMAs

Figure 5 illustrates the comparison of the mini- cyDMA with the Caltech nano-RDMA and the TSI nanoDMA when classifying 1.47 nm ions. We selected the “best” scenario for the overall performance of each DMA under the same aerosol-to-sheath flow ratio of 0.1. The recommended aerosol and sheath flowrates of the Caltech nano-RDMA is 0.6 and 6 lpm, respectively (with f_σ smaller than 1.1). Its penetration efficiency and sizing resolution can be further improved by operating it at higher flowrates of 1 and 10 lpm, though deviation from the ideal transfer function occurs at this conditions. The transfer function of the TSI nanoDMA agrees with the ideal one, while the mini- cyDMA and the Caltech nano-RDMA have additional broadening with f_σ of 1.35 and 1.21 at 2.5/25 lpm and 1/10 lpm, respectively. Compared to the TSI nanoDMA, the mini- cyDMA has better penetration efficiency and sizing resolution, and is capable of operating at higher flowrate. The mini- cyDMA has similar penetration efficiency and sizing resolution to the Caltech nano-RDMA at 1/10 lpm.

5 Applications of the mini- cyDMA

We incorporated the mini- cyDMA into a prototype DEG-SMPS. The operational condition of the cyDMA-incorporated DEG-SMPS was similar to Jiang et al. (2011a) except for a few variations. Aerosol sampling flowrate of the mini- cyDMA was set at 2 lpm to match with the input flowrate of the DEG-UCPC and sheath flowrate of the mini- cyDMA was set at 20 lpm to keep the aerosol-to-sheath flowrate ratio of 0.1. Voltage and flowrates of the mini- cyDMA were calibrated. A linear inversion method (Stolzenburg & McMurry, 2008; Jiang et al., 2011a) was applied to estimate particle size distribution. The inversion equation can be written as,

$$\frac{dN}{d \log d_z} = N_{cpc}(d_z) \cdot \frac{Q_c}{Q_a} \cdot \frac{\ln 10}{\eta_{pene}} \cdot \left\{ 2 - \frac{1}{C_s} \cdot \left(1 - 0.2485 \cdot e^{-0.596/Kn} \right) \right\} \quad [8]$$

where, C_s is the Cunningham slip correction factor estimated using the formula from Allen & Raabe (1982), Kn is the Knutson number, and Q_a and Q_c are aerosol and sheath flowrates, respectively. In this equation, transfer function is assumed to be narrow enough. For sub-5 nm particles, the effect of multi-charging can be neglected.

The DEG-SMPS equipped with the mini- cyDMA was deployed to measure particles in the size range of 1-5 nm in a field campaign in Beijing from March 7th to April 7th, 2016. The monitoring site is on the campus of Tsinghua University which has been an urban PM_{2.5} monitoring station since 1999. No major pollution source exists nearby the station (Cao et al., 2014; He et al., 2001). The objective of the campaign was to characterize new particle formation in a polluted urban environment where new particle formation events occur on ~40% days of each year (Wu et al., 2007). A custom particle size distribution system (PSD) including a SMPS with a TSI nanoDMA, a SMPS with a TSI long DMA, and a TSI aerodynamic particle sizer was also applied in parallel with the DEG-SMPS to measure particles larger than 3 nm (Liu et al., 2016). The TSI nanoDMA was used for sizing particles in 3-55 nm sizes. A typical new particle formation event occurred on March 13rd, 2016, is shown in Figure 6 (a). The size distributions of 1-3 nm particles are from the DEG-SMPS and those of 5-25 nm particles are from the PSD. While in the overlapping size range of 3-5 nm, the size distributions are weighted averages of data from both instruments using Eq. 9. Particle size distributions measured by the DEG-SMPS and the PSD was in good agreement, e.g., the coefficient of determination, R^2 , of particle size distribution of 4.7 nm particles measured by both instruments was ~0.97. The event started at ~8 a.m. after the sunrise and the smallest particles detected by the DEG-SMPS were at ~1.3 nm (in mobility diameter).

$$\left. \frac{dN}{d \log d_z} \right|_{avg} = \left. \frac{dN}{d \log d_z} \right|_{DEG-SMPS} \times \frac{5 \text{ nm} - d_z}{2 \text{ nm}} + \left. \frac{dN}{d \log d_z} \right|_{PSD} \times \frac{d_z - 3 \text{ nm}}{2 \text{ nm}} \quad [9]$$

The mini- cyDMA was also applied in the laboratory soot studies. Nascent soot particles were generated in a laminar, premixed and stagnant ethylene flame and sampled by a sampling probe with in-situ dilution to minimize particle coagulation and growth in the transport tubing. Details about the burner and the sampling systems can be found elsewhere (Tang et al., 2017). The DEG-SMPS equipped with the mini-cyDMA and the PSD were used in parallel to measure soot particles. A typical soot particle size distribution measured at a burner-to-stagnation surface separation distance of 0.6 cm and at the fuel-to-oxygen stoichiometric ratio of 2.0 is shown in Figure 6(b). Size distributions by the DEG-SMPS agree well with those by the PSD. The average relative error between two set of data in 3-5 nm size range is ~2.3%.

6 Conclusion

Stemmed from the cDMA by Mei et al., (2011), a mini- cyDMA was developed for effective classification of particles in 1-3 nm size range. 305 mesh nylon screens (in three layers) were used to keep the DMA sheath flow laminar. Instead of two opposite-positioned inlet tubes, polydisperse aerosol is tangentially transported into the polydisperse aerosol chamber in the mini- cyDMA. The flow chambers for polydisperse aerosol and excess flow were enlarged to enable higher flowrate operation than the cDMA. The mini- cyDMA was calibrated using tetra-alkyl ammonium cations. Transfer functions and penetration efficiencies of the mini-cyDMA classifying 1.16 nm, 1.47 nm, and 1.70 nm particles, respectively, with the sheath flowrate range of 10-30 lpm were measured. A data analysis routine based on the multiplicative broadening factor and the penetration efficiency was used. Effective diffusion lengths of the mini-cyDMA were estimated to be 1.50 m and 1.81 m, respectively, when the aerosol-to-sheath flowrates are 2/20 lpm and 2.5/25 lpm. Compared to the TSI nanoDMA, the mini- cyDMA has better penetration efficiency and sizing resolution. The mini- cyDMA was incorporated into a prototype DEG-SMPS to characterize new particle formation events in the atmosphere and to

measure nascent soot particles generated by a premixed flame. In the overlapping size range of 3-5 nm, good agreements were observed between the DEG-SMPS using the mini- cyDMA and the PSD using a TSI nanoDMA.

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List of Figures

Figure 1 Schematic diagram of the miniature cylindrical differential mobility analyzer.

Figure 2 Schematic diagram of the calibration system.

Figure 3 Influences of sheath flow laminarizer on performance of the mini- cyDMA while classifying 1.47 nm particles. Nylon meshes were evaluated at an aerosol-to-sheath flow ratio of 2.5/25 lpm, and the ultrafine aluminum honeycomb is evaluated at 1.5/15 lpm.

Figure 4 (a) Resolution and penetration efficiency of the mini- cyDMA as a function of sheath flowrate when classifying 1.47 nm particles. The aerosol-to-sheath flow ratio was fixed at 0.1. (b) Measured and calculated penetration efficiencies with the effective diffusion length, L_{eff} , of 1.50 m and 1.81 m at sheath flowrate of 20 lpm and 25 lpm, respectively.

Figure 5 Measured transfer functions of the mini- cyDMA, the TSI nanoDMA, and the Caltech nano-RDMA when classifying 1.47 nm particles. Data for the TSI nanoDMA and the Caltech nano-RDMA were from Jiang et al. (2011b). At the flow ratio of 1/10 lpm, the resolution of the Caltech nano-RDMA deviates from its ideal resolution due to flow disturbances.

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