SCANNING MOBILITY PARTICLE SIZER™ (SMPS™) SPECTROMETER

BIBLIOGRAPHY

APPLICATION: SMPS DESIGN, CHARACTERIZATION, SAMPLING TECHNIQUES, & HISTORY

2006

Hogrefe, O.; Lala, G. G.; Frank, B. P.; Schwab, J. J.; Demerjian, K. L., 2006, "Field Evaluation of a TSI Model 3034 Scanning Mobility Particle Sizer in New York City: Winter 2004 Intensive Campaign," *Aerosol Science and Technology*, **40**(10):753–762

A new "single box" Scanning Mobility Particle Sizer (TSI SMPS Model 3034) was deployed and operated during a period of four weeks as a part of the PMTACS-NY Winter 2004 intensive study in Queens College, New York City. The SMPS 3034 is an alternative to a conventional multi-component TSI SMPS and houses a Differential Mobility Analyzer and butanol-based Condensation Particle Counter in one cabinet. The SMPS 3034 operates at a fixed 1 L/min sample flow rate (4 L/min sheath flow rate) and measures size distributions within a 10-487 nm size range. One size scan is produced every 3 minutes. Four other measurement systems (a conventional TSI SMPS with a Nano Differential Mobility Analyzer, an Aerodynamic Particle Sizer, a stand-alone Condensation Particle Counter, and an R&P Inc. Filter Dynamic Measurement System (FDMS) TEOM mass monitor) were operated side-by-side with the SMPS 3034. It is shown that total particle number concentrations measured by the SMPS 3034 are highly correlated with those from the conventional Nano SMPS, the Condensation Particle Counter and the FDMS TEOM monitor, and that the number median diameters measured by the SMPS 3034 and the Nano SMPS agree within 3 nm.

Lall, A. A. and Friedlander, S. K., 2006, "On-line Measurement of Ultrafine Aggregate Surface Area and Volume Distributions by Electrical Mobility Analysis: I. Theoretical Analysis," *Journal of Aerosol Science*, **37**(3):260–271

Electrical mobility analyzers are usually calibrated for spherical particles, and provide number, area and volume distributions for spherical particles. However, these instruments cannot be directly used to obtain the surface area and volume distributions for aggregates. Aggregates are important in technological applications, such as the manufacture of fine powdered materials, and in air pollution and atmospheric sciences. Thus, nanoparticle chain aggregates of low fractal dimension are another important limiting case, in addition to spheres; a method is described which makes it possible to relate aggregate surface area and volume distributions to the electrical mobility diameter. This is accomplished by equating the migration velocity of an aggregate to that of a sphere. Particles of equal migration velocities will trace similar paths in the mobility analyzer and have the same mobility diameter (neglecting the Brownian diffusive spread). By equating the migration velocities of a sphere and aggregate, the number and size of the primary particles composing the aggregate can be related to the diameter of a sphere with the same migration velocity.

The calculation of aggregate surface areas and volumes requires two theoretical "modules", one for the drag on the aggregates and the other for aggregate charging efficiency. Two modules selected from the literature were used. The results indicate that the surface area distributions of aggregates with random orientation are somewhat over-predicted when calculated directly from the mobility diameter. However, the volume distributions are greatly over-predicted, up to a factor of ten compared with values based on the mobility diameter. The affect of aggregate orientation on surface area estimates was also examined.

Scanning Mobility Particle Sizer and SMPS are trademarks of TSI Incorporated.
TSI and the TSI logo are registered trademarks of TSI Incorporated.

Lall, A. A., Seipenbusch, M., Rong, W. and Friedlander, S. K., 2006, "On-line Measurement of Ultrafine Aggregate Surface Area and Volume Distributions by Electrical Mobility Analysis: II. Comparison of Theory and Measurements," *Journal of Aerosol Science,* **37**(3):272–282

Differential mobility analyzers (DMAs) are sometimes used to characterize aerosols that contain aggregates of low fractal dimension. However, these instruments are normally calibrated for spherical particles and the calibrations are not directly applicable to aggregates. A method proposed by Lall and Friedlander [(2006). On-line measurement of ultrafine aggregate surface area and volume distributions by electrical mobility analysis, I: Theoretical analysis. *Journal of Aerosol Science*, in press] for characterizing ultrafine aggregate number, surface area and volume distributions by electrical mobility measurements was tested experimentally. The method is best applied to idealized aggregates composed of uniform primary particles smaller than the mean free path of the gas. It relates the number and size of the primary particles that compose the aggregate to the mobility diameter of a spherical particle. Aggregate number distributions were obtained by calculations based on aggregate drag and aggregate charging efficiency; surface area and volume were obtained by summing over the primary particles that compose the aggregate.

The theory was tested experimentally using silver aggregates generated by an evaporation–condensation method. Primary particle diameter was 18.5 ±3.5nm. To obtain distributions with respect to particle volume, aggregates were sintered to form spheres. It was assumed that the aggregate volume does not change upon sintering and coagulation was neglected. Thus the number of aggregates in a given *volume* range (number distribution, dN/dlogV vs.Vvs. *v*) should not change after sintering. Agreement between aggregate number distribution based on idealized aggregates and the values measured for spheres of sintered aggregates was good. The agreement also indicates that the aggregate volumes based on idealized aggregates were accurate. The aggregate number distribution and volume based on the conventional calibration for spheres were significantly overpredicted. A separate experimental test of the theory was made using literature data for diesel aggregates. Primary particle diameter was 31.9 ±7.2nm. Aggregate volumes calculated from theory agreed well with aggregate volumes measured by transmission electron microscope analysis.

Lall, A.A., Robertson W.H., Sahay K. and Friedlander, S.K., 2006, "New interpretation of DMA data that makes realistic characterization of diesel emission possible: Theory of idealized aggregates." Poster presentation at 10th ETH-Conference on Combustion Generated Nanoparticles August 21–23, 2006 at ETH Zentrum, Zurich, Switzerland

Differential Mobility Analyzers (DMA) are routinely used to measure ultrafine aerosol number distributions. Current methods are based on spherical particle assumption. Aggregate morphology is the natural state of diesel emission solid particles. We present a novel method to determine the ultrafine aggregate number, surface area and volume distributions from DMA data.

Li, Weiling; Li, Lin; Chen, Da-Ren, 2006, "Technical Note: A New Deconvolution Scheme for the Retrieval of True DMA Transfer Function from Tandem DMA Data," *Aerosol Science & Technology*, **40**(12):1052–1057

A new deconvolution scheme is proposed to retrieve the true transfer function of differential mobility analyzers (DMAs) from tandem DMA (TDMA) experimental data. Apart from the existing methods in which the transfer function is represented as either a triangular or a Gaussian shape, the true DMA transfer function in the new scheme is represented by a piecewise linear function. The conjugate gradient optimization method is used to find the best fit between the calculated and experimental TDMA data. It is shown that the scheme is insensitive to experimental error and able to differentiate the shapes of DMA transfer functions for different particle sizes. The scheme is further applied to obtain the true transfer function of Nano-DMA (Chen et al. 1998).

2005

Han, Hee-Siew; Whitby, Evan R.; Plate, Douglas B.; Albertson, Daniel P., 2005, "Combining TSI Scanning Mobility Particle Sizer and Aerodynamic Particle Sizer for Wide Range Particle Size Distribution Measurement," *European Aerosol Conference Poster Presentation*, Ghent, Belgium, August 28–September 2, 2005

Size distributions of airborne particles generally span a wide range from a few nanometers to several micrometers, which typically exceeds the measurement size of any single instrument. Researchers have frequently combined data from multiple instruments, but the details of the data conversion between units have varied. In this study, a software module, Data Merge Software Module, was developed to combine aerosol size distributions with the Scanning Mobility Particle Sizer™ (SMPS) and the Aerodynamic Particle Sizer® (APS®) spectrometers. This module consists of two parts: data merging and curve fitting. The data merging is to merge SMPS and APS data sets into a single composite data set. This composite data set is then curve-fitted to a multimodal distribution (up to 3 modes). The curve-fitting algorithm is based on the Delta Fitting and Merging (DFM) engine used in the DistFit™ (Chimera Technologies). To verify the performance of the module, aerosols with known densities, in this case, fine and course Arizona Road Dust (ARDs), were used. The composite fit distributions were then compared with distributions measured with a mass-based Micro-Orifice Uniform Deposition Impactor (MOUDI). Ambient aerosols measured with the SMPS and APS were also used to examine the module. It was found that the agreement between the composite fit distributions and measurements with MOUDI was good.

Lawless, Philip A.; Noble, Christopher A.; Rodes, Charles E., 2005, "A sampling approach for evaluating particle loss during continuous field measurement of particulate matter," *Particle and Particle Systems Characterization*, **22**(2):99–106

A method for evaluating sample bias in field measurements is presented. Experiments were performed in the field and laboratory to quantify the bias as a function of particle size for the scanning mobility particle sizer and the aerodynamic particle sizer. Sources of bias and sample loss considered in this work were sampling line loss, instrumental differences and inlet efficiencies. Measurement of the bias and sample loss allow for correction of the data acquired in the field, so as to obtain more representative samples of atmospheric concentrations. Substantial losses of fine and ultrafine particle count were observed, with sampling line losses ranging from 10-50%, dependent on particle size. Only minor line losses were observed for coarse particles (approximately 5 %) because the sampling line was oriented vertically. 32 Refs.

Vasiliou, J., 2005, “An evaluation of a scanning mobility particles sizer with NIST-traceable particle size standards,” *2005 NSTI Nanotechnology Conference and Trade Show*, Anaheim, CA

A scanning mobility particle sizer (SMPS - TSI Model 3936-Series) was evaluated using Duke Scientific NIST-traceable particle size standards and Standard Reference Materials from the National Institute of Standards and Technology (NIST SRM's). The importance of instrument setup, electrospray operation and sample preparation for polystyrene spheres are discussed as well as the results from 14 different size reference standards. Correlations between the SMPS system and established electron microscopy and dynamic light scatting methods are also shown in tabular and graphical forms. Results show that with proper operation, the SMPS results fall within the uncertainty of the NIST traceable diameters in the range that was evaluated - 20 to 100 nanometers.

2004

Bermudez, V.; Desantes, J.M.; Fuentes, E.; Pastor, J.V., 2004, “Methodology for measuring exhaust aerosol size distributions from heavy duty diesel engines by means of a scanning mobility particle sizer,” *Measurement Science and Technology*, **15**(10):2083–2098

A study of the sources of variability in particle size measurements using a dilution minitunnel and a scanning mobility particle sizer (SMPS) has been conducted in order to obtain a comprehensive and repeatable methodology that can be used for measuring the particle size distribution of the exhaust aerosol emitted by a heavy duty diesel engine. The paper includes three experimental phases: an experimental analysis of the SMPS operating parameters' influence; an evaluation of the effect of dilution conditions, such as the dilution ratio and the dilution residence time; and a study of the influence of sampling factors, such as measurement stabilization and the effect of exhaust system pre-conditioning. An examination of the type and degree of influence of each studied factor is presented, recommendations for reducing variability are given and critical parameter values are identified to develop a measurement methodology of low uncertainty that could be applied to a further study concerning the effect of engine operating parameters on the exhaust particle size distribution.

2003

Ayala, Alberto; Olson, Bernard; Cantrell, Bruce; Drayton, Marcus; Barsic, Nicholas, 2003, “Estimation of diffusion losses when sampling diesel aerosol: A quality assurance measure,” JSAE Technical Paper No. 20030138, *2003 JSAE/SAE International Spring Fuels and Lubricants Meeting*, May 19–22, 2003, Yokohama, Japan

Under the sponsorship of the Coordinating Research Council (CRC), the University of Minnesota (UMN) formed an international research team to investigate the physical and chemical nature of diesel emissions from heavy duty vehicles while operating on highways (CRC Project E-43). These ambient measurements of vehicle emissions following their release into and dilution by the atmosphere guided the development of dilution and sampling procedures for laboratory test cells to simulate on-highway conditions. The importance, visibility, and potential implications of the project prompted the adoption of a quality assurance (QA) plan by an independent implementation team. Because exhaust aerosol characterization for mobile sources lacks prescribed sampling methodologies, standard operating procedures were developed as part of the QA effort to ensure the consistency and validity of the data collected. To verify the daily protocols used, the QA team made surveillance visits to observe UMN team performance on project tasks. Evaluation of instrument performance using aerosols of known size was also done as part of QA system audits conducted to assess the accuracy of particle size measurements. QA for particle concentration measurement was hampered by the lack of a concentration standard, which is a problem common to aerosol science investigations today. Thus, the standard practice in aerosol work is to verify particle concentration by comparing results from two identical condensation particle counters (CPC) and rely on instrument manufacturer calibrations. A fundamental component QA for assessment of instruments and sampling system performance was investigation of particle losses. Along an aerosol sample pathway from source to collection media or measuring instrument, some particles are lost to surfaces. The magnitude of these losses as a function of particle size was determined experimentally by challenging the sampling trains with monodisperse particles in the sub-50 nm aerodynamic diameter size range (nm=10sup -sup 9 meters). Since the most probable loss mechanism was diffusion for sub-50 nm sized particles, theoretical calculations of diffusion loss for 100 nm particles and smaller were also made. Results indicated average sampling train total losses of approximately 50% and 20% for 10 nm and 17 nm size particles, respectively. Measured Scanning Mobility Particle Sizer (SMPS) instrument internal losses were approximately 70% for a 10 nm size mono-disperse aerosol. Measured sample line losses were better predicted by theory if the flow in the sampling lines is considered turbulent. However, the flow in the lines was laminar. This noted discrepancy may be the result of local turbulence created by valves and bends in the sample lines and is an area recommended for additional investigation. Finally, application of a particle loss correction to particle size distributions from the study increased SMPS number concentrations at 10 nm by approximately a factor of 5 and at 20 nm by a factor of 2.

Zhao, B.; Yang, Z.; Wang, J.; Johnston, M. V.; Wang, H, 2003, “Analysis of Soot Nanoparticles in a Laminar Premixed Ethylene Flame by Scanning Mobility Particle Sizer,” *Aerosol Science and Technology*, **37**(8): 611–620

Mobility size distributions of soot particles produced from a fuel-rich, laminar premixed ethylene flat flame were obtained by in situ probe sampling and online analysis using a nano scanning mobility particle sizer. The emphasis of the work was the development of an in situ sampling technique to follow the evolution of nanoparticles formed in flames. Particle size distribution functions were obtained along the centerline of the flame in a spatially resolved manner. Considerable efforts were made to eliminate particle losses in the sample probe. To this end, the effect of dilution on particle losses in the sample probe was systematically studied. It is demonstrated that particle losses due to coagulation and diffusive wall deposition were negligible using a dilution ratio greater than ~104. The sampling technique is shown to be capable of closely following the evolution of particle size distribution from the nucleation mode to mass growth mode dominated by particle coagulation and gas-surface reactions. Beyond the particle nucleation region of the flame, the size spectra were found to be distinctively bimodal, indicating sustained particle nucleation throughout the flame studied.

2002

Buttner, H.; Ebert, F.; Mayer, M.; Ober, F., 2002, "Aerosol measurement in low-pressure systems with standard scanning mobility particle sizers," *Particle and Particle Systems Characterization*, **19**(4):229–239

The scanning mobility particle sizers (SMPS) is one of the best known instruments for measuring particle size distributions in the submicron range. The SMPS consists of two parts: an electrostatic aerosol classifier (differential mobility particle analyzer, DMA), followed by a counting device, in general a condensation particle counter (CPC). Unfortunately, commercial measurement devices such as the TSI DMA Model 3071 and the TSI CPC Model 3022 (TSI Inc., St. Paul, MN, USA), can be used only at nearly atmospheric pressure in the sampling line or in slight overpressure mode, but not in low-pressure systems. A modification in the sampling line is shown which enhances the operating range of a standard SMPS system to low pressure. Samples taken under standard and low-pressure conditions show good agreement in the measured particle size distributions and concentration. The behavior observed in experimental studies agrees well with theoretical predictions. 17 Refs.

Dreiseidler, A.; Vogt, U.; Baumbach, G.; Imhof, D.; Rosenbohm, E.; Fuchs, J.; Corsmeier, U.; Baltensberger, U.; Nielsen, O.J.; Scheer, V.; Vogt, R., 2002, "Comparability of the results of different particle size measuring method," *VDI conference: New developments in air quality monitoring and assessment*, with exhibition, 569 pages

The field measurements of gaseous components and particles for calculation of practical emission factors in the course of the Bundes-Autobahn-Projekt II (BAB II) comprised a number of quality assurance measurements. In all, five Scanning Mobility Particle Sizer (SMPS), four Optical Particle Counters (OPC), one relaxation time spectrometer (APS), and an electric low-pressure impactor (ELPI) were used for the measurements of time-resolved particle numbers and size distributions. In spite of the different measuring principles and the detectable differences in the raw data, the final data were in good agreement.

Schmid, O.,Trueblood, M.B.,Gregg N.,Hagen D.E.,Whitefield, P.D., 2002, "Sizing of Aerosol in Gases Other Than Air Using a Differential Mobility Analyzer," *Aerosol Science & Technology*, **36**(3), 351–360

The differential mobility analyzer (DMA) is a device that sizes aerosol particles based on their electrical mobility. The relationship between particle size and mobility depends, among other factors, on three gas specific parameters, namely, dynamic viscosity, mean free path, and Cunningham slip correction factor C_c. Provided these parameters are known, DMA theory is expected to be valid independent of gas type. The present study demonstrates the sizing accuracy of DMAs for gases other than air using monodisperse polystyrene latex (PSL) spheres with nominal diameters of 60 nm, 149 nm, and 343 nm in He, Ar, H_2, CO_2, and N_2O. Eliminating possible systematic errors due to uncertainties in DMA geometry and nominal PSL diameter by normalizing the measured PSL diameters to their respective diameters measured in air, the sheath flow rate Q_{sh} and C_c are expected to be the main sources for measurement errors. Since C_c data are lacking for PSL spheres in gases other than air, an expression given by Allen and Raabe (1985b) was used to approximate C_c. The experimental results of the present study are consistent with a 2% accuracy of this expression for C_c, which is considerably better than the 5% accuracy estimated by Rader (1990) for a similar expression for oil drops. Finally, we discuss other aspects of operating a DMA with gases other than air, namely, flow meter calibration and dependence of electrical breakdown voltage on gas type. In the present study a thermal mass flow meter (MFM) was used to measure Q_{sh}. Calibration of this MFM revealed that the gas specific MFM correction factors (K factors) provided by the technical literature can be highly inaccurate (here between -12% and +31%). More accurate K factors are presented.

Shen, S.; Jaques, P. A.; Zhu, Y. F.; Geller, M. D.; Sioutas, C., 2002, "Evaluation of the SMPS-APS system as a continuous monitor for measuring PM 2.5 , PM 10 and coarse (PM 2.5-10) concentrations," *Atmospheric Environment*, **36**(24):3939–3950

Respirable particulate matter (PM) has been linked to mortality and morbidity by a variety of epidemiological studies. This research has led to the creation of a new PM standard for particles with diameters <2.5 μm ($PM_{2.5}$). Since the conclusion of these studies, many leaps have been made in the realm of continuous particle measurement. Because the literature is still dominated by 24-hour averaged data, the US Environmental Protection Agency still uses this time average as the basis of its federal reference method, despite the fact that PM varies on much shorter time intervals. The purpose of this work is to compare the Scanning Mobility Particle Sizer and Aerodynamic Particle Sizer tandem (SMPS–APS) to other continuous PM measurement devices and to time-integrated mass samplers. The instruments used for comparison include the DataRAM nephelometer, Micro-Orifice Uniform Deposit Impactor (MOUDI), and Partisol Dichotomous Sampler. The data was collected over 4–5 months at various sites in the Los Angeles basin. The results show excellent agreement between the SMPS–APS and the mass based MOUDI and Partisol samplers for $PM_{2.5}$. The DataRAM and SMPS–APS continuous monitors show robust correlation with each other when relative humidity <70%. The coarse fraction ($PM_{2.5-10}$) measured by the Partisol, however, does not track well with the same size range measured by the APS. Several sources of sampling error are discussed to account for this. Finally, mass concentrations collected in individual size ranges of the MOUDI were compared with those determined by the SMPS. While the size ranges from 0.32 to 10 μm agree between samplers, the size ranges <0.32 μm are significantly different from MOUDI to SMPS, probably due to the differences between the aerosol sizing principles underlying each technique.

2001

Wieser, U.; Gaegauf, Ch.; Macquat, Y., 2001, "Particle emissions from wood-fired boilers - Examination of emission rates in practical use," *Technical Report No. ENET-210221*, Oekozentrum, Langenbruck (Switzerland), in German

This report made for the Swiss Federal Office of Energy (SFOE), the Swiss Agency for the Environment, Forests and Landscape (SAEFL) as well as for the air pollution inspection offices of 5 Swiss Cantons, presents the results of measurements made on 14 different types of wood-fired heating appliances and boilers with respect to their emissions of particulate matter, including units fired with wood logs, wood chippings and pellets. For comparison, the results for fossil-fuel-fired units are also quoted. The laboratory equipment and the measurement methods used are described which were used to determine the total amount of particles emitted and, in particular, the emissions of particles in the sub-micrometer range. The results of the measurements made are presented and discussed in detail. A second phase of the project is described which allowed the measurement of particulate matter emissions in the field. The report is concluded with a discussion on the

collection of data on particle emissions using SMPS (Scanning Mobility Particle Sizer) analysis methods, particle, size distribution and particle emission factors.

2000

Tokonami, Shinji; Knutson, Earl O., 2000, "The Scan Time Effect on the Particle Size Distribution Measurement in the Scanning Mobility Particle Sizer System," *Aerosol Science and Technology*, **32**(3):249–252

The scan time effect in the scanning mobility particle sizer was confirmed. The magnitude of this effect was shown in a typical situation. The cause of this scan time effect is the mixing process described by Russell et. al. (1995). In that case, the result obtained at the longer scan time is the more accurate one.

1999

Flagan, Richard C., 1999, "On Differential Mobility Analyzer Resolution," *Aerosol Science & Technology*, **30**(6):556–570

The resolution of the differential mobility analyzer (DMA) is conveniently described as the ratio of the mobility at the peak of the column transfer function to the full width of the transfer function at 1/2 of its maximum value. The best resolution that can be achieved is that for nondiffusive particles, -nd=beta1, where beta is the flow rate ratio, beta = (Q a + Q s)/(Q sh + Q e) . Brownian diffusion causes particles to deviate from the ideal electrophoretic migration trajectories, thereby reducing the resolution. The relative importance of electrophoretic migration to diffusion can be expressed as a function of the migration Peclet number, which can be expressed either in terms of mobilities, dimensions, and flow rates or as Pe m ig = (qV / k T) f , where q is the charge on the particle, V is the applied voltage, and f is a geometry factor that accounts for nonuniformities in the electric field along the migration pathway. Expressed in this way, the performance of DMAs with different geometries, operating at different flow rates, are, in the absence of distortions in the flows and electric fields, shown to be nearly indistinguishable. Diffusion is shown to dominate at operating voltages below a critical value that is proportional to the square of the limiting resolution. Since the voltage range for DMA measurements is limited, the dynamic range decreases with increasing - nd . Because of the changing size dependence of the mobility, this limitation is more pronounced for free-molecular aerosols than for larger particles.

1998

Chen D.-R., Pui D.Y.H., Hummes D., Fissan H., Quant F.R., Sem G.J., 1998, "Design and evaluation of a nanometer aerosol differential mobility analyzer (Nano-DMA)," *Journal of Aerosol Science*, **29**(5):497–509

A nanometer aerosol differential mobility analyzer, Nano-DMA, has been developed for measuring the size distribution of nanometer aerosols in the particle size range of 3–50 nm. The design is based on a cylindrical configuration and is optimized by means of the numerical model of Chen and Pui (1997, *J. Aerosol Sci*. 28, 985–1004). Important design features include high particle penetration (low loss) through the Nano-DMA and high sizing resolution. For reducing particle loss in the aerosol transport passage, the aerosol residence time in the Nano-DMA is reduced by shortening the inlet transport passage. An optional feature of high inlet flow (up to 16.5 L/min) is designed in order to further reduce the residence time between the aerosol inlet and the slit in the classifying region of the Nano-DMA. A new entrance slit is designed to have optimal aerosol and sheath flow matching at a flow ratio of 1 : 10, and has a wide dynamic flow-ratio range (up to aerosol/sheath flow ratio of 1/70) compared with the TSI-standard DMA design. This slit improvement makes the Nano-DMA suitable for high resolution particle sizing and classification. For reducing the effect of Brownian diffusion broadening on the transfer function of the Nano-DMA, the collector tube length is shortened to 5.0 cm compared to the TSI-Standard DMA of 44.44 cm and TSI-Short DMA of 11.11 cm. At the design flow condition of 1.5 L/min aerosol (or 16.5 L/min aerosol high inlet flow case) and 15.0 L/min sheath flow rates, the measurable size range is from 3–50 nm. The lower detection limit of 3.0 nm coincides with the lower detection limit of the TSI UCPC (Ultrafine Condensation Particle Counter). The base of the Nano-DMA is completely re-designed to avoid particle loss due to the undesirable electrostatic effect observed by Kousaka *et al*. (1986, *J. Chem. Eng. Japan* 19, 401), and to obtain an uniform electric field in the entire classifying region. The overall performance of the Nano-DMA is then evaluated by the numerical model of Chen and Pui (1997, *J. Aerosol Sci*. 28, 985–1004) before its construction and experimental evaluation. By comparing with the experimental results obtained using the Tandem DMA technique described in Hummes *et al*. (1996, *J. Aerosol Sci*. 27, S135–S136; *Part. Part. Syst. Charact*. 5, 327–332), it is concluded that the Nano-DMA is performing well in the designed size range and its transfer function agrees well with the numerical prediction.

Flagan, Richard C., 1998, "History of Electrical Aerosol Measurements," *Aerosol Science and Technology*, **28**:301–380

Early studies of atmospheric electricity suggested that the electrical conductivity of the atmosphere would be sufficient to dissipate the charge on the surface of the earth in a matter of minutes. Efforts to understand how substantial electric fields could be maintained globally in spite of the high dissipation rates were propelled into the forefront of physics research at the turn of the century when it was observed that the newly discovered X-rays produced ions that behaved much like those in the atmosphere. Many of the approaches that are now employed in electrical measurements of aerosols were first conceived during the first three decades of this century. Initially the focus was on gas ions, but they were found to consist of charged clusters of water molecules that exhibited a number of distinct mobilities that were substantially lower than those that resulted after long efforts to dry the gas. The coaxial condenser mobility analyzer, introduced by McClelland in 1898 and enhanced by Zeleny in 1900, was used to measure atmospheric ions as early as 1901 by Ebert. Based upon atmospheric measurements with this device in 1905, Langevin reported on the existence of ions with mobilities 3000 times lower that those observed in the laboratory studies. These so-called large ions correspond to particles in what we now know as the accumulation mode of the atmospheric aerosol. The aspiration condenser dominated measurements of atmospheric ions for six decades even though Erikson developed a differential mobility analyzer by 1921, and Rohmann produced a differential mobility sampler in 1923. Only after electronics was improved in the 1950s and 1960s were these instruments reintroduced. It was based upon condenser measurements of atmospheric "ions" that Junge first described the structure of the ultrafine particle size distribution in 1955.

Ristovski, Z. D.; Morawska, L.; Hitchins, J.; Barron, W., 1998, "Influence of the Sheath Air Humidity on the SMPS Measurements of Hygroscopic Aerosols," *Journal of Aerosol Science*, **29**(1):S327–S328

The hygroscopic growth of Sodium Chloride (NaCl) aerosols inside an electrostatic classifier, during an scanning mobility particle size (SMPS) measurement cycle, was measured as a function of relative humidity. The purpose of this study was to determine how the humidity and temperature of the sheath air, and the residence time in the system, affect the sizing accuracy of the SMPS, during measurements of hygroscopic aerosols such as NaCl.

Walton, W. Henry; Vincent, James H., 1998, "Aerosol Instrumentation in Occupational Hygiene: An Historical Perspective," *Aerosol Science and Technology*, **28**(5)417–438

Occupational hygiene has always been very influential in aerosol science - and vice versa. This paper gives an historical overview of this interaction, in particular how aerosol measurement instrumentation has evolved for the measurement of workers' exposures to aerosols in the occupational setting. It shows how health-related criteria for aerosol measurement have shifted from ones based on airborne particulate mass to ones based on particle count concentration, and then back again, depending on the aerosol science knowledge that was available at the time. It also draws the distinction between instrumentation based on time weighted-average sampling and direct-reading measurement, and the factors that govern how the choice of type of measuring instrument was made in the past, the way it is made now, and the way it might be made in the future.

1997

Chen, D., Pui, D.Y.H, 1997, "Numerical Modeling of the performance of differential mobility analyzers for nanometer aerosol measurements," *Journal of Aerosol Science*, **28**(6):985–1004

A numerical model was developed to predict the performance of differential mobility analyzers (DMAs) for nanometer aerosol measurements. The model consists of three parts: flow field, electric field, and aerosol transport formulations. In order for the model to be applicable for all the existing DMAs, the swirling flow effect due to tangential aerosol injection is included. The tangential inlet design was used in several recently designed DMAs, e.g., Hauke, SMEC and RDMA. The swirling is incorporated in the model by introducing the assumption of negligible variation of the circumferential flow component. Mixed Galerkin and SUPG finite-element formulations with a nine-node velocity, three-node pressure flow elements and bilinear element are proposed. For the electric field, the space charge effect is neglected and the equation is solved by Galerkin finite element method with the second-order isoparametric element. The aerosol transport is modeled by the convective aerosol transport equation with external electrical force. The equation is further simplified by using the same assumption made for the flow field in the circumferential flow component. A modified adaptive characteristic Petrov-Galerkin finite-element method is proposed to overcome the difficulty involved in numerically solving the simplified equation. The model was used to calculate the transfer functions of TSI-short DMA for particle sizes between 5 and 50 nm. They were then validated by comparing the numerical and experimental results for simulated scans from two DMAs operating in series. The numerical transfer functions are compared with the available experimental data from two sources, namely, Hummes et al. (1996) Part. Part. System Charact. 13, 327–332 and Kousaka et al. (1986) J. Chem. Engng Japan 19, 401–407. A good agreement between them is obtained.

Chen D.-R., Pui, D. Y. H., Hummens, D., Fissan, H., Quant, F. R., Sem, G. J., 1997, "Design and Evaluation of a Nanometer Aerosol Differential Mobility Analyzer (Nano-DMA)," *Journal of Aerosol Science*, **29**(5–6):497–509

A nanometer aerosol differential mobility analyzer, Nano-DMA, has been developed for measuring the size distribution of nanometer aerosols in the particle size range of 3-50 nm. The design is based on a cylindrical configuration and is optimized by means of the numerical model of Chen and Pui (1997, J. Aerosol Sci. 28, 985-1004). Important design features include high particle penetration (flow loss) through the Nano-DMA and high sizing resolution. For reducing particle loss in the aerosol transport passage, the aerosol residence time in the Nano-DMA is reduced by shortening the inlet transport passage. An optional feature of high inlet flow (up to 16.5 L/min) is designed in order to further reduce the residence time between the aerosol inlet and the slit in the classifying region of the Nano-DMA. A new entrance slit is designed to have optional aerosol and sheath flow matching at a follow ratio of 1:10, and has a wide dynamic flow-ratio range (up to aerosol/sheath flow ratio of 1/70 compared with the TSI-standard DMA design. This slit improvement makes the Nano-DMA suitable for high resolution particle sizing and classification.

1996

Birmili, W.; Stratmann, F.; Wiedensohler, A., 1996, "Determination of DMA transfer functions using identical instruments in series," *Journal of Aerosol Science*, **27**(S1):S169–S170

The Differential Mobility Analyzer (DMA) is an important tool to determine particle size distributions. The physical performance of a DMA is quantified by the concept of the transfer function. Therefore, knowledge of the transfer function is important to interpret the mobility distributions recorded by a DMA.

Stratmann et al. (1996) showed that recalculated size distributions are improved when utilizing a more accurate, size-dependent transfer function for the data inversion. Especially, the number of ultrafine particles (dp < 20 nm) can thus be better estimated. In this size range, the DMA deviates significantly from its theoretically derived transfer functions (Kousaka et al., 1985, Stolzenburg, 1988, Zhang et al., 1995, Fissan et al., 1996). Deviations occur with respect to the shape and the area of the transfer function. Both are altered by Brownian diffusion.

Chen, D, Pui, D.Y.H., Hunnes, D., Fissan, H., Quant, F.R., Sem, G.J," 1996,"Nanometer differential mobility analyzer (Nano-DMA): design and numerical modeling," *Journal of Aerosol Science*, **27**:S137–S138

The importance of nanometer particles for practical applications is well documented. To study the behavior of nanometer aerosols and to control the production process, it is important to have available a well-characterized size analyzer in the nanometer particle size range. In a recent paper by Fissan et al. (1996), the performance of four differential mobility analyzers (DMAs) were evaluated and their transfer functions determined. The results show that below 10 nm, all four DMAs experienced a deterioration in size resolution and detection sensitivity due to the effect of diffusional loss and broadening. There is a need to develop an optimized DMA for the nanometer size range.

This paper describes the development of a nanometer DMA (Nano-DMA) optimized for the particle size range from 3 to 50 nm. It is based on the cylindrical configuration. The design is facilitated by the numerical model (Chen et al., 1995) which incorporates the flow field, electric field, and aerosol transport calculations inside the DMA. This paper describes design considerations and numerical modeling efforts. A companion paper by Hummes et al. (1996) describes the experimental evaluation and performance verification of the nano-DMA.

Fissan, H.; Hummes, D.; Stratmann, F.; Buscher, P.; Neumann, S., 1996, "Experimental Comparison of Four Differential Mobility Analyzers for Nanometer Aerosol Measurements," *Aerosol Science and Technology*, **24**(1):1–13

The performance of four differential mobility analyzers (DMAs), namely the TSI-long, the TSI-short, the Hauke 3/150, and the Spectrometre de Mobilite Electrique Circulaire (SMEC) were evaluated under the same conditions of flow rates, flow ratio, input monodisperse aerosols, and transport-line lengths. The evaluations were performed under the conditions of 10 1/min sheath air and 1 1/min aerosol flow rates, and at a flow ratio of 10:1. Monodisperse aerosols in the size range of 6 nm to 50 nm were obtained by classifying condensation aerosols using a Hauke DMA operated at 20:1 flow ratio. The transfer functions of all four DMAs have been obtained by deconvoluting the scan results of the evaluated DMA (DMA2), and by using the empirical transfer function of the first DMA (DMA1, the Hauke DMA at 20:1 flow ratio). The half-width, height, and area of the transfer functions have been compared for the four DMAs tested. These results provide a quantitative comparison of the mobility resolution and diffusion loss of the nanometer aerosols in the DMAs.

Hummes, D., Neumann, S., Fissan, H., Chen, D., Pui, D.Y.H. 1996a, "Nanometer differential mobility analyzer: experimental evaluation and performance verification," *Journal of Aerosol Science*, **27**:S135–S136

The Differential Mobility Analyzer (DMA) is an established instrument to classify and generate particles in the nanometer size range. In recent papers by Fissan et al. and Hummes et al. the transfer function of commercial DMAs were determined using the procedures described by Stratmann et al.. The results showed that it is necessary to develop a new device which has higher resolution and lower losses in the size range between 3 nm and 50 nm. The design is based on the cylindrical configuration and is optimized to reduce particle losses in the inlet and exit passages. Furthermore the aerosol inlet passage is optimized by the numerical model of D. Chen et al. which enables a wide range of aerosol/sheath air ratio. Using a larger aerosol flow up to 16.5 l/min the device can be used to generate a high concentration of a monodisperse size fraction. In this paper we describe the performance to evaluate the transfer function of the Nano-DMA. Assuming a triangular transfer function the parameter half-width and height were determined. The NDMA was operated with an aerosol/sheath air flow rate ratio of 1:5, 1:10, 1:20 and 1:30.

Hummes, D., Stratmann, F, Neumann, S., Fissan, H., 1996b, "Experimental determination of the transfer function of a differential mobility analyzer (DMA) in the nanometer size range," *Particle and Particle System Characterization*, 391–400

The Differential Mobility Analyzer (DMA) is a widely used instrument to classify the size distribution of aerosols as well as to generate monodisperse aerosol. The behavior of a DMA is described by its transfer function with the parameters height and half-width. The half-width depends only on the ratio sheath air/aerosol flow for particles larger than 50 nm. For smaller particles diffusional effects increase the half-width and decrease the height. This was experimentally observed and described for different DMAs by Fissan et al. Up to now, it was not shown that the transfer function reflects the real size distribution of the particles.

1995

Quant, F.R.; Flagan, R.C.; Horton, K.D., 1995, "Implementation of a Scanning Mobility Particle Sizer (SMPS)" *Journal of Aerosol Science*, **24**(S1) S83–S84

A system for rapid size measurement of submicrometer aerosols consisting of a differential mobility analyzer (DMA), condensation particle counter (CPC), computer and software has been developed based on work done by Wang and Flagan. The scanning mobility particle sizer (SMPS) measures, with high resolution, airborne particle size distributions in the 5-1000 nm diameter range. Particles within a small electrical mobility range are separated from the aerosol stream by a DMA. The mobility of the selected particles is ramped by an exponentially increasing or decreasing voltage applied to the center rod of the DMA. Particles exiting the DMA are detected by a CPC which is connected to a computer. The data is inverted to provide particle size distributions. The ability to provide a continuous 'scan' over particle mobilities results in measure particle size distributions that lack the voids or 'holes' that can occur in a stepped differential mobility particle sizing (DMPS) system as described by Keady et at., 1983. Measurement times between 30 and 300 seconds can be achieved, compared to the 10- to 45- minute measurement periods required for a DMPS system. Scanning also improves particle counting statistics by eliminating the stabilization time required between measurements in a stepped system.

1993

Fotou, George P.; Pratsinis, Sotiris E., 1993, "A Correlation for Particle Wall Losses by Diffusion in Dilution Chambers," *Aerosol Science and Technology*, **18**(2):213–218

A mass transfer correlation for particle wall losses by Brownian and turbulent diffusion in dilution chambers is presented that uses an effective Reynolds number for jet mixing. The validity of this correlation is investigated with experiments of NACl aerosols (dp=0.01-0.2 μm) in spherical and cylindrical dilution chambers. The proposed correlation is also in good agreement with experimental and theoretical studies in the literature.

1992

Karg, E.; Dua, S.K.; Ferron, G.A., 1992, "Performance of a Differential Mobility Analyzer at Different Gas Compositions," *Aerosol Science*, **23**(S1):S389–S392

A differential mobility analyzer (DMA) was tested at different compositions of aerosol and sheath gas flow using monodisperse polystyrene latex particles. The actual size of the particles had been determined by scanning electron microspray. We found that different conditions of relative humidity in aerosol and sheath flow in the DMA cause changes less than 3% in particle size. Different gas compositions (air and

nitrogen, air and carbon dioxide and air and helium) result in a change of particle size less than 6% if the density ratio k of aerosol and sheath flow is close to one (0.95 < k < 1.05). For ratios of k much smaller or larger than one the changes depend on the gas used for the composition. They may range from poor resolution to no resolution at all.

Tamm, E., 1992, "Electrical Classification as a Basis of the Aerosol Standard," *Aerosol Science*, **23**(S1):S285–S288

An attempt is made to develop a general theory of the electrical classification method of aerosol particles for aerosol standard purposes. Ideal conditions in the classifier are considered.

1991

Kinney, P.D., D.Y.H. Pui, G.W. Mulholland, and N.P. Breyer, 1991, "Use of the Electrostatic Classification Method to Size 0.1 µm SRM Particles—A Feasibility Study," *Journal of Research of the National Institute of Standards and Technology*, **96**:147

The use of the electrostatic classification method for sizing monodisperse 0.1 µm polystyrene latex (PSL) spheres has been investigated experimentally. The objective was to determine the feasibility of using electrostatic classification as a standard method of particle sizing in the development of a 0.1 µm particle diameter Standard Reference Material (SRM). The mean particle diameter was calculated from a measurement of the mean electrical mobility of the PSL spheres as an aerosol using an electrostatic classifier. The performance of the classifier was investigated by measuring its transfer function, conducting a sensitivity analysis to verify the governing theoretical relationships, measuring the repeatability of particle sizing, and sizing NIST SRM 1691, 0.269 µm and NIST SRM 1690 0.895 µm particles. Investigations of aerosol generator's performance focused on the effect of impurities in the particle-suspending liquid on the resulting particle diameter.

The uncertainty in particle diameter determined by electrical mobility measurements is found to be -3.3% to +3.0%. The major sources of uncertainty include the flow measurement, the slip correction, and a dependence of particle size on the aerosol flow rate. It was found that the classifier could be calibrated to indicate the correct size to within 0.1% for both SRM particle sizers if the defined classification length is decreased by 1.8%

Reischl, G. P., 1991, "Measurement of Ambient Aerosols by the Differential Mobility Analyzer Method: Concepts and Realization Criteria for the Size Range between 2 and 500 nm," *Aerosol Science and Technology*, **14**:5–24

Stober, J.; Schleicher, B.; Burtscher, H., 1991, "Bipolar Diffusion Charging of Particles in Noble Gases," *Aerosol Science and Technology*, **14**:66–73

The bipolar diffusion charging of particles, suspended in argon is investigated. Particle charge is measured as function of particle size and ion concentration. Since rare gases do not attach electrons, free electrons are available in the gas. This leads to a large difference in mobility and attachment coefficients between negative and positive charge carriers and also of the resulting particle charge. Additionally, negatively charged particles have a maximum as function of the ion concentration, before the equilibrium is reached. This can be explained by the existence of two types of negative charge carriers: free electrons and negative ions, formed by attachment of electrons to impurities in the gas.

1990

Wang, Shih Chen; Flagan, Richard C., 1990, "Scanning Electrical Mobility Spectrometer," *Aerosol Science and Technology*, **13**:230–240

The measurement of particle size distributions using electrical mobility can be accelerated significantly by an alternate mode of operating mobility instruments. Rather than changing the electric field in discrete steps to select particles in a given mobility range, the electric field can be scanned continuously. The particles are classified in a time-varying electric field, but for an exponential ramp in the field strength there remains a one-to-one correspondence between the time a particle enters the classifier and the time it leaves. By this method, complete scans of mobility with as many as 100 mobility measurements have been made in 30 seconds using a differential mobility classifier with a condensation nuclei counter as a detector.

1989

Roth, C.; Berlauer, U.; Heyder, J., 1989, "Particle Size Analysis of Log-Normally Distributed Ultrafine Particles using a Differential Mobility Analyzer," *Journal of Aerosol Science*, **20**(5):547–556

Polydisperse aerosol size distributions measured with a differential mobility analyzer show deviations of the measured size parameters from those parameters of the input distributions. The dependence of the measured modal particle diameters and the geometric standard deviations on the size parameters of log-normal input distributions is derived and the results are proved experimentally by means of fluorescein particles and electron-microscopy.

1988

Schmidt-Ott, A., 1988, "New Approaches to in Situ Characterization of Ultrafine Agglomerate," *Journal of Aerosol Science*, **19**(5):553–563

Agglomerates composed of 7.5 nm primary particles of Ag were produced by coagulation. Heating induced collapse of these agglomerates into close-packed clusters. Further heating led to coalescence of primary particles. This was observed in situ by aerosol photoemission (APE). Shape factors and the fractal dimension D were derived by measuring electrical mobility and APE. A shape factor S is introduced. S is shown to be size invariant for diffusion grown agglomerates, and defines a basic relationship between the agglomerate mass and the

interface to the surrounding diffusion field. A formula was derived to express the dynamic shape factor in terms of fractal dimension and mobility.

Wiedensohler, A., 1988, "An Approximation of the Bipolar Charge Distribution for Particles in the Submicron Size Range," *Journal of Aerosol Science*, **19**(3):387–389

In recent years there has been an increased number of investigations to determine particle size distributions for the submicron regime. These distributions are frequently obtained using a differential mobility analyzer (DMA). Raw data from the DMA can be converted into a size distribution if the bipolar charge distribution for the aerosol is known. Hence the size distribution will be representative only if the bipolar charge distribution is accurately described. Bipolar charge distributions measured by Hussin et al. (1983), Adachi et al. (1985) and Wiedensohler et al. (1986) for particles in air at room temperature support the diffusion charging theories proposed by Fuchs (1963) and Gunn (1956). Fuchs (1963 developed a model to describe the bipolar charging of submicron particles; the charging theory proposed by Gunn (1956) is only valid for particles with diameters greater than approx. 50 nm. An analytical solution is obtainable for the Gunn theory, while the Fuchs model must be solved numerically. To permit a rapid calculation of the bipolar charge distribution in the size range 1-1000 nm, an empirical expression is presented to approximate the distribution calculated from the Fuchs model.

Wiedensohler, A., H.J. Fissan, 1988, "Aerosol Charging in High Purity Gases," *Journal of Aerosol Science*, Vol. **19**

In recent years the measurement of particles suspended in technical gases has become of greater interest. As the structures of integrated electronic circuits become smaller, the submicron particles depositing from these gases cause more and more circuit defects. Electrical measurement techniques, such as differential electrical analysis, can be used to measure particle size distributions if the bipolar charge distributions in technical gases are known. In this paper we present measured data of charge levels in high purity gases. Also, we report about a modification of the diffusion charging theory of Fuchs (1963), which describes the observed data in different gases.

1986

Kousaka, Yasuo; Okuyana, Kikuo; Adachi, Motoaki; Mimura, Tadaaki, 1986, "Effect of Brownian Diffusion on Electrical Classification of Ultrafine Aerosol Particles in Differential Mobility Analyzer," *Journal of Chemical Engineering of Japan*, **19**(5):401–407

Effect of Brownian diffusion on the electrical classification of ultrafine particles in the differential mobility analyzer (DMA) has been studied theoretically and experimentally. Two kinds of particle losses which are undesirable in size analysis, (1) loss caused by the Brownian diffusion of particles traversing the sheath air stream toward the collector rod of the DMA, and (2) loss caused by Brownian diffusive deposition of particles on every wall of the DMA excluding the collector surface, were theoretically evaluated by solving the diffusion equation. Some of the calculation results were confirmed by experiments for particles of various sizes, two different lengths of DMA and various ratios of flow rate of aerosol to sheath air.

Reineking, A.; Porstendorfer, J., 1986, "Measurements of Particle Loss Functions in a Differential Mobility Analyzer (TSI, Model 3071) for Different Flow Rates," *Aerosol Science and Technology*, **5**:483–486

Particle losses in a differential mobility analyzer (TSI, Model 3071) caused by diffusive deposition and Brownian diffusion are measured for particles in the diameter size range between 3 and 100nm. For small sampling and aerosol flow rates (0.3 liters/min) at 20 nm, nearly 50% of the primary particles are lost; and for 2 liters/min, the particle losses have to be considered in the diameter size range below 30 nm (50% at 7 nm). From the measured penetration values, an effective tube length is derived which is useful to calculate particle losses for other flow rates through the analyzer.

Wiedensohler, A., E. Lütkemeier, M. Feldpausch, and C. Helsper, 1986, "Investigation of the Bipolar Charge Distribution at Various Gas Conditions," *Journal of Aerosol Science*, **17**:413

In recent years the determination of particle size distributions with differential mobility analyzers in the size range below 1 µm has become more and more important. The bipolar diffusion charging process used in this technique has been described experimentally for air at room temperature (293 K) by Hussin et al. (1983) and Adachi et al. (1985). Their results show good agreement with the theoretical approach by Fuchs (1963). In this paper results are reported which describe the influence of temperature and gas composition on the charging process. The influence of temperature has been described both theoretically and experimentally, while the influence of the gas composition has only been shown experimentally so far, using pure nitrogen (99.996%) instead of air as the carrier gas.

1984

Keady, Patricia B.; Quant, Frederick R.; Sem, Gilmore J., 1984, "Automated Differential Mobility Particle Sizer," *Aerosols*, 71–74

The differential mobility particles sizer (DMPS) measures the size distribution of aerosol particles in the 0.01-1.0 um diameter range. The polydispersed aerosol particles are size classified with high resolution by a differential mobility analyzer (DMA) and counted by a continuous-flow condensation nucleus counter (CNC). A microcomputer automates the system by controlling the instruments, collecting raw data, performing the data inversion to obtain concentration as a function of diameter and providing data output. Several approaches for the data reduction have been developed and refined over the past twelve years. The approach chosen for the commercial version is based on methods developed by ten Brink et al (1983) and Fissan (1982).

Wen, H.Y.; Kasper, G., 1984, "Dynamics and Measurement of Smokes III - Drag and Orientation of Chain Aggregates in an Electrical Mobility Spectrometer," *Aerosol Science and Technology*, **3**(4):397 403

Simultaneous measurements of electric mobility and geometric size have permitted determination of the drag force of chain aggregates as a function of Knudsen number for the orientation prevalent in a differential electric mobility classifier. (DMA). The measurements indicate that chains are oriented along the field lines (i.e., in the orientation) in a DMA. In combination with earlier measurements of drag in the Orientation with an aerosol centrifuge (Part II; Kasper, 1928b), these data give a complete description of the translational drag on fibrous

particles in the Knudsen number regime below about 10. Indirectly, these measurements also present a validation of the shape factor concept and the equivalent diameters DAE, DVE, and DME associated with it (Part I; Kasper, 1982a).

1983

Hagen, Donald E.; Alofs, Darryl J., 1983, "Linear Inversion Method to Obtain Aerosol Size Distributions from Measurements with a Differential Mobility Analyzer," *Aerosol Science and Technology*, **2**:465–475

The use of differential mobility analyzer to perform aerosol size spectrum measurements requires an inversion method to go from the measured sensor responses to the desired size spectrum information. Here we present a linear inversion method that can be run on a microcomputer or a small minicomputer. It does not use some of the approximations made in the techniques currently available an hence gives better inversion accuracy. The method shows good immunity to both random and systematic experimental error. It is applied to numerous test case aerosols.

Keady, Patricia B.; Quant, Frederick R.; Sem, Gilmore J., 1983, "Differential Mobility Particle Sizer: A New Instrument for High-Resolution Aerosol Size Distribution Measurement Below 1 um," *TSI Quarterly*, **IX**(2):3–14

The differential mobility particle sizer (DMPS) measures airborne particle size distributions in the 0.01-1.0 um diameter range with high resolution. The DMPS consists primarily of a differential mobility analyzer (DMA) which removes a narrow range of particle sizes from the sampled aerosol stream and a condensation nucleus counter (CNC) which measures the concentration of the particles in the narrow size range. A microcomputer controls the system, collects the raw data, performs the data inversion to obtain particle concentration as a function of diameter, and displays the results in a user-selected format on a video display and/or a printed page. The use of simulated data illustrated that the data reduction inversion program is well behaved if all particles larger than the upper limit of the DMPS are removed before the aerosol enters the DMA. Further work is needed to properly account for the characteristics of the large particle removal device at the inlet to the DMA. An experimental comparison of the DMPS with an EAA shows excellent agreement. The DMPS measured number mean diameter = 0.057 um. The EAA measured 0.059 um. The DMPS measured geometric standard deviation = 1.86. The EAA measured 1.88. The DMPS measured total particle concentration 13% higher than a CNC. While the EAA measured only 9% higher than a CNC.

Sem G.J., P.B. Keady, and F.R. Quant, 1983, "High-Resolution Size Distribution Measurements of 0.01–15 μm Aerosol Particles," *TSI Incorporated, Proceedings Sixth World Congress on Air Quality*, Paris, France, Vol **1**, pp. 283–290, 16–20 May

The new instruments make it possible to measure the size distribution of 0.005-15 um atmospheric aerosol particles with considerably higher size and concentration resolution than was previously possible. The aerodynamic particle sizer (APS) measures the aerodynamic diameter of particles in the 0.5-15 um range. Aerodynamic diameter is the parameter which plays the largest role in determining how rapidly these particles settle out of the atmosphere or how deeply they penetrate into the respiratory system. The AOS accelerates the aerosol stream through an orifice, then measures the velocity of each particle at the exit of the orifice. Since large, heavy particles cannot accelerate as rapidly as small, light ones can, the measured velocity of each particle is inversely proportional to its aerodynamic diameter. The differential mobility particle sizer (DMPS) measures the 'electrical mobility/aerodynamic' diameter of 0.005–1 μm particles. This size range includes most combustion-generated aerosol particles which subsequently grow into larger particles by condensation, diffusion, and coagulation. A differential mobility analyzer first acts as a narrow-band-pass filter, allowing only those particles within a narrow selected size range to pass through. A single-particle-counting condensation nucleus counter (CNC) then measures the concentration of these particles. Both commercial instruments use on-line, dedicated computers for control and data processing. Resulting size distributions may be displayed and/or printed in any or all of a large number of graphical and tabular forms. Since both instruments use single-particle-counting detectors, they can measure any concentration from very clean, remote atmospheres to polluted urban aerosol. These 2 new instruments allow detailed studies of the character and effects of atmospheric and other aerosols. Since each operates completely independently of the other, they are discussed separately below.

1982

Alofs, D.J.; Balakumar, P., 1982, "Inversion to Obtain Aerosol Size Distributions from Measurements with a Differential Mobility Analyzer," *Journal of Aerosol Science*, **13**(6):513–527

To measure size distributions of submicrometer aerosols with an electrical differential mobility analyzer (DMA) requires an inversion procedure. The Knutson (1976) and the Hoppel (1978) inversion procedures were numerically investigated for the case of log-normal aerosol size distributions. It was found that the Hoppel procedure converges to the same result as that given by the Knutson procedure. The computational range for geometric mean diameter (xg) was 0.025-0.25 um, and for geometric standard deviation (of) was 1/1-2.4. The inversion error was found to be greater than 10% in certain 'forbidden zones' of xg and og values. For the case of an ideal DMA having no lower mobility limit, only one forbidden zone exists, this consisting of small og values. The boundary of this forbidden zone intercepts the computational range boundaries at og=1.25,xg=0.025 um and og=1.62, xg=0.25 um. These results also apply to an actual DMA when the size distribution of particles larger than DMA singly charged mobility limit is available a priori. If such information is not available, the concentration of these larger particles is assumed to be zero in performing the inversion. This assumption adds a second forbidden zone, consisting of large og values and having the intercepts og=2.44, xg=0.025 um and og=1.50, xg=0.25 um. The first forbidden zone remains nearly the same.

1978

Hoppel, W.A., 1978, “Determination of the Aerosol Size Distribution from the Mobility Distribution of the Charged Fraction of Aerosols,” *Journal of Aerosol Science*, **9**:41–54

The differential mobility chamber of Knutson and Whitby (1975a) is analyzed in terms of the mobility distribution function, and a new iterative scheme for converting the mobility distribution to a size distribution taking into account multiply charged aerosols is given. The scheme has been verified for trial size distributions and shown to converge rapidly to the correct distribution. A differential mobility chamber has been constructed and data obtained with the instrument demonstrate its utility in obtaining the size distribution of aerosols in the size range from 0.008 to 0.7 um radius.

1976

Knutson, E. O., 1976, “Extended Electric Mobility Method for Measuring Aerosol Particle Size and Concentration,” *Fine Particles* 739–762

Whitby, Kenneth T., 1976, “Electrical Measurement of Aerosols,” *Fine Particles*, 581–624

This paper reviews the basic principles of electrical size distribution and concentration measuring methods. Electrical aerosol measuring instruments are discussed under three headings: charging, classification and detection. Recent work by Liu and his students shows that the particle charging rate, based on the Boltzmann Law, can best describe bipolar and unipolar diffusion charging of aerosol particles, over the size range and charging conditions of most interest to electrical aerosol measurement. Working equations for calculating diffusion charge are presented and the latest experimental charging data are presented. Several charged aerosol classifiers or mobility analyzers are described, including the latest differential mobility analyzers developed at the University of Minnesota. Particle charge versus size curves for bipolar, diffusion and field charging are integrated with some of the latest aerosol size distribution models, in order to calculate the response characteristics of the different kinds of electrical instruments. Three late model electrical aerosol instruments developed at the University of Minnesota are described. These are the Electrical Aerosol Analyzer, The Differential Mobility Analyzer, and an Electrical Aerosol Concentration Meter.

1975

Knutson, E.O.; Whitby, K.T., 1975, “Aerosol Classification by Electric Mobility: Apparatus, Theory, and Applications,” *Journal of Aerosol Science*, **6**:443–451

An improved version of the Hewitt (differential) electric mobility analyzer was developed and its classifying characteristics were determined theoretically. The central mobility of the classified aerosol was found to be (qe+qm)/4^N, where qe and qm are the clean air and main outlet flows, respectively. ^ is a geometric factor, and V is the center rod voltage. The half-width of the mobility band was found to be (qa+qs)/4n^V, where qa and qs are the aerosol and sampling outlet flows, respectively. These expressions were verified by the test with a monodisperse aerosol of known size and low charge. A major advantage of this device is that the classified aerosol fraction remains airborne, ready for further use or analysis. Thus, one application of the device is the production of monodisperse test aerosols of known size, charge, and concentration by classification of a polydisperse aerosol. Other current applications include accurate measurement of particle electric mobility moments and high-resolution particle size for polydisperse aerosols in the 0-005-1.0 um size range.

Knutson, E. O., and Whitby, K. T. (1975b), “Accurate Measurements of Aerosol Electric Mobility Moments,” *Journal of Aerosol Science*, **6**:453–460

A procedure for the accurate determination of moments of aerosol electric mobility distributions was developed. The main apparatus required is a carefully constructed Hewitt (differential) electric mobility analyzer. The method does not require vanishingly small aerosol flow rates to obtain accuracy. The procedure may be considered a primary standard measurement technique, since no calibration with particles of known characteristics is required.

One application of the procedure is the determination of the mean and standard deviation of particle size for near-monodisperse aerosols. As an illustration, a Dow LS- 1117-B polystyrene latex aerosol was analyzed. The mean and standard deviation of the particle diameter were found to be 0·80 and 0·018 μm, respectively. The accuracy of the mean dia. determination is estimated to be 2 per cent.

UNDERSTANDING, ACCELERATED

TSI Incorporated – Visit our website **www.tsi.com** for more information.

USA	**Tel:** +1 800 874 2811	**India**	**Tel:** +91 80 67877200
UK	**Tel:** +44 149 4 459200	**China**	**Tel:** +86 10 8251 6588
France	**Tel:** +33 4 91 11 87 64	**Singapore**	**Tel:** +65 6595 6388
Germany	**Tel:** +49 241 523030		

(11/8/2012) Rev. D ©2012 TSI Incorporated Printed in U.S.A.