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*Review Article*

# An overview of differential mobility analyzers for size classification of nanometer-sized aerosol particles

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**Abstract**

Size classification of nanoparticles is an important process in the electrical mobility particle size analyzer. The differential mobility analyzer (DMA) is one of the most commonly used devices for classifying and measuring nanometer-sized aerosol particles between 1 nm to 1 μm in diameter, based on their electrical mobility. The DMA can be described as an assembly of two concentrically cylindrical electrodes with an air gap between the walls. In the DMA, air and aerosol flows enter from one end, pass through the annulus and exit the other end. An electric field is applied between the inner and outer electrodes. Particles having a specific mobility exit with the monodisperse air flow through a small slit located at the bottom of the inner electrode. These particles are transferred to a particle counter to determine the particle number concentration. In the past several decades, there have been numerous extensive studies and developments on the DMA. Nonetheless, they are different in terms of specific applications, construction, particle size range, as well as time response and resolution. The purpose of this article is to provide an overview of the state-of-the-art existing cylindrical DMAs for aerosol particle size classification as well as for the generation of monodisperse aerosol in nanometer size range. A description of the operating principles, detailed physical characteristics of these DMAs, including the single-channel and multi-channel DMAs, as well as some examples of applications to nanotechnology are given.

**Keywords:** aerosol, differential mobility analyzer, electrical mobility, nanoparticles, nanotechnology

## 1. Introduction

Nanoparticles formed in chemical, physical, and biological processes are generally referred to particles of diameter in nanometer size range. The importance of nanoparticles for technological applications is well known. They have found applications in diverse fields, including materials synthesis, biotechnology, semiconductor manufacturing, pharmaceutical products, nano-composites and ceramics, emission control, health effects, measurement and instrumentation, and studies of fundamental transfer processes (Hinds, 1999). An important physical parameter for characterizing the behavior of these nanoparticles is the size. It is therefore desirable to measure and classify the size of nanoparticles and to yield monodisperse nanoparticles in order to gain understanding of the particle dynamics and control particle contamination. Among the various methods developed for the analysis of nanometer aerosol particles, the differential mobility analyzer (DMA) has become the most common instrument widely used in classifying and generating monodisperse particles. A typical setup of a general DMA consists of two concentric electrodes between which a potential is applied. An aerosol flow containing charged particles is introduced adjacent to one of the electrodes. A particle-free

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sheath air flow initially separates the aerosol flow from the opposite electrode. The electric field formed between the electrodes causes charged particles to move towards the opposite electrode across the gap between the electrodes at distinct axial locations, according to their electrical mobility, which are related to their size.

The history of an electrical mobility aerosol measurement dated back to the first half of the 20th century. The electrical mobility determination method was initially used to measure ions in gases (Erikson, 1922; Zeleny, 1929) and in the atmosphere (Erikson, 1927; Chapman, 1937). Rohmann (1923) later investigated and employed this method to measure atmospheric airborne particles. Among the earliest and notable studies, which were carried out by Hewitt (1957), Whitby and Clake (1966), Liu and Pui (1974), Knutson and Whitby (1975), and Liu and Pui (1975). Hewitt (1957) was one of the first researchers to apply such a device to measure electrically charged particles. The first practical analyzer was materialized by Whitby and Clark (1966), known as Whitby Aerosol Analyzer, and subsequently developed into a successful commercial device known as the Electrical Aerosol Analyzer (EAA) by Liu and Pui (1974; 1975). The EAA was used in the measurements of nanometer urban aerosol size distributions, down to 10 nm (Whitby *et al*., 1972). Further extension of Rohmann's concept led Knutson and Whitby (1975) to devise the differential mobility particle sizer (DMPS), which eventually replaced the EAA. It was capable of measuring particle size distributions in the range of 3-500 nm in diameter (Keady *et al*., 1983). The DMPS comprises an arrangement between a DMA and a particle counter. The relationship between the measured concentration and the size distribution was theoretically well described by Hoppel (1978) and Fissan *et al*. (1983). Wang and Flagan (1990) later showed that measurement times of the DMPS can be reduced by ramping the applied voltage continuously. During the same period, a new current measuring technique for an electrical aerosol analyzer was proposed by Lehtimaki (1987). It was observed that the transport of particles inside the DMA is affected by Brownian diffusion, especially for particles smaller than 50 nm. Quantitative investigations of the particle diffusion effect in the DMA were first reported by Kousaka *et al*. (1985, 1986) and Stolzenburg (1988). An alternative cylindrical design was found to offer advantages in flow stability at high flow rates, which in turn helped minimize diffusion losses of nanometer-sized particles. This idea was proposed by Reischl and coworkers, and developed into a Vienna-type DMA (Winklmayr *et al*., 1991). An electrostatic classifier with radial flow between a pair of flat, parallel circular discs was introduced by Zhang *et al*. (1995). A newly designed nano-DMA was also reported to minimize particle diffusional losses and diffusional broadening by Chen *et al*. (1996). Chen and Pui (1997) and Chen *et al*. (1998) subsequently used the numerical method to improve the nano-DMA design. De la Mora and coworkers showed that the detrimental effects of diffusion can be eliminated for the Vienna-type DMA if minor design modifications are incorporated that permit operation at high flow rates (Rosell-Llompart *et al*., 1996; Seto *et al*., 1997; de Juan and de la Mora, 1998; Rosser and de la Mora, 2005). New developments were constantly tested and compared to assess their performance (e.g., Fissan *et al.,* 1996; Brimili *et al.,* 1997; Flagan, 1999; Martinsson *et al.,* 2001; Karlsson and Martinsson, 2003) and to expand the measurement range. An adjustable-column length DMA for wide particle size range measurements was developed by Seol *et al*. (2002). Shimada *et al.* (2005) developed the long differential mobility analyzer-faraday cup electrometer system, capable of measuring particle sizes up to larger than 1 μm. Koyama *et al*. (2007) recently developed a large annular-type DMA to increase the sampling flow rate of size-classified aerosols up to 30 L/min. Mirme (1994) first designed and developed an electrical aerosol spectrometer (EAS), which was later improved by Tammet *et al.* (2002). The EAS is able to classify particles in a similar fashion, but faster than a typical DMA, due to its multi-channel measurement capability. Graskow (2001) developed a multi-channel fast aerosol spectrometer (FAS) to measure nanometer-sized particles. His FAS prototype has a better time response than the EAS. Biskos *et al.* (2005) later reported a development and investigation of a differential mobility spectrometer (DMS), derived from Graskow's concept. A new dual-type DMA, which can detect transient number concentrations of airborne nanoparticles with diameters centralized at around 10 nm and 100 nm in automobile exhaust gas, was developed by Takeuchi *et al*. (2005). Based on a similar principle to the previously mentioned instruments, Intra and Tippayawong from Chiang Mai University, Thailand, designed, built and tested a multi-channel electrical mobility sensor for aerosol size distribution measurement in the size range of approximately 10-1,000 nm (Intra, 2006; Intra and Tippayawong, 2006a, b; 2008).

In this paper, an overview of the design and development of existing cylindrical DMA for size classification of nanometer-sized aerosol particles, as well as operating principles, detailed physical characteristics, and size calibration methods are described. The basic principles of the DMA and some applications to nanotechnology are also presented.

## 2. Basic Principles

This section describes the theory and operation of a general DMA, shown in Figure 1. The DMA essentially consists of two concentric metal electrodes with the inner electrode maintained at a controlled negative voltage, ranging from 1 V to 10 kV, while the outer electrode is electrically grounded. This creates an electric field between the two electrodes. The polydisperse charged aerosol ($Q_a$) and particle-free sheath air ($Q_s$) are introduced at the top of the DMA and flow down the annular space between the electrodes. The aerosol surrounds the inner core of sheath air, and both flows pass down the annulus with no mixing of the two laminar streams. The electric field causes positively

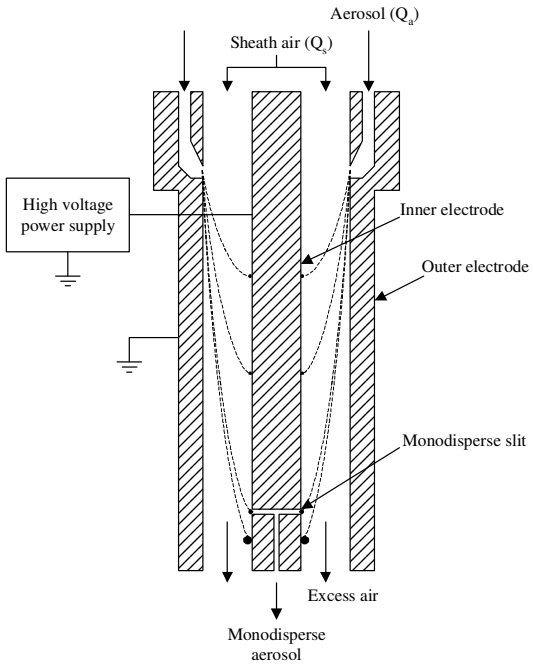


Figure 1. Basic principle of a general DMA.

charged particles to be attracted through the sheath air to the negative charged collector rod. Particles are collected along the length of the collector rod. The location of the collecting particles depends on the particle electrical mobility ($Z_p$), the fluid flow rate, and the DMA geometry. The electrical mobility of the collected particles is a function of the dimensions of the DMA, the applied voltage, and the fluid flow rate, and it given by (Knutson and Whitby, 1975)

$$Z_p = \frac{(Q_s + Q_a)\ln(R_2/R_1)}{2\pi LV}, \quad (1)$$

where $R_1$ and $R_2$ are the radii of the outer and inner electrodes, $L$ is the effective electrode length, and $V$ is the applied voltage. The electrical mobility is related to particle diameter, $d_p$, by using Stokes' law as

$$d_p = \frac{neC_c}{3\pi\mu Z_p}, \quad (2)$$

where $n$ is the number of elementary charge units, $e$ is the elementary unit of charge ($1.61\times10^{-19}$ C), $C_c$ is the Cunningham slip correction factor, and $\mu$ is the gas viscosity. $C_c$ is a function of the particle Knudsen number, $Kn$ ($=2\lambda/d_p$, where $\lambda$ is the mean free path of a gas molecule) given by Cunningham (1910):

$$C_c = 1 + Kn\left[1.257 + 0.40\exp\left(-1.10/Kn\right)\right], \quad (3)$$

Particles with a high electrical mobility are collected along the upper portion of the rod. Particles with a low electrical mobility are collected on the lower portion of the rod. Particles with narrow range of electrical mobility exit with the monodisperse air flow through a small slit located at the bottom of the collector rod. These particles are transferred to a particle counter to determine the particle number concentration. The remaining particles are exhausted out as excess air flow. The size distribution is obtained by varying the applied voltage.

## 3. DMA Designs

A number of DMA designs have been developed and presented in the literature. They can be divided into: (i) single-channel DMAs and (ii) multi-channel DMAs. This section provides a brief review of the development of different DMAs and a comparison, based on the particle size measurement range and resolution, as well as time response. Some of these DMAs are commercially available, while others are still laboratory prototypes.

### 3.1 Single-channel DMAs

The ancestor of the DMAs is the EAA, shown in Figure 2. The measurement is performed by first exposing the aerosol to unipolar gaseous ions in the diffusion charger and then charged particles are passed through the mobility classifier and directed through a small slit at the outlet to a Faraday-cage electrometer, where the total charge of the aerosol is measured. The current obtained is converted to particle number concentration. Varying the voltage in the mobility analyzer, particles of different mobility are detected, and the size distribution of the aerosol is measured. Knutson

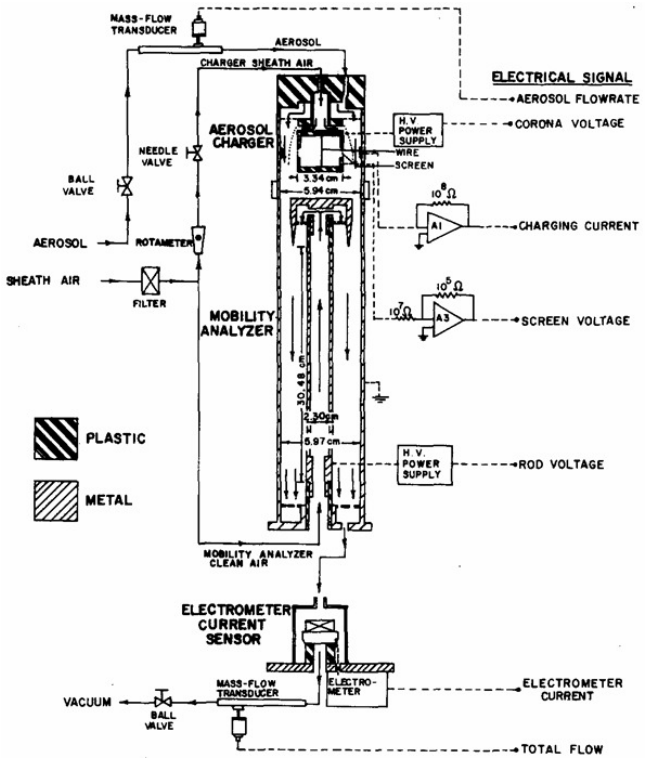


Figure 2. The electrical aerosol analyzer developed by Liu and Pui (1975).

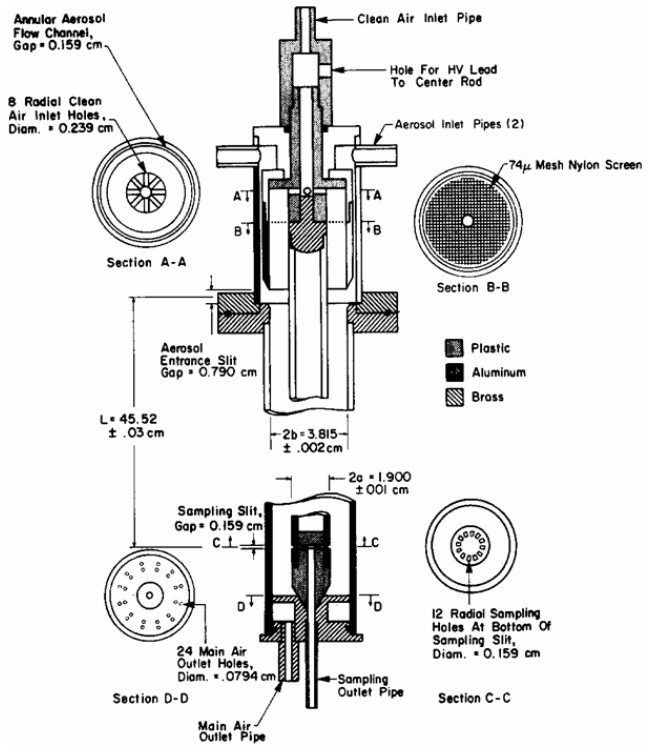


Figure 3. The mobility analyzer developed by Knutson and Whitby (1975).

and Whitby (1975) improved the Hewitt analyzer and presented the basic theory of aerosol classification by electrical mobility. The analyzer is shown in Figure 3. It was a coaxial cylinder arrangement with two flow inlets and two outlets, similar to that used by Hewitt (1957). The column length of the analyzer was 45.52 cm, and the radii of outer and inner electrodes were 3.815 cm and 1.9 cm, respectively. Clean air entered the mobility analyzer through the axial pipe at the top of the analyzer. This air flowed downward through the axial hole in the two plastic pieces, then outward through the eight holes, each 0.239 cm in diameter. The flow continued axially downward through a 74 μm mesh nylon screen, in order to evenly distribute and smooth the clean air flow before it entered the annular space between the mobility analyzer center rod and the mobility analyzer housing. The aerosol flow entered the mobility analyzer, and then flowed axially downward through a narrow annular space (gap = 0.159 cm), which distributed the aerosol evenly to all sectors of the mobility analyzer. At the bottom of this annular space was a circumferential gap, through which the aerosol entered the main analyzing region of the analyzer and met the clean air flow. The clean air flow forced the aerosol to flow downward in a thin layer on the outer wall of the analyzing region. The two streams merged smoothly without mixing. A small portion was withdrawn through a circumferential groove near the bottom of the center rod. This sample flowed through the 12 holes, each with a diameter of 0.159 cm. Particles with higher electrical mobility deposited on the center rod upstream of the sampling slit. Those with lower mobility were carried out with the main outlet flow. In between, there is a narrow range of specific mobility for which the particles reached into the sampling slit and out with the sampling flow. The early applications of the device were primarily used as a generator of relatively monodisperse aerosol for the calibration of instruments such as the condensation nucleus counter and the EAA. Calibration of the instrument using polystyrene latex particles revealed that the shape of the transfer function was closely reproduced for relatively large particles as shown in Figure 4. It was reported that this analyzer can be used to measure particles in the size range between 5-1,000 nm.

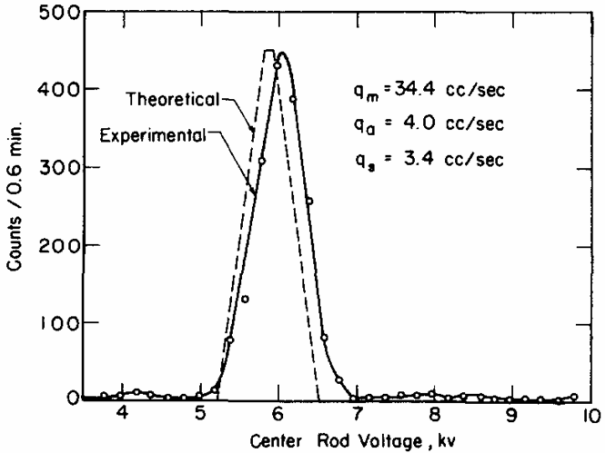


Figure 4. Comparison of the transfer function for the DMA predicted by Knutson and Whitby with their measurement using monodisperse polystyrene latex aerosol (Knutson and Whitby, 1975).

Lehtimaki (1987) developed a new current measuring aerosol analyzer that was able to continuously measure the electric current collected by the mobility analyzer. This system consisted of a zeroth-order mobility analyzer and an electrometer current sensor. The principle of the analyzer was similar to that used in ion meters (Israel, 1970), shown in Figure 5, with an aerosol charger similar to that used in the electrical aerosol detector (Lahtimaki, 1986). In the charger, ions were generated by a corona discharge from a needle electrode installed inside a cylinder. The zeroth-order mobility analyzer consisted of a coaxially cylindrical electrode (2.5 cm and 3.0 cm radius). The mobility analyzer was installed inside the grounded metallic tube. PTFE insulator rings were used to isolate the analyzer from the ground potential. The DC high voltage power supply was installed inside the inner electrode, which functions as the voltage electrode. The length of the voltage section of the inner electrode was 13.0 cm. The continuous power transfer to the floating high voltage supply was realized by means of the isolation transformer. The filter charge collector consisted of an electrical isolated filter element connected to the electrometer amplifier. Experimental tests with dioctyl phthalate and NaCl particles against the EAA and the optical particle

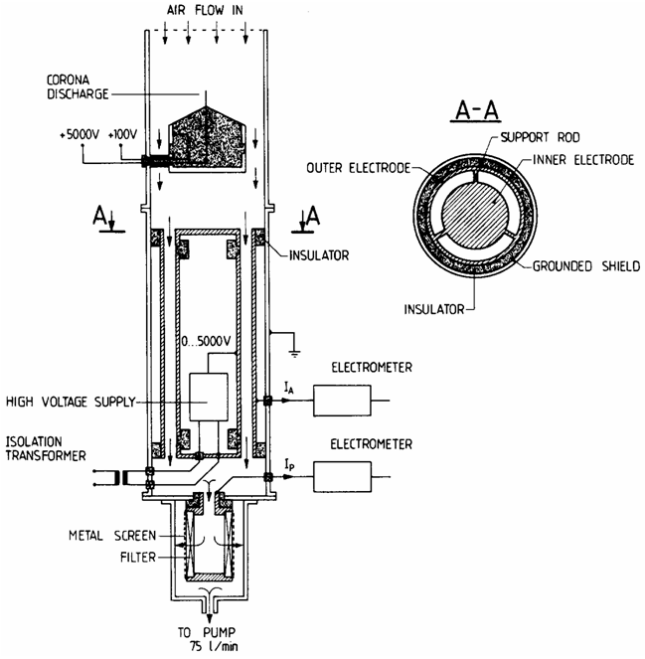


Figure 5. Schematic diagram of the analyzer developed by Lehtimaki (1987).

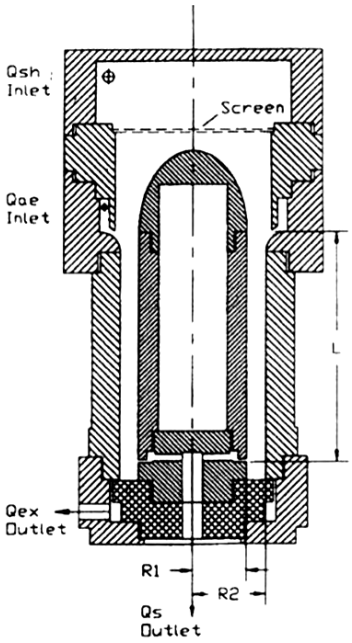


Figure 6. The University of Vienna DMA (Winklmayr *et al*., 1990).

analyzer showed that it was possible to measure the collected electric current down to 0.01 pA.

Winklmayr *et al*. (1990) developed the Vienna DMA, shown in Figure 6. The column length is 11 cm, and the radii of the outer and inner electrodes are 3.3 cm and 2.5 cm, respectively. The aerosol was introduced tangentially into the annular region around the aerosol entrance slot to provide a uniform distribution of aerosol particles, while keeping particle losses small. The sheath air was introduced through a nylon mesh screen above the central electrode and then entered into the classification region. In the original version, the outlet was connected directly to an extremely sensitive Faraday cup electrometer detector with a sensitivity of $10^{-16}$ A. This system was designed for classification of particles in the size range of 3 to 150 nm in diameter, but can be applied to measurements in the 1 to 40 nm size range.

Seto *et al.* (1997) developed a low pressure DMA (LPDMA) with a Faraday cup electrometer for measuring nanometer sized aerosol particles, shown in Figure 7. This LPDMA was similar to that of the Vienna DMA. The column length of the LPDMA is 1.8 cm, and the radii of its outer and inner electrodes are 3.3 cm and 2.5 cm, respectively. The aerosol particles were charged using bipolar ions, which were generated by á-ray irradiation using $^{241}$Am in an aerosol bipolar charger. The bipolar charging of nanometer sized particles at low pressure was analyzed using Fuchs theory. The equilibrium charge distribution obtained at low pressure was used to calculate the size distribution from the mobility distribution. The performance of the LPDMA was investigated experimentally using a tandem DMA technique as shown in Figure 8. The monodisperse silver particles were used as test particles. It was found that LPDMA can be used to measure nanometer-sized particles in the range between 4-10 nm under low pressure conditions in the range of 60-760 Torr. This technique can be applied to nanometer sized particles and ions in physical vapor deposition and low pressure chemical vapor deposition systems.

Chen *et al.* (1998) and Pui *et al*. (2001) developed and optimized a nano-DMA, for measuring 3 to 50 nm particles, shown in Figure 9. The column length of the nano-DMA is 5 cm, and radii of outer and inner electrodes are 3.82 cm and 1.88 cm, respectively. The design was based on a cylindrical configuration and optimized numerically by Chen and Pui (1997). Important design features included high particle penetration and high sizing resolution. To

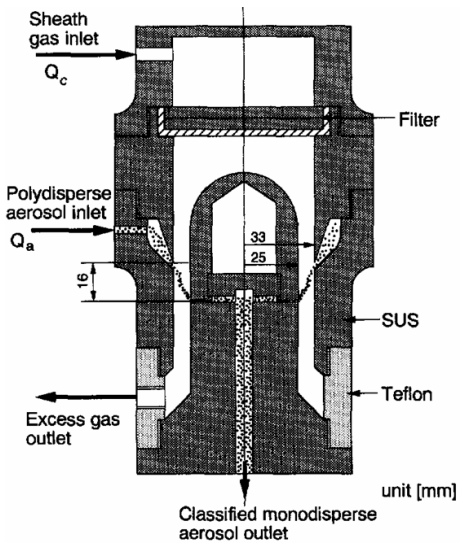


Figure 7. Schematic diagram of the LPDMA developed by Seto *et al*. (1997).

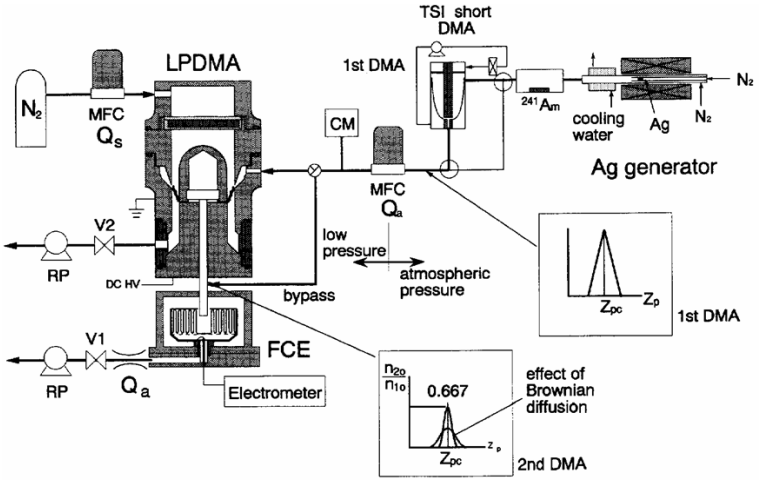


Figure 8. Experimental system for calibration of LPDMA (Seto *et al*., 1997).

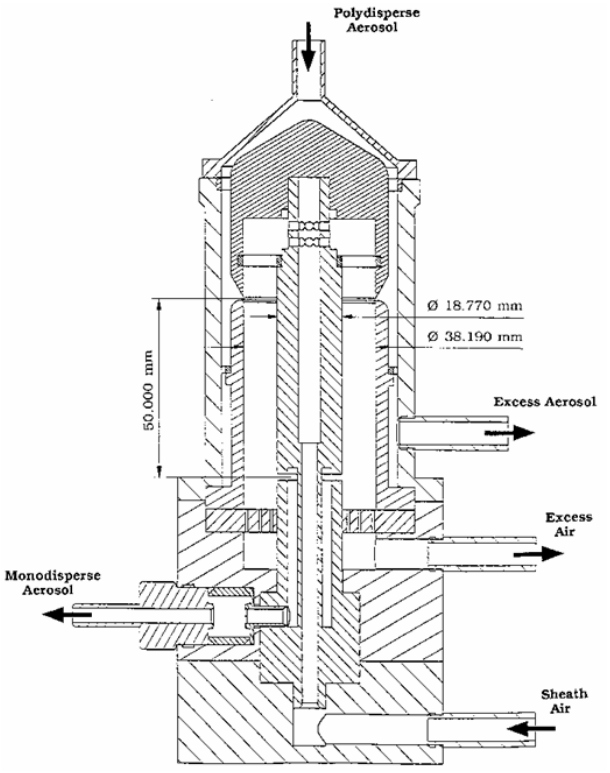


Figure 9. Schematic diagram of the Nano-DMA developed by Chen *et al*. (1998).

reduce particle loss in the aerosol transport passage, the aerosol residence time in the nano-DMA was reduced by shortening the inlet transport passage. An optional feature of high inlet flow was designed in order to further reduce the residence time between the aerosol inlet and the slit in the classifying region. A new entrance slit was designed to have optimal aerosol and sheath air flow matching at a flow ratio of 1:10 with a wide dynamic flow-ratio range (aerosol/sheath flow ratio up to 1/70). This improvement made the nano-DMA suitable for high resolution particle sizing and classification. To reduce the effect of Brownian diffusion broadening, the collector tube length was shortened to 5.0 cm compared to a typical DMA of 44.44 cm. At the designed flow conditions of 1.5 L/min aerosol and 15.0 L/min sheath air flow rates, the measurement size range was from 3 to 50 nm. The base of the nano-DMA was completely re-designed to avoid particle loss due to the undesirable electrostatic effect observed by Kousaka *et al*. (1986). Comparing the experimental results obtained by using the tandem DMA technique, described in Hummes et al. (1996), the nano-DMA was reported to perform well in the designed size range and its transfer function agreed well with the numerical prediction.

Seol *et al*. (2002) designed and constructed an adjustable-column length DMA (ACLDMA) with a capability of measuring particle sizes between 1 nm to hundreds of nanometers. The basic structure of the ACLDMA, shown in Figure 10, was similar to that described by Knutson and Whitby (1975). The ACLDMA was characterized by an adjustable inner electrode, whose length can be varied from 0 to 30 cm. The inner and outer electrode radii were 2.5 cm and 3.8 cm, respectively. The inner electrode was moved with a servomotor and reduction gear with a position accuracy of 0.3 μm. The position of the inner electrode was monitored with a laser displacement sensor with a resolution of 2 ìm. From these characteristics and for $L$ = 16 mm, the uncertainty of the mobility was ±0.0125 % of the set mobility. To minimize the eccentricity of the inner electrode, a pair of sliding guide rings was used. Metallic seals were used to separate the classification and drive parts of the electrode. The ACLDMA also adopted a built-in Faraday cup electrometer to measure the total particle current. The Faraday cup was placed inside the inner electrode of the DMA. The classification characteristics of the ACLDMA were investigated by two methods: a tandem DMA and $C_{60}$ monomer measurement methods. It was reported that the resolution of the DMA obtained agreed with that expected by the diffusing transfer theory (Stolzen-

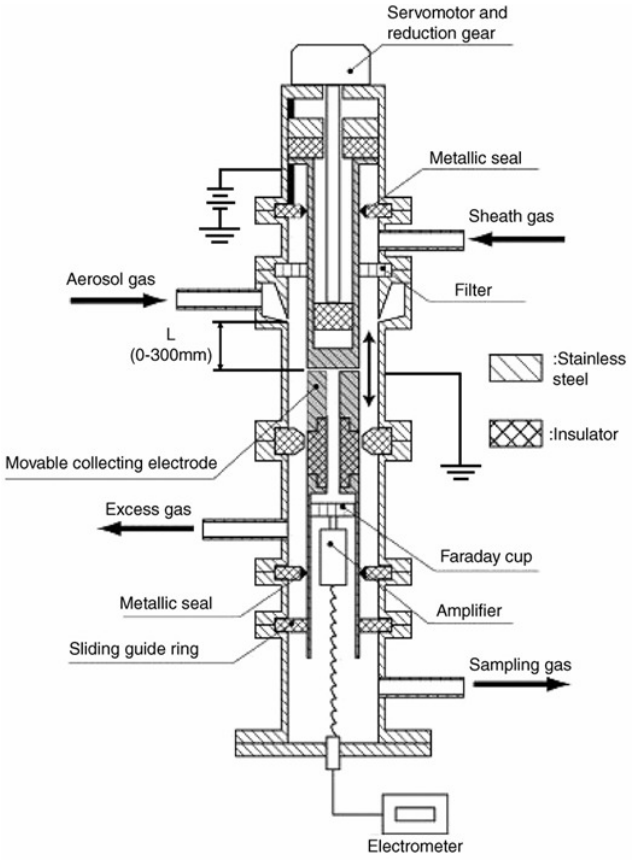


Figure 10. Schematic of an adjustable-column length DMA (ACLDMA) (Seol *et al*., 2002).

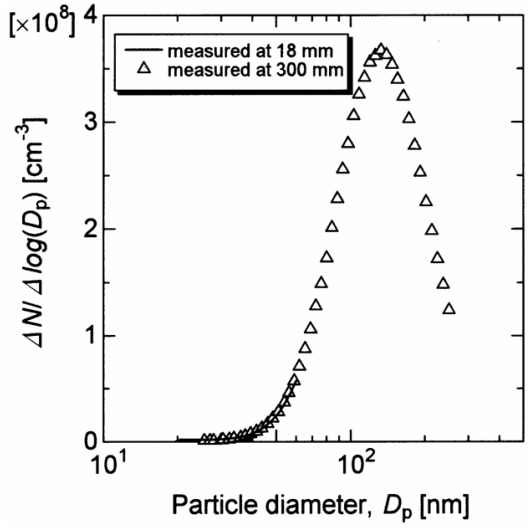


Figure 11. Particle size distribution measured with the ACLDMA when $L$ = 18 and 300 mm (Seol *et al*., 2002).

burg, 1988) when $L \leq 15$ cm. The height of the transfer function showed an anomalous dependence on $L$, i.e. the height reaches a maximum at $L = 3.6$ cm, which cannot be explained by diffusing transfer theory and/or space charge effects. Figure 11 represents a particle size distribution of NaCl

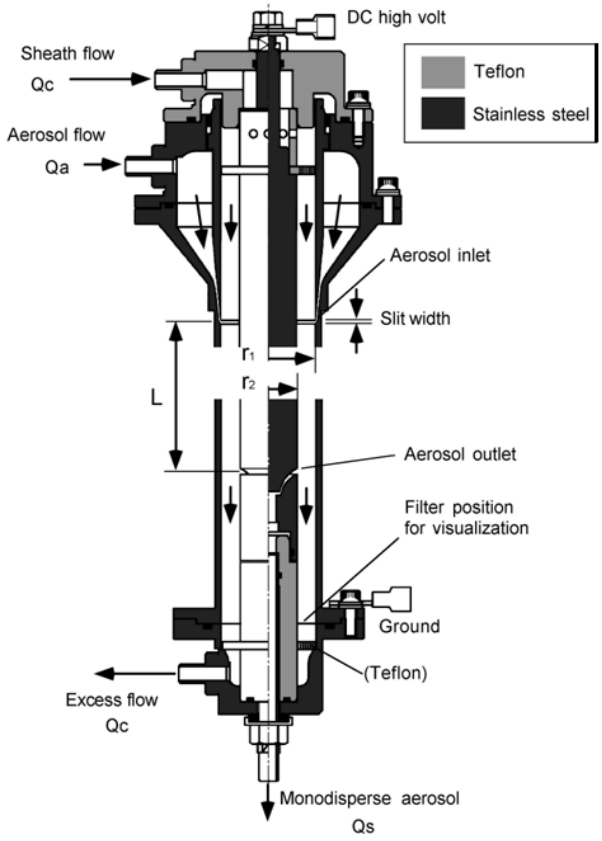


Figure 12. Schematic of the LDMA-FCE system (Shimada *et al*., 2005).

particles that were formed by evaporation of NaCl powder at 700°C and measured with the ACLDMA when $L$ = 1.8 cm and 30 cm. The particle size obtained at $L$ = 1.8 cm ended at approximately 30 nm, while the size distribution obtained at $L$ = 30 cm extended up to approximately 270 nm.

Shimada *et al.* (2005) developed the long DMA-faraday cup electrometer system, capable of measuring particle sizes up to larger than 1 μm. In the LDMA, shown in Figure 12, the effective electrode length is 60 cm, and radii of the outer and inner electrode are 2.5 cm and 1.5 cm, respectively. The charged particles classified by the LDMA are introduced into the faraday cup electrometer and mainly captured on the bottom electrode. Since both electrodes are connected to the copper rod, the current from captured charged particles is magnified by the amplifier and measured by the sensitive electrometer. The performance of the LDMA-FCE was found to be effective for measurements of submicron aerosol particles with wide range size.

Rosser and de la Mora (2005), Martinez-Lozano and de la Mora (2006), and Martinez-Lozano *et al*. (2006) designed and developed the new nano-DMA with the ability to attain much higher sheath air flow rates and to maintain the flow laminar at the correspondingly higher Reynolds numbers. Figure 13 shows a schematic diagram of the short Rosser DMA. The radii of the inner and outer electrode are

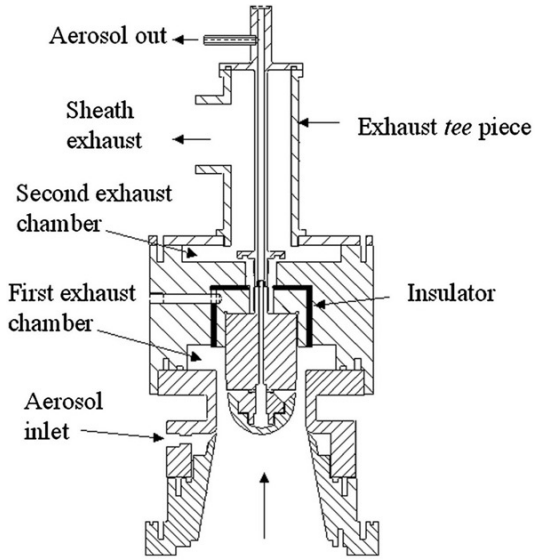


Figure 13. Schematic of the Nano-DMA developed by Rosser and Fernandez de la Mora (2005).

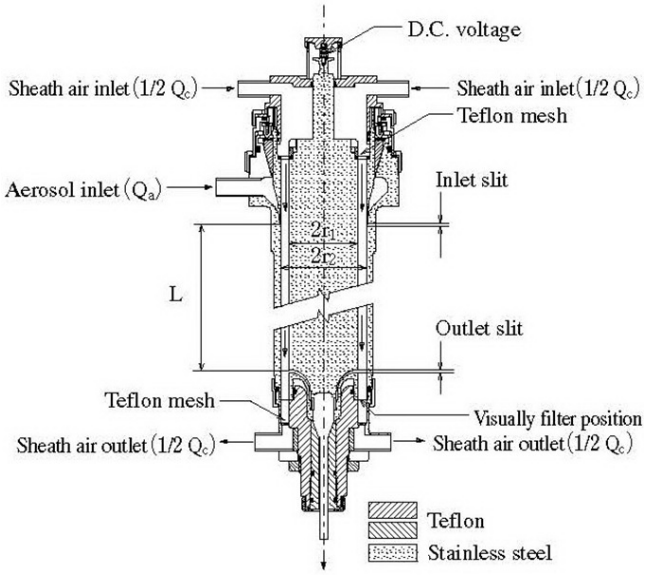


Figure 14. Schematic of the large flow annular-type DMA (Koyama *et al*., 2007).

2.5 cm and 3.3 cm, respectively, and the conventional trumpet inlet diameter is 9.7 cm. The gas enters from the bottom, passing two laminarization screens into the conical trumpet, flows around the bullet, enters the first exhaust chamber, passes into the second exhaust chamber through 10 exhaust holes, and exists through the exhaust tee piece, first axially and then through an exhaust line to the left. It was reported that this DMA had excellent resolution at 1 nm, yet with a sufficiently wide and long working section to cover the size range up to 100 nm.

Recently, Koyama *et al*. (2007) developed a large annular-type DMA, having an outer electrode diameter of 10 cm to increase the sampling flow rate of size-classified aerosols up to 30 L/min. The schematic of the new DMA is shown in Figure 14. The new DMA was calibrated with three types of standard monodisperse particles (nominal diameter ranging from 28 to 100 nm). It was reported that nominal and measured diameters are in good agreement, and it was shown that this DMA is useful to classify large volumes of nanometer-sized aerosols and for advanced measurements, such as chemical analysis of particulate materials or inhalation experiments.

### 3.2 Multi-channel DMAs

Mirme (1994) was among the first researchers to develop a multi-channel DMA. His electrical aerosol spectrometer (EAS) was developed at Tartu University, Estonia, and later improved by Tammet *et al*. (2002), schematically shown in Figure 15. It contains two DMAs, one provided with a weak electric field or diffusion charger (D-analyzer), and the other with a strong electric field charger (E-analyzer). Positive polarity of charge is used. Unipolar diffusion charging is the dominant mechanism for particles less than 0.5 μm in diameter, whereas unipolar field charging is the dominant mechanism for particles larger than 0.3 μm in diameter. For the particles in the size range of 0.3-0.5 μm in diameter, the combined field and diffusion charging is used in this size range. The mobility analyzers of the EAS are cylindrical capacitors consisting of particle repulsive inner electrodes and particle collecting outer electrodes. The collecting electrodes of the mobility analyzers are divided into isolated sections, each of which is provided with an electrometer. Each section together with its electrometer corresponds to a measuring channel of the analyzer. The EAS has 32 measuring channels. The aerosol is introduced into

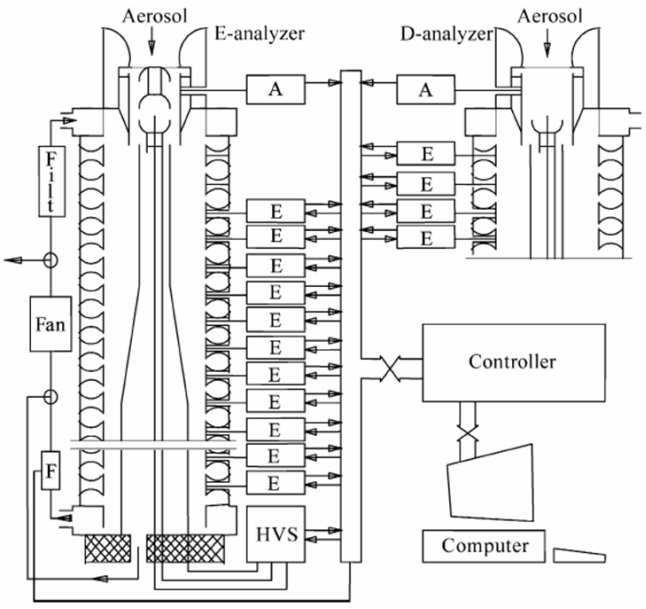


Figure 15. Schematic of the EAS (Mirme, 1994).

the analyzers through preconditioning facilities (laminarizers, dischargers) and through charging zones of the chargers close to the inner (repulsive) electrodes. Charging conditions in the chargers are stabilized by feedback circuits. Charged particles moving in radial electric fields of the mobility analyzers precipitate on the different sections of the mobility analyzers according to their electrical mobility. The electric currents carried over these sections by particles are measured by electrometers and form output signals vector of the apparatus (apparatus record). The time uncertainty of measurements is reduced by measuring the same aerosol sample synchronously with its movement in the analyzer. A special controller has been designed to control the measurement and record the data. Maximum resolution of the electrometric signal is 0.25 mV, making about $2.5\times10^{-16}$ A on the scale of the aerosol electric current. The main spectrometer parameters, such as charging currents and air flow rates, are also controlled. The time response of the EAS is approximately 1 second for the fastest sampling rate. The particle number concentration that the EAS can measure ranges between $10^2$ - $10^5$ particles/cm$^3$ for particles as small as 10 nm, and between $2\times10^{-2}$ - $5\times10^1$ particles/cm$^3$ for particle sizes up to 10 μm.

Graskow (2001) designed and developed the f ast aerosol spectrometer (FAS) at Cambridge University, UK, for classification and measurement of particles in the range of 1-100 nm. A schematic diagram of the FAS is shown in Figure 16. The overall design and operating principle of the FAS is similar to the EAS. A difference between the two instruments is the charging method. Particle charging of the FAS is accomplished by a photoelectric charger resulting in bipolarly charged aerosol particles. The FAS classifier consists of two coaxial electrodes with the central rod maintained at a positive high voltage range, varying between 1 and 10 kV, and with the outer chassis of the classification section being grounded. The central rod is made of a stainless steel rod with 2 cm diameter and the outer chassis is made of a stainless steel tube with 5 cm diameter and 15 cm in length. There are two streams, which are the aerosol and sheath air flows. The charged particles are introduced into the classification section near the central rod by a continuous flow of air, and surrounded by a sheath air flow. Since the central rod is kept at a positive voltage, the charged particles are deflected outward radially according to their electrical mobility and they are collected on a series of eleven isolated electrode rings at the inner surface of the outer chassis of the FAS classifier. Each electrode ring was 10 mm wide with a 0.6 mm gap in between the electrometer rings for isolation. The electric currents due to the charged particles are measured by an electrometer and then are translated to particle number concentrations, corresponding to the size range collected on each electrode ring. The electrometer circuit used for current measurement in the FAS employs the feedback amplifier Analog Device AD549L. This circuit gives an output of 10 mV/pA of input current signal. It was reported that the time response of the FAS is approximately 38 milliseconds.

The engine exhaust particle sizer (EEPS) is a commercial instrument for fast response aerosol measurements in the diameter range of 5.6 to 560 nm (TSI, 2004). It is similar to the EAS, described previously. It employs a unipolar diffusion charger to charge the incoming aerosol sample, and an "inside-out" electrostatic classifier to separate particles according to their electrical mobility. It detects and measures particle concentrations by a series of 22 electrometer rings along the column classifier. The particle size distribution is then estimated using the current measurements from individual channels and a data inversion algorithm (Mirme, 2005). The time response of the EEPS is approximately 100 milliseconds.

Based on the FAS, Reavell and Collings (2004) developed the differential mobility spectrometer (DMS), which was later modified by Biskos *et al* (2005). Particle charging is accomplished by a corona-wire diffusion charger resulting in unipolarly charged aerosol particles. The DMS operates at pressure below ambient (250 mbar). Figure 17 represents a schematic diagram of the DMS. The DMS classifier is capable of fast response aerosol classification and measurement in the size range of 5 to 1,000 nm in diameter, with a time response of 200 milliseconds. The DMS classification column is 70 cm long with an internal diameter of 5.3 cm. The inner electrode has a diameter of 2.5 cm and is made of modified acetyl plastic, selected for its electrical properties. The DMS classifier consists of two concentric electrodes with an axially increasing electric field established in between. This varying electric field is created by a linearly increasing (from the aerosol inlet to the end of the column) potential along the central rod. This varying electric field results in a

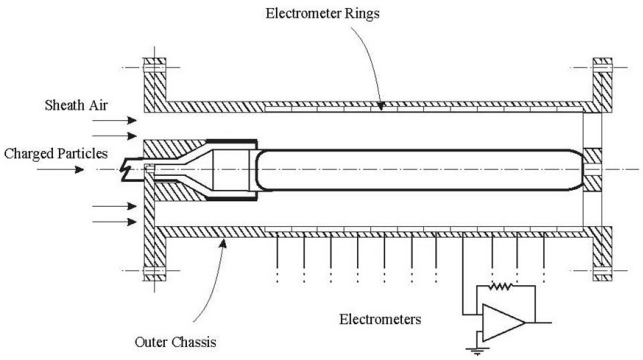


Figure 16. Schematic of the FAS (Graskow, 2001).

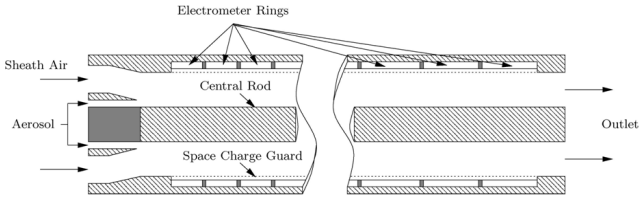


Figure 17. Schematic of the DMS (Biskos, 2004).

better resolution of the particle size distribution. The actual number concentration of the charged particles is determined by a series of 26 metallic rings connected to sensitive electrometers placed in the inner surface of the outer electrode of the column. The first eight rings from the inlet are 1.45 cm wide, while the rest have a width of 2.95 cm. The start of the first electrometer ring is located 1.85 cm downstream of the aerosol inlet, and a 0.05 cm gap is allowed between the electrometer rings for isolation. The actual size distribution of the input aerosol can be determined by deconvoluting the electrometer current readings. It was reported that the DMS classifier can measure particle sizes with number concentrations in the range from approximately $1\times10^3$ - $4\times10^7$ particles/cm$^3$.

Takeuchi *et al*. (2005) developed a new dual-type DMA to detect transient number concentrations of airborne nanoparticles with diameters centralized at around 10 nm (for nuclei mode particles) and 100 nm (for accumulation mode particles) in automobile exhaust gas. Figure 18 shows the configuration and external appearance of the dual-type DMA. It divides the gas sample into two parts, and each part is sent through one of two coaxially nested sections for analysis. The first sample gas flows into DMA2, located at the center of the apparatus. DMA2 is responsible for classifying relatively large nanoparticles in the 20-280 nm range and leading the particles to the Faraday cup electrometer. The second sample gas flows into DMA1, located on the periphery of DMA2. The DC voltages applied to the DMAs are controlled independently. Voltages between 0.8 and 293 V are used to scan particle size distributions. For the scanning mode measurement, the nanoparticles are charged by $^{241}$Am and their size distributions are determined by varying the applied voltage over 2 min. During the transient mode measurement, the nanoparticles are charged by a corona charger and the fixed voltage for the two sections are peaked near 10 and 100 nm in order to monitor the transient behavior of the exhaust nanoparticles. It was shown that the apparatus responded quickly and can be reliably implemented as a standard apparatus.

Intra and Tippayawong (2006a, b) designed and developed the electrical mobility spectrometer (EMS) at Chiang Mai University, Thailand, with support from the National Electronics and Computer Technology Center. The EMS is a multi-channel size analyzer capable of classifying and measuring the aerosol particles near real time in the size range of approximately 10-1,000 nm. Its geometrical configuration is similar to the classifier used by Graskow (2001) and Biskos *et al.* (2005). Nonetheless, there are collective differences between the EMS and the other existing instruments, which are as follows: (i) the concept of the present instrument is based on a compact, inexpensive and portable unit. A short column classifier and a small number of detection channels are used to reduce diffusion effects of the particles inside the classifier. Overall dimensions and weight are such that it is easy to handle and moveable; (ii) the instrument adopts a tangential aerosol inlet upstream of the first electrode ring to ensure uniform particle distribution across the annular aerosol entrance to the classifier column; (iii) rather than diffusion charging, the instrument employs unipolar corona (diffusion and field) charging method; and (iv) the applied voltage is set to maintain at low level, well below the corona onset voltage, to avoid unintentional charging of the particles inside the classifier. A schematic diagram of the EMS classifier is depicted in Figure 19. It has one short column, which consists of coaxially cylindrical electrodes. The outer chassis is made of a stainless steel tube with 5 cm in diameter and the inner electrode is made of an aluminum rod, 2 cm in diameter and 13.1 cm in length. The inner electrode was polished to an extremely fine surface finish to avoid undesirable electric field effects on particle motion due to a non-uniform electric field, which results from small surface scratches and imperfections. Both ends of the inner electrode were rounded to a 0.5 cm radius to avoid distortion of the electric field, which would result from sharp edges. The advantage of a cylindrical geometry is that distortion of electric field between the electrodes is minimal due to the absence of corners and edges. The inner electrode of the

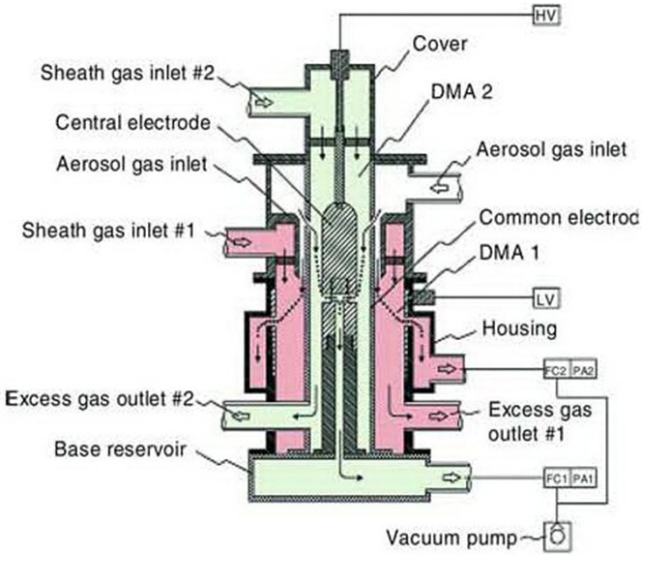


Figure 18. Schematic of the new dual-type DMA (Takeuchi *et al*., 2005).

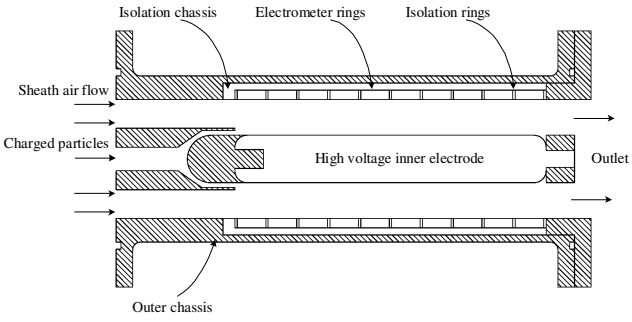


Figure 19. Schematic of the EMS (Intra and Tippayawong, 2006).

EMS classifier is maintained at a positive high voltage, while the outer chassis of the classifier is grounded. An adjustable DC high voltage power supply is used to maintain this voltage difference, generally in the range between 500 V and 3.0 kV. Resolution and size range of the EMS classifier is mainly determined by the number and width of the electrometer rings. The 10 electrometer rings used result in the classification of every measured aerosol into 10 mobility ranges. The electrometer rings have a width of 1.2 cm. The first electrometer ring is located 0.1 cm downstream the aerosol inlet, while a 0.10 cm gap is allowed between the electrometer rings for isolation. Electrical current detection method was considered to be easier and faster than direct particle detection measurements. The size range and resolution of particles collected on the electrometer rings can be also varied by adjusting the sheath air and aerosol flow rates, the voltage applied to the inner electrode, and the operating pressure.

Recently, Intra and Tippayawong (2008) developed the new long EMS to extend the measured particle size range and resolution, shown in Figure 20. Its outer chassis is made of a 48.1 cm long aluminum tube with an internal diameter of 5.5 cm. The inner electrode is made of a 2.5 cm in diameter stainless steel rod. Width of the aerosol inlet channel is 0.2 cm. The 22 electrometer rings used result in the classification of every measured aerosol into 22 mobility ranges. The electrometer rings have a width of 1.9 cm. The first electrometer ring is located 2 cm downstream the aerosol inlet, while a 0.1 cm gap is allowed between the electrometer rings for electrical isolation. In this new long EMS, Brownian diffusion effect was found to be significant for particles smaller than 100 nm.

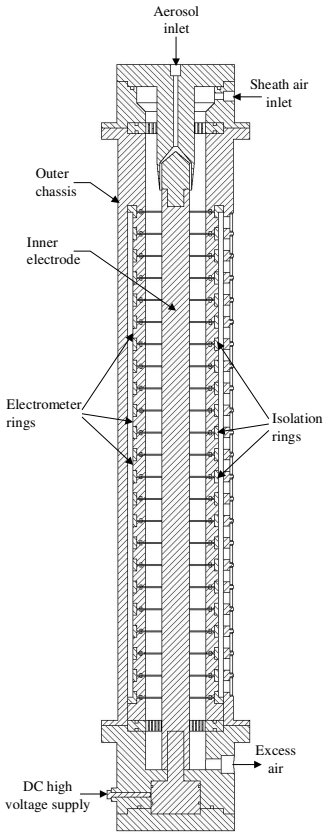


Figure 20. Schematic of the new EMS (Intra and Tippayawong, 2008).

## 4. Summary and Recommendations of Future Research

Particle size is an important parameter for characterizing the behavior of the aerosol particles, and this is especially the case for nanometer aerosol particles. The DMA is an aerosol instrument widely used to measure size distribution and to classify monodisperse from polydisperse aerosol particles in the nanometer scale. This paper has presented an overview of the available DMAs for size classification of nanometer aerosol particles. A brief outline has been given, focusing on the cylindrical differential mobility analyzer. It has covered the operating principles as well as detailed physical characteristics of single- and multi-channel DMAs. The main purpose of these DMAs is to classify and measure aerosol particles with a wide range of particle sizes, rapid time response, high particle size resolution, and minimal losses. This is highly desirable in any particle sizing instruments. These DMAs differ in terms of specific application, construction, particle size measurement range, and resolution. Table 1 summarizes different designs of the DMAs for nanometer aerosol particles described in this paper.

The following paragraphs give specific recommendations for further research on both the theoretical and experimental parts of the DMA development.

- Detection range on both ends of the size spectrum should be extended, so that a single instrument is able to cover various particles in nature. Different measurement techniques should be combined to perform multi-parameter studies and to measure nanoparticles from the molecular cluster size to particle sizes up to 100 nm. Apart from size, these parameters may include composition analysis.

- Further research in the design and refinement of the DMA should be carried out, focusing on the effect of the design configuration, manufacturing precision, practical materials and fabrication/assembly limitations, and flow setting accuracy on the size classification performance and accuracy of the DMA, such as non-ideal flow or electric field, inner electrode eccentricity, and misalignment of various components.

- The effect of particle shape on the classification performance and accuracy of the DMA should be explored. Most aerosol particles in nature, such as asbestos fibers, soot aggregates, and bio-aerosols, are non-spherical. The shape affects the drag force, settling velocity and electrical mobility. Non-spherical particles have smaller electrical mobility than the spherical particles.

- In order to measure transient behavior of airborne particles, such as those found in automotive exhaust gas, the time response of the instrument should be further improved.

Table 1. Comparison of available DMAs.

| Reference | Electrode length ($L$) (cm) | Inner electrode ($R_1$) (cm) | Outer electrode ($R_2$) (cm) | Operating pressure | Channels | Particle diameter ($d_p$) range (nm) |
|---|---|---|---|---|---|---|
| Knutson and Whitby (1975) | 45.52 | 1.9 | 3.815 | Ambient | 1 | 5-1,000 |
| Lehtimaki (1987) | 13 | 2.5 | 3.0 | Ambient | 1 | 20-1,200 |
| Winklmayr *et al.* (1990) | 11 | 2.5 | 3.3 | Ambient | 1 | 3-150 |
| Seto *et al*. (1997) | 1.8 | 2.5 | 3.3 | Low | 1 | 4-10 |
| Chen *et al*. (1998) | 5 | 1.88 | 3.82 | Ambient | 1 | 3-50 |
| Seol *et al*. (2002) | 30 | 2.5 | 3.8 | Ambient | 1 | 30-270 |
| Shimada *et al.* 2005 | 60 | 1.5 | 2.5 | Ambient | 1 | 1-1,000 |
| Rosser and Fernandez de la Mora (2005) | n/a | 2.5 | 3.3 | Ambient | 1 | 1-100 |
| Koyame *et al*. (2007) | n/a | n/a | 10 | Ambient | 1 | 28-100 |
| Mirme (1994) | n/a | n/a | n/a | Ambient | 32 | 10-10,000 |
| Graskow (2001) | 15 | 1.0 | 2.5 | Ambient | 10 | 1-100 |
| TSI Incorporated (2004) | n/a | n/a | n/a | n/a | 22 | 5.6-560 |
| Biskos *et al.* (2005) | 70 | 1.25 | 2.65 | Low | 26 | 5-1,000 |
| Takeuchi *et al*. (2005) | n/a | n/a | n/a | Ambient | 2 | 10-280 |
| Intra and Tippayawong (2006a, b) | 13.1 | 1.0 | 2.5 | Low | 10 | 10-1,000 |
| Intra and Tippayawong (2008) | 48.1 | 1.5 | 2.75 | Low | 22 | 10-1,000 |

n/a: information not available

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