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## UPCOMING EVENTS

5th International Symposium on Nanotechnology Safety and Occupational Health

Boston, MA - August 9-12  
Booth # 10

Particle College

Boulder, CO - August 9-10

2011 European Aerosol Conference (EAC)

Manchester, England - September 4-9

2011 American Association of Aerosol Research (AAAR)

Orlando, FL - October 3-7

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## NEXT GENERATION NANO AND ULTRAFINE PARTICLE CHARACTERIZATION

Particle Measuring Systems introduces a family of instruments and accessories designed to address emerging needs in Aerosol Science Research. Innovative new technology and a creative design approach have produced a suite of products offering an array of novel features.

## PRODUCT SPOTLIGHT – NPS500 NANOPARTICLE SPECTROMETER



Particle Measuring Systems NPS500 Nanoparticle Spectrometer sets a new standard for high sensitivity and selectivity aerosol measurements. It provides the ability to measure particle size distributions over a range of 5 nm to 500 nm with 128 user-selectable channels. A proprietary corona charger system is used instead of traditional low-level radioactive sources. A short video that provides an operational overview of the NPS500 can be viewed on our [website](#).

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## APPLICATION NOTES

### Nanoparticle Spectrometer Performance Summary and Instrument Comparison

Scanning Mobility Particle Sizers (SMPS) have been an indispensable laboratory tool for aerosol scientists, metrologists, environmental researchers, toxicologists and others for more than two decades. The performance of the core technology has advanced over time, and the instruments remain operationally complex. [Click to read more...](#)

### Novel Unipolar Corona Charger for generating Monodisperse Nano and Sub-Micron Aerosols

Many applications in aerosol science require the production of monodisperse aerosols. The most common way of producing a monodisperse aerosol is based on electrostatic classification with the use of a Differential Mobility Analyser (DMA). The DMA requires that the aerosol sample must be electrically conditioned (charged or neutralized) prior to classification (reference ISO 15900). [Click to read more...](#)

## PRODUCT BRIEFS



The C2000 Unipolar Corona Charger is used with experimental aerosols to produce particles that have a single elemental charge. This versatile laboratory accessory is a replacement for low-level radioactive neutralizers that are used with a Differential Mobility Analyzer (DMA) for generating monodisperse aerosols over the range of 5 nm to 500 nm. [Click to Learn More...](#)



The PMC500 Particle Mobility Classifier is a self-contained, easy to use differential mobility analyzer. The instrument can be used to generate monodisperse aerosols across the range from 5 nm to 500 nm, with flow rates ranging from 0.05 LPM to 5 LPM. Sample aerosols with particle concentrations up to  $10^7/\text{cm}^3$  can be classified. The PMC500 includes a large touch screen display and has the form factor of a standard cleanroom particle counter. Because the unit is portable and weighs only 7 kg, it can be readily used outside of a standard laboratory environment, as well as shared between labs or used in multiple projects because configuring the instrument for operation takes only minutes. [Click to Learn More...](#)

## APPLICATION NOTES

### **Nanoparticle Spectrometer Performance Summary and Instrument Comparison**

Scanning Mobility Particle Sizers (SMPS) have been an indispensable laboratory tool for aerosol scientists, metrologists, environmental researchers, toxicologists and others for more two decades. The performance of the core technology has advanced over time, and the instruments remain operationally complex. They are not suitable for in-situ measurements, they require dedicated lab space, periodic user upkeep, maintenance of regulatory licenses and record keeping, factory calibration and highly trained technicians to operate.

Particle Measuring Systems and Naneum have recently introduced a novel nanoparticle spectrometer based on SMPS technology. The instrument meets or exceeds performance requirements established by the market; these include sensitivity, resolution, measurement time to results and counting efficiency. In addition, it provides improvements to the characteristics viewed by many as limitations to the traditional SMPS technology. This article gives an overview of the key performance capabilities of the nanoparticle spectrometer, including comparison data with established US-based and European-based manufacturers. [Click to Continue...](#)

### **Novel Unipolar Corona Charger for generating Monodisperse Nano and Sub-Micron Aerosols**

Many applications in aerosol science require the production of monodisperse aerosols. The most common way of producing a monodisperse aerosol is based on electrostatic classification with the use of a Differential Mobility Analyser (DMA). The DMA requires that the aerosol sample must be electrically conditioned (charged or neutralized) prior to classification (reference ISO 15900). There are a variety of established approaches for accomplishing this, and the pros and cons of each have been well documented. There remains, however, a fundamental problem that has yet to be adequately addressed for generating a monodisperse aerosol for particle sizes greater than about 60 nm due to the effects of multiple charging. In some applications, these effects can be dealt with by applying theoretical correction factors to the measured data, but this remains an important consideration that can negatively affect the precise measurement and the integrity of the resulting data. This paper describes a new technology that has proven to substantially decrease, if not eliminate the effects of multiple charges on measured particle size distributions covering the range of 60 nm to 500 nm. The benefit is experimental results that are representative of the aerosol sample under test and significantly more reliable than those obtained using arithmetic factors and assumptions. [Click to Continue...](#)



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## Nanoparticle Spectrometer Performance Summary and Instrument Comparison

Scanning Mobility Particle Sizers (SMPS) have been an indispensable laboratory tool for aerosol scientists, metrologists, environmental researchers, toxicologists, and others for more than two decades. Although the performance of the core technology has advanced over time, the instruments remain operationally complex. They are not suitable for in-situ measurements, they require dedicated lab space, periodic user upkeep, maintenance of regulatory licenses, record-keeping, and factory calibration, and must be operated by highly-trained technicians.

Particle Measuring Systems and Naneum recently introduced a novel nanoparticle spectrometer based on SMPS technology. This instrument, the Nano-ID™ NPS500 Nanoparticle Spectrometer, meets or exceeds performance requirements established by the market. These include sensitivity, resolution, measurement time to results, and counting efficiency. In addition, the Nano-ID NPS500 provides improvements to the characteristics viewed by many as limitations to the traditional SMPS technology as described above.

This article gives an overview of the key performance capabilities of the Nano-ID NPS500 Nanoparticle Spectrometer, including comparison data with established US-based and European-based manufacturers.



### Introduction

The Nano-ID NPS500 Nanoparticle Spectrometer offers numerous technological advancements over traditional Differential Mobility Analyzers (DMA) and Scanning Mobility Particle Sizers (SMPS). The core elements of the NPS500 design are described below.

#### Parallel Plate Geometry DMA

The most common DMA design used in commercial DMA and SMPS instruments is a cylindrical column. Two types are generally offered: the long-column DMA that offers a wide-range of particle classification (10 nm to 1 µm) and the short-column DMA that is

used for nanoparticle classification (a few nanometers to 100 nm). Both types provide good sizing accuracy (2-3%) and resolution (typically  $\geq 10\%$ ). The physical size and form factor of both column styles is suitable for laboratory/bench-top style instruments. These designs however, are not practical for use in a compact, self-contained and portable instrument.

The DMA used in the NPS500 is designed to provide exceptional sizing and resolution, while at the same time allowing use in a compact, portable instrument. The resolution of the NPS500 DMA has been shown to be  $< 5\%$ , which is more than two times better for the same ratio of flow rates than that for a leading European manufacturer. Sizing accuracy is 3%, which compares favorably with similar commercial instruments.

#### High-Stability Unipolar Corona Charger System (UCC)

Low-level radioactive sources such as  $^{85}\text{Kr}$ ,  $^{210}\text{Po}$  and  $^{241}\text{Am}$  aerosol neutralizers are commonly used in commercially-available DMA and SMPS instruments. Although suitable for use in laboratory instruments that require electrical charging of the source aerosol, they pose significant problems from a regulatory standpoint – most notably licensing, storage, transportation, disposal, training, and cost. The NPS500 uses a novel UCC designed specifically to meet/exceed market requirements for sizing accuracy.

[Click Here to Return to Page 1](#)

## Low-Maintenance Condensation Particle Counter (CPC)

The NPS500 does not use alcohol or water as the CPC working fluid; therefore it does not produce the offensive odor and handling issues commonly associated with some CPCs, and it is immune to particle sizing inaccuracies caused by the physical/chemical characteristics of the particle itself.

The working fluid used in the NPS500 is a non-toxic organic compound, which is odorless and has a low vapor pressure. Since the performance of the condensation chamber in the NPS500 is largely driven by the vapor pressure 3D field of the hydrophobic working fluid (which is not the case with water-based systems), the sizing accuracy of the NPS500 is mostly independent of the particle's physical/chemical nature, e.g., water soluble versus insoluble particles.

### Core Technology Miniaturization

A completely fresh approach has been used in the design of the NPS500 in order to produce a portable, easy-to-use instrument capable of meeting the most demanding performance requirements of aerosol researchers. Each of the components has been miniaturized or developed so that they can be incorporated in a light-weight, compact instrument. Because the NPS500 is self-contained, it can easily be moved within a laboratory, shared among researchers and departments, or taken to a specific environment where in-situ measurements are needed. The performance improvements in each of the building blocks come together to create a truly unique scientific instrument suitable for any aerosol characterization application.

### Instrument Features

The Nano-ID NPS500 Nanoparticle Spectrometer has the following features.

- Particle size distributions from 5 nm to 500 nm
- Dual-function instrument – user-selectable Particle Counter mode; operates as a 5 nm portable particle counter
- Non-radioactive particle charging source
- Fast scan speeds giving reliable results in as few as 30 seconds
- Uses non-toxic, organic working fluid – provides up to 2,000 hours of operation between refills
- Fast warm-up; begin sampling in 90 seconds
- Large touch screen, easy to navigate user interface, and on-board computer
- Portable and self-contained; weighs only 7 kg

## Operating Modes

The NPS500 provides three operational modes.

- **Scanning Mobility Particle Sizer (SMPS)** mode. Measures particle size distributions over a range of 5 nm to 500 nm with up to 128 user-selectable channels.
- **Condensation Particle Counter (CPC)** mode. Measures the total particle concentration.
- **Single Channel (SC)** mode. Measures the particle concentration at a specific particle size held constant during the sampling.

### SMPS Mode

In SMPS mode the NPS500 provides Particle Size Distributions (PSD) over a range of 5 nm to 500 nm with up to 128 user-selectable channels. It samples the desired aerosol at a fixed flow rate and, through an ionization process, establishes a known charge on individual particles. It then separates/classifies particles by passing them through an electric field before introducing them to a miniaturized condensation chamber where they are grown to a size suitable for counting with an optical particle counter. The classifying electric field is continuously varied over a specified range, repeating the sizing and counting process in a sequential manner over the particle size range of interest. The result is a particle size distribution continuum showing particle number concentration versus size without gaps in the data.

### CPC Mode

In the CPC mode the NPS500 measures the total particle concentration over a user-selectable time period. All particles above 5 nm to over 1  $\mu\text{m}$  are counted, and sample updates as fast as one second are possible.

### SC Mode

In SC mode the NPS500 measures the total particle concentration at a user-selectable (fixed) particle size. The SC mode is very similar to the CPC operational mode, but with the difference of applying a constant voltage (specific for a certain particle size) to the classifier during the sampling process.

## Instrument Comparisons

### 1. Size Accuracy of the NPS500 Compared to a Reference Instrument

The sizing accuracy of the NPS500 was compared against that for a comparable model sold by a leading US-based supplier of the DMA and SMPS instruments (the term Reference Instrument is used throughout this paper to describe a comparable commercially-available instrument used for this comparison testing). Eight different monodisperse aerosol challenges were generated for this test. Aerosols of NaCl and of PSL spheres were generated for challenges from 50 nm to 350 nm and classified with a commercially-available DMA.

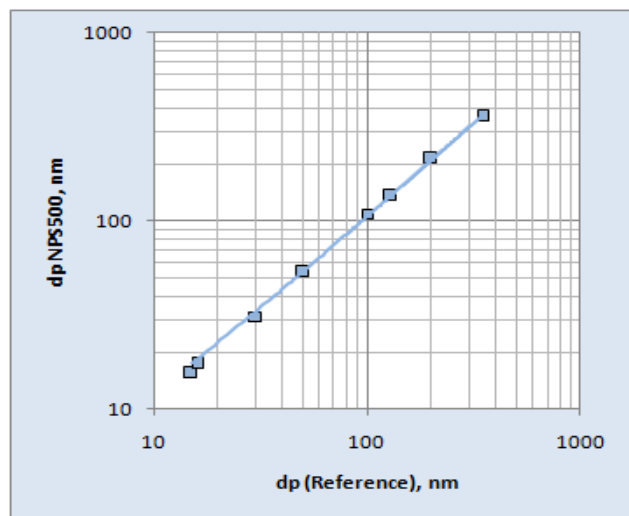
An aerosol of Cr<sub>2</sub>O<sub>3</sub> particles was generated for all challenges < 50 nm and classified with the same DMA. The NPS500 and the Reference Instrument were plumbed in parallel downstream of the source DMA. Both instruments were allowed sufficient time to warm up and any differences in the instruments' inlet flow rates were accounted for.

The comparison of the particle sizing accuracy obtained with the NPS500 compared to the European-based Reference Instrument (Figure 1 and Table 1) show excellent agreement.

**Table 1**

**Note:** *dp* is a designation for the measured peak size in the distribution.

Reference Instrument <i>dp</i> , nm	NPS500 <i>dp</i> , nm	Difference (%)
15	15.5	3
16	17.4	9
30	31	3
50	53	6
100	109	9
130	135	4
200	215	8
350	358	2

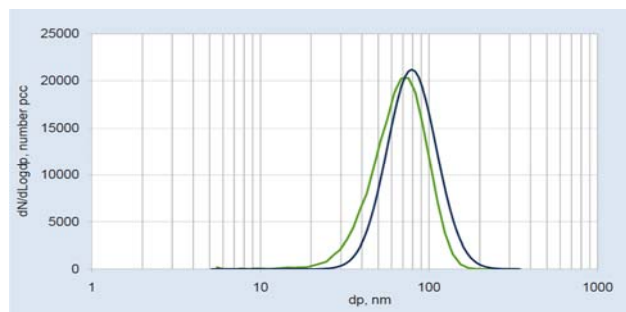


**Figure 1.** Comparison of NPS500 aerosol particle size data with the Reference Instrument

## 2. Comparison of a PSD Measurement between the NPS500 and a Reference Instrument

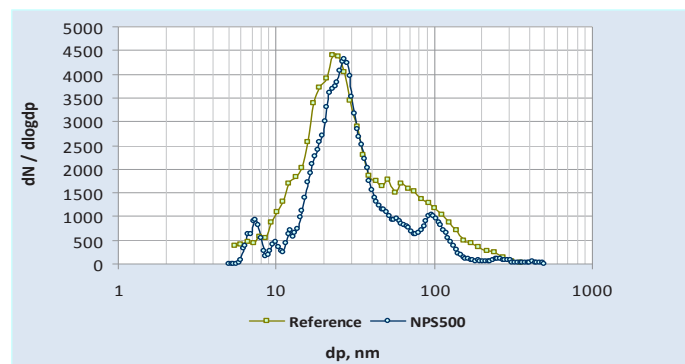
The NPS500 was challenged with a Cr<sub>2</sub>O<sub>3</sub> aerosol and an atmospheric aerosol, and the PSD it produced was then compared with that from a Reference Instrument sold by a leading European-based manufacturer. The results are shown in Figures 2, 3 and 4. All of the size distributions are very similar in the figures and positioned at a similar peak size. The NPS500 PSD revealed a complex structure for two of the challenges that were not resolved with the Reference Instrument. The narrower distribution and evidence of structure indicates higher resolution of the

NPS500.



**Figure 2.** PSD comparison of a Cr<sub>2</sub>O<sub>3</sub> challenge. The maximum of the size distribution for the NPS500 is 79 nm (Blue) and the Reference Instrument is 73 nm (Green). The vertical axis shows number concentration per cm<sup>-3</sup>. This data shows sizing agreement between the two instruments is 8%.

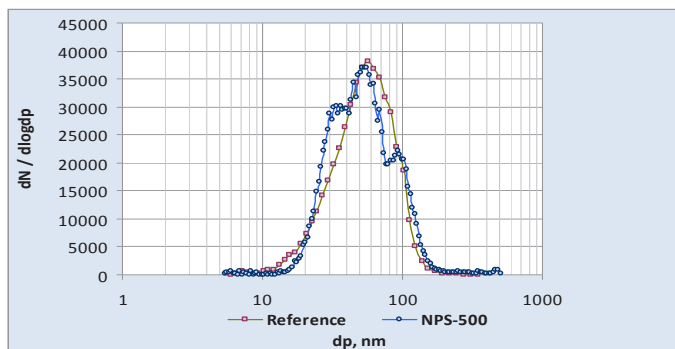
Figure 3 shows three distinct modes positioned at 7.5 nm, 28 nm and 100 nm produced by the NPS500. These modes were not resolved in the data obtained with the Reference Instrument. Atmospheric aerosols often reveal complex bi-modal or multi-modal structure. The nature of these peaks may be related to complex atmospheric chemistry or caused by man-made aerosol particles. A further analysis of this size distribution revealed that the peaks could not be explained by multiple charging. This data demonstrated the NPS500's ability to provide information about an aerosol under test that would have been missed if the Reference Instrument was used in this experiment.



**Figure 3.** PSD comparison of an atmospheric aerosol challenge. The vertical axis shows number concentration per cm<sup>-3</sup>. The NPS500 shows higher resolution than the Reference Instrument.

A second series of tests was conducted using a Zn and a ZnO aerosol. Figure 4 (on the next page) provides the typical PSD as measured by both the NPS500 and Reference Instrument. Two or three distinct modes were normally observed in the tests. These represent various mechanisms of nanoparticle formation, as well as the variation in chemical composition of the particle, e.g., Zn or ZnO (confirmed with TEM data). The data shows three

peaks at 35 nm, 54 nm and 90 nm. The Reference Instrument did not resolve these peaks. Again, the results confirmed that the higher resolution NPS500 allows characteristics of a sample aerosol to be seen that other commercially-available instruments would miss altogether.



**Figure 4.** PSD comparison for a ZnO challenge. The vertical axis shows number concentration per  $\text{cm}^{-3}$ . Three distinct modes are observed in the test and are clearly resolved better by the NPS500.

## NPS500 Resolution

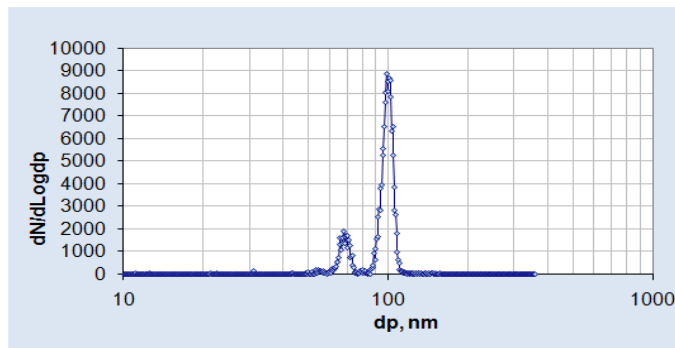
Instrument resolution may be the single most important performance characteristic of high-sensitivity aerosol spectrometers. Each distinctive mode or feature in an aerosol particle size distribution, as well as their combination, can identify a unique signature or fingerprint of the aerosol nature and its evolution. The NPS500 provides resolution that is equivalent to or generally exceeds other commercially-available instruments.

The resolution of NPS500 was evaluated by measuring monodisperse challenges of PSL spheres and NaCl aerosols generated with a nebulizer and fractionated with a DMA (upstream of the NPS500). The results are shown in Figure 5 and Figure 6.

**Note:** The term  $\sigma_g$  is used in this section as an indication of instrument resolution (geometric standard deviation). Technically, resolution as described here is a simplified figure of merit. The data presented using  $\sigma_g$  takes into account the ratio of  $q_a / q_{sh}$ . A full theoretical treatment of particle mobility is beyond the scope of this of article.

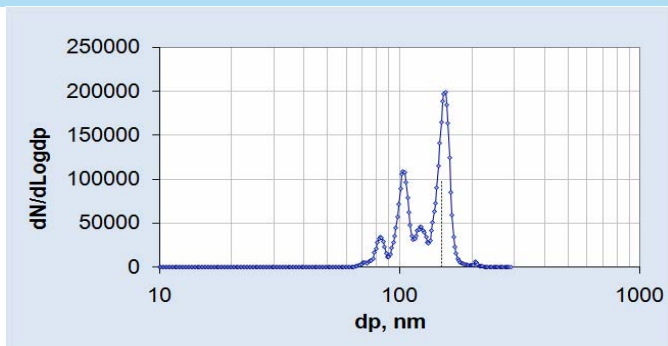
The data in Figure 5 was generated by classifying a 100 nm PSL sphere with a DMA upstream of the NPS500. This DMA included a  $^{85}\text{Kr}$  neutralizer used intentionally to generate multiple charges on the aerosol under test. The monodisperse output from this DMA served as the input for the NPS500. There are two distinct peaks in Figure 5. The primary peak at 100 nm is simply the output of the first DMA being properly sized by the NPS500. The small secondary peak at 68 nm comes from the singly-charged 100 nm particles coming from the upstream DMA that

have accepted a second single positive charge from the NPS500. Figure 5 clearly demonstrates how well the NPS500 can resolve a monodisperse distribution that may have some accompanying structure or modes to it. The  $\sigma_g$  for both the main peak and the secondary peak is 4.7%, which is very close to the theoretical limit determined in the modeling of the NPS500 DMA.



**Figure 5.** Example of resolution obtained with the NPS500 for a 100 nm PSL particle challenge. The double-charged particle peak is at 68 nm. This peak appears from the NPS500 adding a single charge to a small percentage of the 100 nm classified particles from the upstream DMA.

A more structured size distribution measurement is shown in Figure 6 on the next page. Here, the upstream DMA with  $^{85}\text{Kr}$  neutralizer was used to classify a polydisperse aerosol of NaCl at 150 nm. There are secondary modes measured by the NPS500 at 99 nm and 79 nm that are attributed to multiple charging effects. Specifically, these are singly-charged 150 nm particles that have had additional +1 and +2 charges intentionally introduced with the use of an external neutralizer to create the complex distribution for measurement by the NPS500. The excellent resolution is clearly seen in this figure. The small peak observed at 134 nm (just to the left of the main peak) is further evidence of the instrument's ability to resolve minute structure in a complex distribution. This particular peak originated from doubly-charged 234 nm particles produced by the upstream DMA (these particles have the same mobility as 100 nm singly-charged particles). They have accepted a third positive charge prior to being characterized by the NPS500. The result in Figure 6 is a small peak at 118 nm, again, clearly resolved by the NPS500 (the triply-charged 234 nm particle has the equivalent mobility as a singly-charged 118 nm particle). This is an excellent practical demonstration of the science behind equivalent mobility diameter and the effects of multiple charging on aerosols.



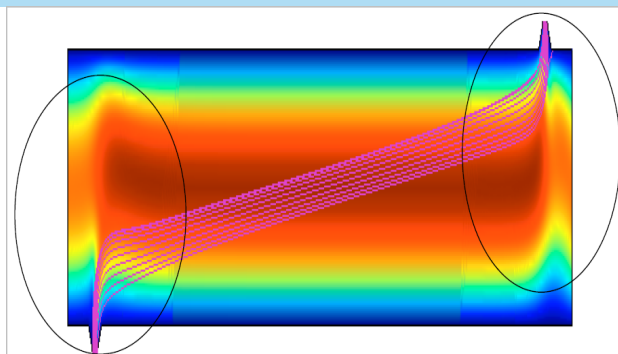
**Figure 6.** Example of a complex aerosol distribution obtained with the NPS500 for a NaCl particle challenge. The structure in the figure is a result of multiple charging effects.

## NPS500 DMA Design Overview

From a general standpoint, the resolution of a DMA or SMPS is determined by the ratio of the aerosol flow rate ( $q_a$ ) to the sheath flow rate ( $q_{sh}$ ). The resolution of most commercially-available instruments based on the common cylindrical shaped separating column is expected to be approximately 10% (if  $q_{sh}/q_a=10$ ). For example, consider an instrument with  $q_a$  of 0.3 lpm and a  $q_{sh}$  of 3 lpm. The resolution of the Reference Instruments used in the testing described in this paper has been proven experimentally to meet this performance level.

The DMA used in the NPS500 is based on novel parallel plate geometry and incorporates a unique aerosol inlet/outlet configuration that together, provides higher resolution than standard commercially-available cylindrical shaped DMAs. The design was based upon modeling that produced an optimal DMA geometry; it yields the highest possible resolution in a miniaturized form factor suitable for use in portable instrumentation.

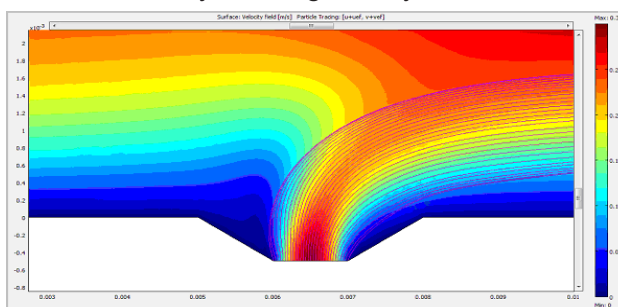
An example of the modeling and aerosol flow trajectories is shown in Figure 7. Here the trajectories are shown for the potential difference of + 360 Volts (top to bottom of view). Regions of red, yellow, green, and blue color represent the air velocity field. The sheath flow mass moves from the left to right at a flow rate of 3 lpm. The aerosol flow mass moves at a rate of 0.3 lpm. The sample aerosol inlet is on the lower left side of the image and the monodisperse aerosol outlet is shown on the top right side of the image. The trajectories of the charged aerosol particles are shown in pink. The gap between the plates is 5 mm and the distance between aerosol inlet-outlet is 110 mm.



**Figure 7.** A side-view profile of the DMA used in the NPS500. The aerosol (sample) flow trajectory is shown in pink. Regions of red, yellow, green, and blue color represent the velocity field profile. The flow velocity is greatest in the region of dark red and gradually decreasing to the lowest region indicated in blue.

The trajectories in the DMA chamber are formed by both an electric field and a velocity field. It is important to recognize that the velocity field is not symmetrical in respect of the inlet and outlet due to the influence of the momentum of the air flow, which is a combination  $q_a$  and  $q_{sh}$ . Careful examination of the area within the ovals in Figure 7 shows the subtle differences of the input and output velocity profiles (represented as an asymmetry in the appearance of the color profiles). These differences are responsible for non-linear aerosol particle trajectories caused by the complex interaction of the air mass velocity and the electric field.

Figure 8 shows a close-up of the aerosol sample inlet trajectory, which is the left-hand side of Figure 7. The two important aspects of the DMA design that have an effect on the resolution are the defocusing and focusing of the aerosol particle trajectories in the chamber. Naneum modeling confirms that with the combination of the completely new design of the parallel plate DMA chamber (including optimized inlet and outlet flow regions) and operating at  $q_a$  and  $q_{sh}$  flow rates of 0.2 lpm and 1.8 lpm, the resulting resolution of the NPS500 is 3.8%. This is considerably (almost 3 times) better than the resolution for a cylindrical geometry DMA.

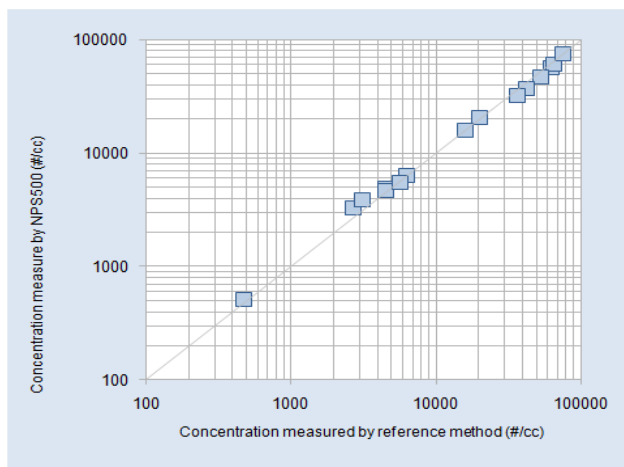


**Figure 8.** A close-up of the aerosol inlet from Figure 7. The air flow trajectory is uniquely controlled by the special design of the inlet and outlet flow geometries to optimize the effects of the electric and velocity fields.

## Particle Concentration Measurement using the NPS500

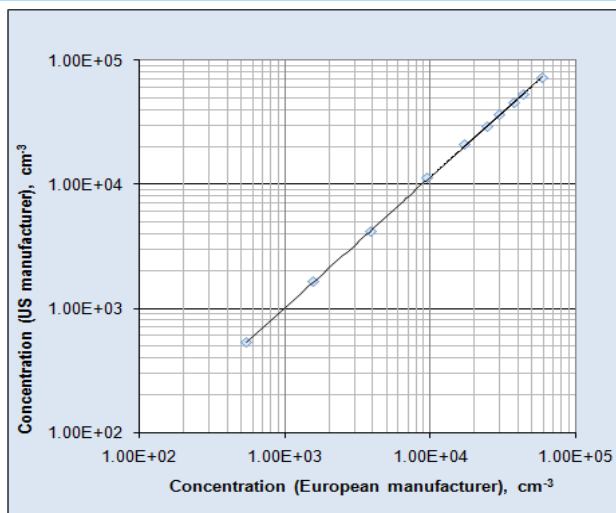
### Comparison of the NPS500 Operating in CPC Mode and a Reference Instrument

A test aerosol of  $\text{Cr}_2\text{O}_3$  nanoparticles was generated and sampled simultaneously with the NPS500 and a Reference Instrument (in this case a popular CPC produced by a US-based manufacturer). The small difference in sample flow rate was compensated for in the results by using a simple correction factor. The test concentration was adjusted to provide 14 measured points between several hundred particles per  $\text{cm}^3$  and  $10^5$  particles per  $\text{cm}^3$ . Figure 9 shows the comparison of the NPS500 particle number concentration result with the Reference Instrument result to be in excellent agreement. The average difference in the number concentration of aerosol particles is less than 10% across the entire measurement range.



**Figure 9.** Comparison of aerosol number concentration data obtained with a NPS500 operating in CPC mode compared to the US-based Reference Instrument.

An additional comparison using the same methodology as in the previous test was made between a popular CPC produced by the US-based manufacturer and a CPC produced by the European-based manufacturer. Figure 10 shows the comparison particle number concentration data. The average difference in the readings across the entire range is less than 20%. The results from both tests prove that the performance of the NPS500 operating in CPC Mode is equivalent to that of the most popular commercially-available CPCs.



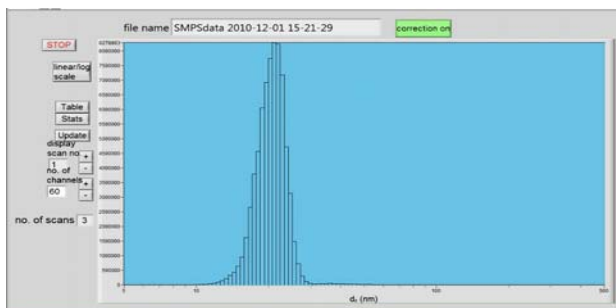
**Figure 10.** Comparison of aerosol number concentration data obtained with Reference CPC instruments from US and European-based manufacturers.

### Maximum Concentration in SMPS Mode

A test aerosol of ZnO particles was generated and sampled by the NPS500 operating in SMPS mode. A measurement range of 10 nm to 100 nm was configured and set to display 60 channels after the measurements were complete. Three, one-minute samples were taken.

Figure 11 shows the resulting PSD for this test. The maximum particle concentration for the NPS500 operating in this mode is  $10^7$  particles per  $\text{cm}^3$ . The peak of the PSD at 20 nm measures a concentration density of  $8.27 \times 10^6$  particles per  $\text{cm}^3$ .

The PSD shows the maximum particle concentration specification will easily be met if the sum of each of the individual channels is combined. In addition, the PSD displays a smooth Gaussian shape as would be expected (in this regime of the generator) based on empirical data using the ZnO source material, the NG100 particle generator, and Reference SMPS Instruments.



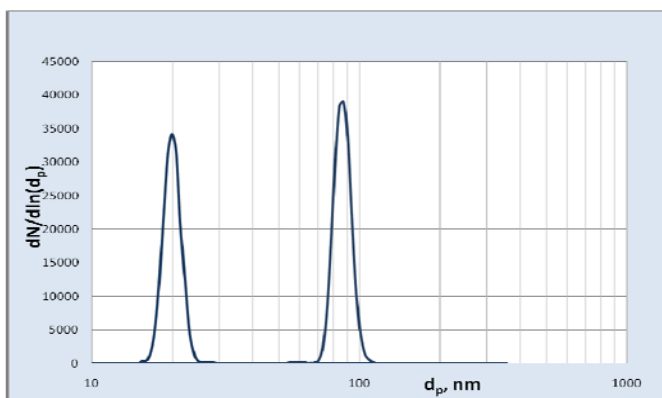
**Figure 11.** The ZnO distribution as measured with the NPS500. Combining the counts from all channels demonstrates that the instrument exceeds the particle concentration specification of  $10^7$  counts per  $\text{cm}^3$ .

## NPS500 Unipolar Corona Charger (UCC)

### Controlling Multiple Charges

Commercially-available DMA and SMPS instruments have traditionally used neutralizers comprised of low-level radioactive materials such as  $^{85}\text{Kr}$ ,  $^{210}\text{Po}$  and  $^{241}\text{Am}$ . The regulatory and safety issues associated with these materials have been problematic for users of these instruments. The NPS500 uses a unique UCC specifically designed to overcome shortcomings of corona chargers for this particular application.

The primary feature of the UCC technology is the ability to produce/charge a sample aerosol with a single elemental charge. Figure 12 provides a typical example of monodisperse aerosol particle size distributions without multiple charges produced by the UCC.

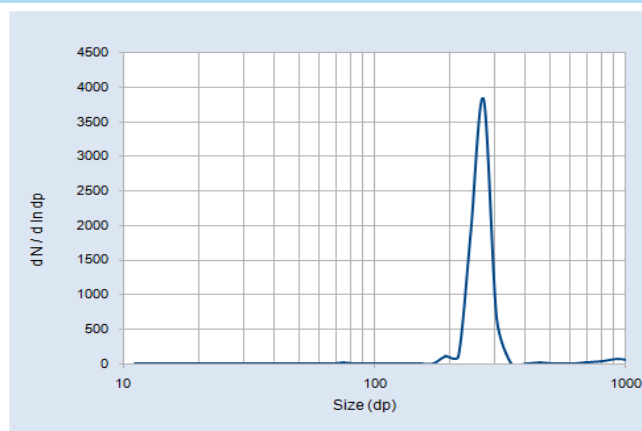


**Figure 12.** An example of two aerosol size distributions obtained with the NPS500 for  $\text{Cr}_2\text{O}_3$  nanoparticles fractionated with the PMC500 Particle Mobility Classifier.

**Note:** Each distribution was measured individually; the two were combined here simply for presentation purposes.

The real challenge for the UCC in maintaining a singly-charged aerosol sample begins when the particles are  $> 100$  nm. The proprietary design of the UCC enables even larger particles to be charged in a way that predominantly singly-charged particles are produced. An example of this is shown in Figure 13. Particles were generated and charged with the UCC. There are practically no multiple charges in the size distribution spectrum shown. This feature is very useful for accurate interpretation of the aerosol size distributions and simplifies the transfer function considerably. On the contrary, conventional bi-polar neutralizers based on radioactive sources produce more particles with multiple charges, which makes determining the relationships between the measured counts and size distributions more complex and can lead to errors; see for example Figure 6.

**Note:** Figures 5 and 6 do not represent the UCC performance in the NPS500; they were obtained in a regime when multiple charging occurs for illustration of the resolution.



**Figure 13.** A monodisperse aerosol size distribution with a peak at 270 nm charged with the UCC and measured with the NPS500.

### Ion/Charge Stability

Two of the traditional drawbacks posed when considering corona chargers for use in scientific instrumentation are 1) poor long-term stability and 2) the need for frequent maintenance or replacement. Both of these considerations have been accounted for and the technical issues resolved with the UCC. The long-term ion/charge stability of the UCC was quantified using an ion counter and the results are shown in Figure 14 on the following page.

### Summary

Testing was performed on the Nano-ID NPS500 Nanoparticle Spectrometer for each of the key specifications associated with commercially-available Scanning Mobility Particle Sizers (SMPS). The testing was not exhaustive in the sense that all commercially-available instruments were evaluated and individually compared with the NPS500 for each individual specification. For the purpose of this study, two like instruments were used for comparison. One was from a US-based manufacturer and the other from a European-based manufacturer.

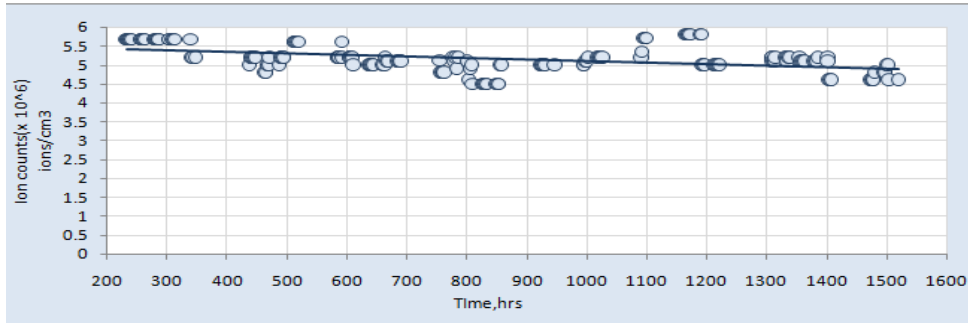
The results provided for comparative testing including sizing accuracy, resolution, counting efficiency, aerosol charging effectiveness, and the maximum measurement aerosol concentration demonstrate that the NPS500 meets or exceeds the performance levels of Reference Instruments from the established manufacturers identified for this study.

Technological innovations that clearly differentiate the NPS500 from traditional SMPS instruments include:

- 3 operating modes – **SMPS Mode** for making PSD measurements, **CPC Mode** for total (cumulative) particle counts and **Single Channel Mode** for total counts at a specific particle size. Modes can be switched and testing started in seconds.
- Self-contained instrument. Portable; weighs 7 kg.

- Unipolar Corona Charger is non-radioactive and requires no special logistics for transportation, use, or storage.
- CPC working fluid is odorless and lasts up to 2,000 hours before the need to re-fill.
- Does not require an external PC to operate.
- On-board data storage for up to 3,000 measurements.

The Nano-ID NPS500 Nanoparticle Spectrometer provides the performance of a laboratory-grade instrument while satisfying general application-based needs that include portability, only minutes to configure and begin gathering data, simple to operate with no special training procedures, and no special licensing, storage, disposal or transportation logistics to manage.



**Figure 14.** The long-term ion concentration produced by the UCC showing ion count stability (precision) of 7% over a period of 1,500 hours.

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## Novel Unipolar Corona Charger for Generating Monodisperse Nano and Sub-Micron Aerosols

Many applications in aerosol science require the production of truly monodisperse aerosols with a selected central peak. These include:

- Instrument calibration
- Metrology
- Inhalation studies
- Filter testing
- Aerosol science
- Atmospheric science and environmental research
- Drug delivery

The most common way of producing a monodisperse aerosol is based on electrical classification with the use of a Differential Mobility Analyzer (DMA). The DMA requires that the aerosol sample must be electrically conditioned (charged or neutralized) prior to classification<sup>1</sup>. There are a variety of established approaches for accomplishing this, and the pros and cons of each have been well documented. There remains, however, a fundamental problem that has yet to be adequately addressed for generating monodisperse aerosols for particle sizes greater than about 60 nm due to the effects of multiple charging. In some applications, these effects can be dealt with by applying theoretical correction factors to the measured data, but this remains an important consideration that can negatively affect the precise measurement and the integrity of the resulting data.

This paper describes a new technology that has proven to substantially decrease, if not eliminate the effects of multiple charges on measured particle size distributions covering the range of 60 nm to 500 nm. The benefit is results that are representative of the sample under test and significantly more reliable than those obtained using arithmetic factors and assumptions.

### Introduction

Commercially-available DMA and Scanning Mobility Particle Sizer (SMPS) instruments have traditionally used neutralizers comprised of low-level radioactive sources such as <sup>85</sup>Kr, <sup>210</sup>Po, and <sup>241</sup>Am. The regulatory, safety, and cost issues associated with these materials are problematic and costly for users of these of these products. Corona chargers are an alternative to neutralizers, but have seen limited commercial adoption in this area because of several undesirable technical characteristics. First, there typically is a trade-off between sufficient charging efficiency for small particles and one that results in excessive multiple charges on larger particles. The next primary concern relates to the need for periodic cleaning or replacement of this component, as it becomes contaminated due to unwanted chemical reactions occurring within its vicinity. Finally, commercial chargers can become contaminated due to intrinsic particle generation from the corona electrode (tip).

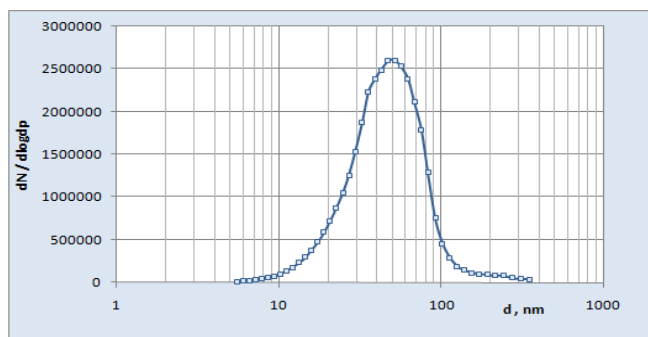
This paper describes a novel Unipolar Corona Charger (UCC) specifically designed to overcome the issues associated with conventional aerosol neutralizers. The primary feature of this UCC is the ability to produce a sample aerosol with a single elemental charge over the range of 60 nm to 500 nm. The novel design inhibits external contamination of the corona tip allowing operation for long periods of time without maintenance or replacement. In addition, intrinsic particle generation from wear of the corona tip has been eliminated.

### Principle of Operation

The UCC works on the principle of corona discharge. A non-uniform electrostatic field is created in a region around the discharge electrode within the corona chamber. The electrons in this region have sufficient energy to knock an electron from the surrounding gas molecules and in the process create positively-charged ions. The aerosol flow is directed through this field and the particles to be characterized are charged due to the random collisions between the ions.

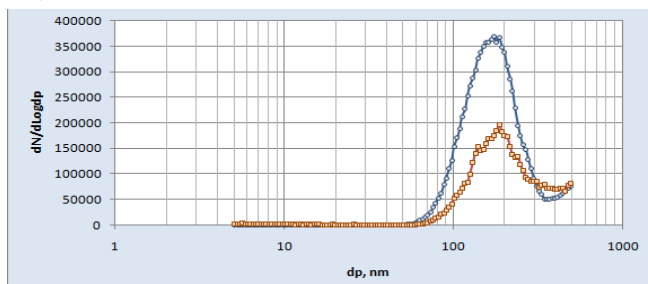
## 1. Generating Polydisperse Aerosol Particle Distributions

Most commercially available aerosol generators produce polydisperse distributions with a geometric standard deviation ( $\sigma_g$ ) ranging from 1.4 to 1.7 (see Figure 1). In this example, the peak of the aerosol number concentration is at 50 nm. The distribution spreads from 7 nm to 300 nm. A sufficiently high concentration of particles is in the wide range from 15 nm to 120 nm (that is, greater than  $260,000 \text{ cm}^{-3}$  or 10% of the maximal concentration of  $2,600,000 \text{ cm}^{-3}$ ).



**Figure 1.** A typical PSD (Particle Size Distribution) of  $\text{Cr}_2\text{O}_3$  particles generated by the Naneum model NG100 particle generator and recorded with the NPS500 Nanoparticle Spectrometer. The concentration is in particles per  $\text{cm}^{-3}$ .

Another example of a polydisperse aerosol is shown in Figure 2 for high and low concentrations of large particles. Here the peaks of the distributions are between 180 nm and 190 nm. The size distributions are spread from about 70 nm to 500 nm and possibly more (measurements were not taken beyond 500 nm).



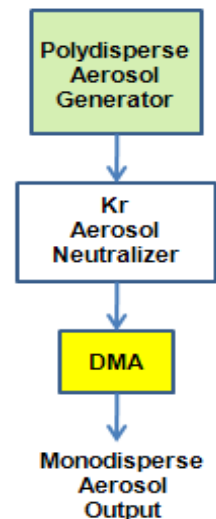
**Figure 2.** A typical PSD of dimethyl sebacate (DMS) particles generated by the Naneum model MG100 particle generator and recorded with the NPS500 Nanoparticle Spectrometer. The concentration is in particles per  $\text{cm}^{-3}$ .

## 2. The Conventional Approach

This section describes the conventional approach used to produce monodisperse aerosols and the effects of multiple charging.

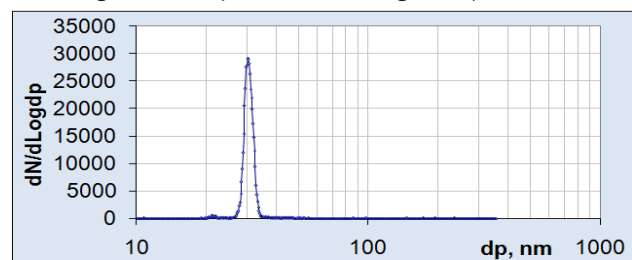
It is desirable to produce monodisperse aerosols for many applications, e.g., instrument calibration.

Usually, a DMA that includes an aerosol neutralizer is used. A simple block diagram of such a set-up is shown in Figure 3.



**Figure 3.** A typical setup for using a DMA and a radioactive source neutralizer to produce monodisperse aerosols.

In this setup, aerosols with a wide size distribution similar to those in Figures 1 and 2 are first produced by an aerosol generator. Next, the polydisperse aerosols are charged by the aerosol neutralizer. Finally the aerosols are directed to a DMA. Aerosol particles in the DMA pass through a strong electric field and are separated according to their electrical mobility. Particles with a certain predetermined mobility are directed to the outlet of the DMA. If a particle entering the DMA has a single charge there is a one to one relationship between the size of the particle and its electrical mobility. Thus, mobility selection enables particles of a certain narrow size range to be selected. An example of a monodisperse distribution obtained with a neutralizer and a DMA is shown in Figure 4. This distribution is much narrower than a distribution recorded directly from a generator (as shown in Figure 1).



**Figure 4.** A typical aerosol PSD obtained with NaCl particles fractionated at 30 nm using the Naneum DMA model PMC500 with an external  $\text{Kr}$  source neutralizer and recorded with the NPS500 Nanoparticle Spectrometer.

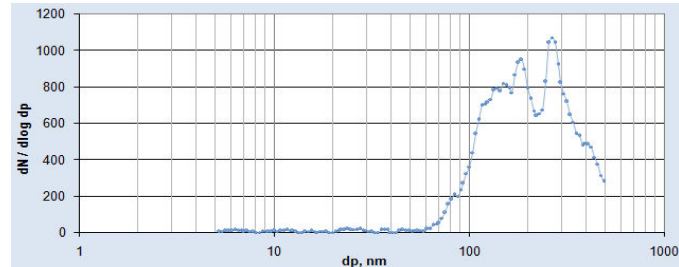
It is well known that monodisperse aerosols similar to the ones in Figure 4 can be produced as described above for mean sizes below 60 nm. For larger particles, however, there is an increasing tendency for larger proportions of particles emerging from the neutralizer to be multiply charged. As there is no longer a direct one-to-one relationship between mobility and size, these multiple charging effects cause very complicated size distributions to be generated, as shown in Figure 5.



**Figure 5.** A typical PSD obtained with NaCl particles fractionated using the Naneum DMA model PMC500 configured for mobility equal to 150 nm for a singly-charged particle. The sample aerosol was charged with a  $K_r$  source and recorded with the NPS500 Nanoparticle Spectrometer neutralizer.

In Figure 5 there are several peaks – at 84, 105, and 116 nm – in addition to the main peak at 150 nm that was selected with the DMA. Thus, the approach that works for small particles does not work for larger particles. The reason for this is that the DMA separates particles according to their electrical mobility and not their size.

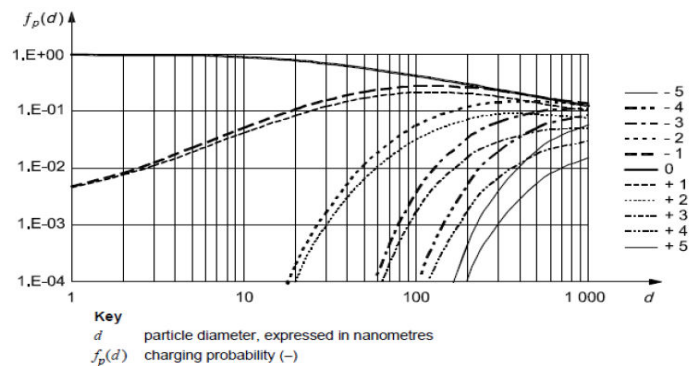
Another example of an aerosol particle size distribution heavily distorted by multiple charging is shown in Figure 6. Here we see an aerosol of DMS similar to one shown in Figure 2. A DMA is now used to fractionate 270 nm particles. The size distribution obtained with an SMPS shows well-resolved peaks at 270 nm and 185 nm, as well as unresolved peaks at 150 nm to 170 nm, and a broad shoulder at approximately 100 nm. The main peak at 270 nm is produced by particles with a single charge. All of the other peaks are produced by multiple charging. This complex size distribution has a 10% spread from 75 nm to more than 500 nm ( $105 \text{ cm}^{-3}$  or 10% of the maximal concentration of  $1,050 \text{ cm}^{-3}$ ). This spread is the same as it was in the original aerosol before fractionating with the DMA. However, the fractionated distribution is more complex and its half-width (spread at 50% of the maximal concentration) is considerably greater than the original size distribution that has been recorded without multiple charging.



**Figure 6.** A DMS aerosol fractionated at 270 nm with the Naneum DMA model PMC500 and neutralized using an external  $K_r$  source.

The reason for a complex size distribution for larger particles lies in the nature of charge distributions when using a neutralizer. A neutralizer produces a defined equilibrium charge distribution in an aerosol population. The fraction of multiple charges is influenced by the size of the particles as shown in Figure 7. This influence is greater for larger particles than for small particles.

Figure 7 presents a theoretical calculation of the charging probability for spherical uniform particles with certain physical properties. In practice, the charging probability may be different depending on the nature of particles. However, it is clear that smaller particles are mainly singularly charged, while larger particles have an increasing proportion of particles with two or more elemental charges. The important conclusion is that a level of multiple-charging is a fundamental consequence of the equilibrium charge distribution of an aerosol neutralizer. This is determined by the charge equilibrium in a particle population.



**Figure 7.** An aerosol particle charge distribution calculated for various particle diameters. The different lines indicate a different number of elemental charges on particles. The diagram is taken from International Standard ISO 15900 (2009-05-15).

The complexity of size distributions obtained with a conventional neutralizer makes this approach to selecting monodisperse size distributions problematic for larger particles, as it generates even

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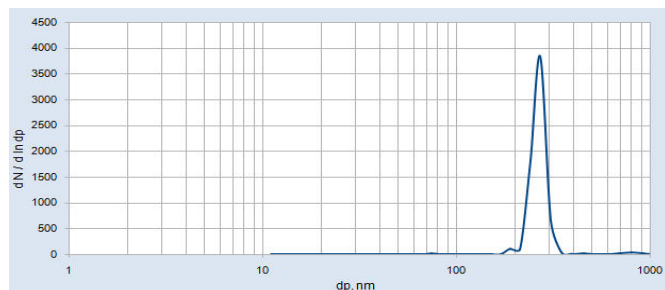
wider distributions than the original ones. Thus, the conventional approach based upon a neutralizer prevents the production of monodisperse aerosols for particles greater than about 100 nm.

### 3. A New Approach using the Naneum C2000 UCC

This section describes a new approach using the Naneum C2000 UCC to produce monodisperse aerosols minimizing the effects of multiple charges.

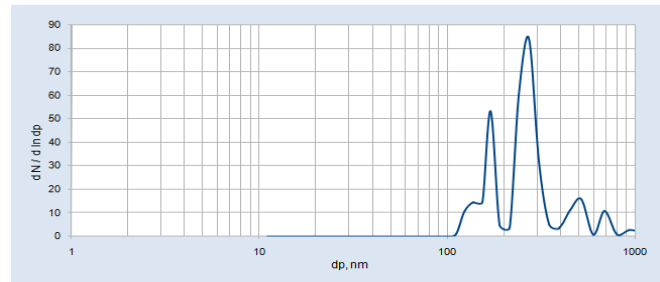
Charging aerosol particles with a radioactive neutralizer inevitably generates multiple charges especially for particles greater than 100 nm. The Naneum C2000 UCC enables aerosol particles of sizes greater than 100 nm to be charged practically without multiple charges. Therefore, *all* of the particles in an aerosol sample are singularly-charged. Monodisperse aerosols with a  $\sigma_g$  of 1.1 or less for particles up to 500 nm can be reliably produced. The width of the fractionated monodisperse aerosol distribution is now primarily influenced only by the DMA resolution, not the multiple-charging distribution, because the broadening effects of multiple charging are all but eliminated by the C2000 UCC.

An example of an aerosol particle size distribution obtained with the C2000 UCC is shown in Figure 8. It is much narrower than a size distribution obtained with a typical neutralizer; compare Figure 8 with Figure 9. One can see a striking difference between the two.



**Figure 8.** Monodisperse aerosol distribution obtained using the Naneum DMA model PMC50 and charged with the C2000 UCC.

Figure 8 shows a monodisperse aerosol distribution obtained with DMS particles fractionated at 270 nm using the Naneum DMA model PMC50 and charged with the C2000 UCC. The polydisperse input aerosol was produced by the Naneum model MG100 particle generator. The size distribution was measured with a commercially available SMPS produced by a European manufacturer.

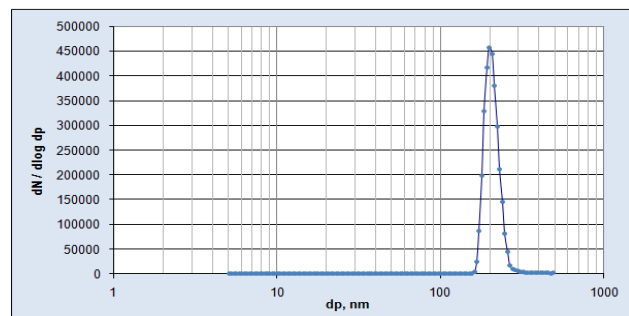


**Figure 9.** PSD when the particles were charged with a commercially available  $K_r$  neutralizer.

Figure 9 shows a particle size distribution produced exactly the same way as in Figure 8, except the particles were charged with a commercially available  $K_r$  neutralizer produced by a US-based manufacturer.

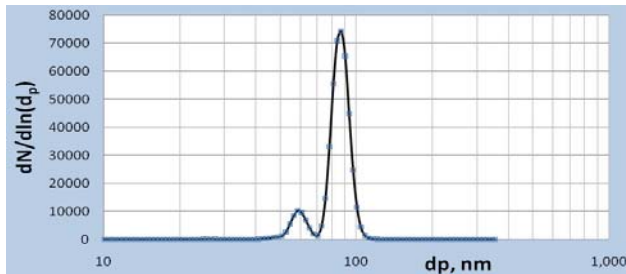
Figures 8 and 9 also illustrate the charging efficiency of the DMS particles by the C2000 UCC is significantly higher than that for the  $K_r$  neutralizer. With the aerosol generating rate held relatively constant for purpose of comparison, the data shows close to a 50 times higher charging rate at 270 nm with the C2000 UCC.

Figure 10 shows a monodisperse distribution obtained with DMS particles fractionated at 200 nm using the Naneum DMA model PMC500 and charged with the C2000 UCC. In this example, the distribution was measured with the Naneum NPS500 Nanoparticle Spectrometer.

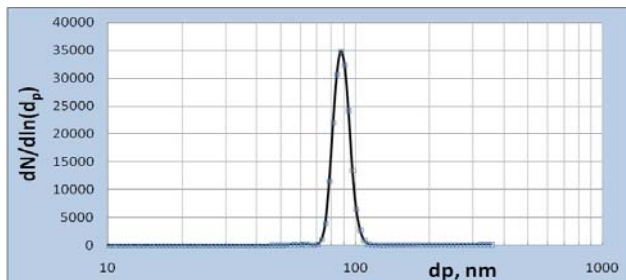


**Figure 10.** Monodisperse aerosols produced over a size range where traditional neutralizers produced unwanted effects caused by multiple charges.

Finally, Figures 11 and 12 on the next page compare the monodisperse output measured by the NPS500 for a  $Cr_2O_3$  aerosol using a neutralizer in Figure 11 and the C2000 in Figure 12.



**Figure 11.** A monodisperse Cr<sub>2</sub>O<sub>3</sub> aerosol using a neutralizer.



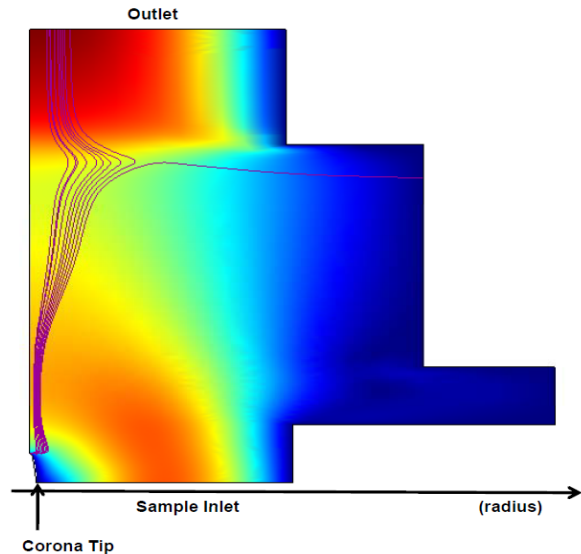
**Figure 12.** A monodisperse Cr<sub>2</sub>O<sub>3</sub> aerosol using the C2000 UCC.

The C2000 UCC design provides a unique possibility to control the level of charging efficiency; high levels of charging are realized for small particles with virtually no multiple charging for larger particles. The most important aspect in achieving this design objective is to develop a system capable of producing monodisperse aerosols in a regime that prevents singly charged particles from acquiring an additional charge. As previously discussed, this cannot be achieved with a neutralizer.

Corona discharge is a combination of complex physical and chemical processes involving a highly unstable plasma. Many chemical reactions occur in the gas phase and on the surface of the tip. Byproducts of these reactions include the promotion of new particles (contamination) resulting from nucleation and the erosion of the corona tip to name a few. Computer modeling of the corona provide insight into some of these complex processes and aid in the research and development of new technology.

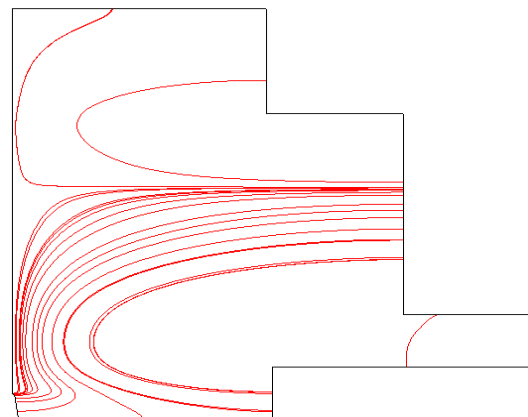
The C2000 UCC utilizes combinations of the electric field configuration, corona tip properties and the velocity flow pattern to achieve optimal charging performance to produce monodisperse nano and sub-micron aerosols. Figure 13 shows the ion trajectories in a corona charger with the applied high voltage equal to 3,000 volts and the corona tip radius of 55 μm. The velocity field is shown in color ranges; dark red (equates to 0.752 m/s) through dark blue (equates to 0 m/s). The ions are generated near the corona tip in the bottom left corner where the high voltage is applied. The air flow moves from

the bottom to the top of the diagram. The ions follow the same path and are shown in magenta color lines.



**Figure 13.** Ion trajectories the C2000 UCC

The left vertical line is the axis of symmetry (axial symmetry). Ions in the diagram move mainly in the center of the corona canal. However, one trajectory indicates ions losses due to discharge onto an internal surface. It is important to minimize the ion losses. However in practice it is nearly impossible to eliminate losses completely. The figure shows that only one trajectory of 10 is finished inside the corona body. This confirms the origin of the high-charging efficiency. Additional computer modeling confirms a complex velocity field and electric potential (shown in Figure 14).

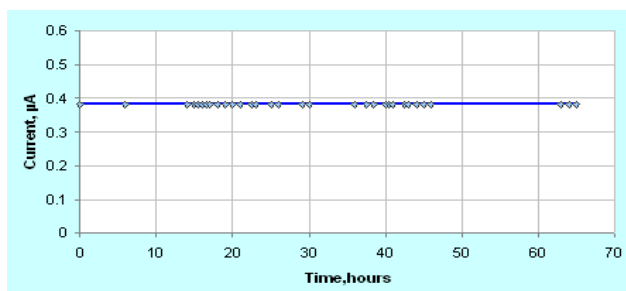


**Figure 14.** Electric strength field line in a corona for an applied high voltage of 3,000 V and a corona tip diameter of 55 μm.

Figure 14 shows that the electric field lines change their direction. In some places they are almost vertical but in other places they are horizontal. This

increases the chances for particles to pick up charges.

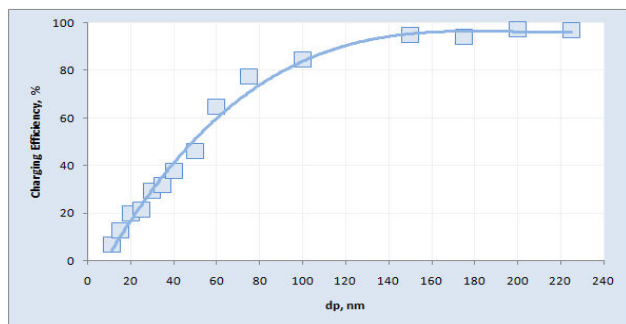
The modeling reveals that the performance of a corona is influenced by its geometry, gas velocity field, and electric field. The shape of the internal space and flow patterns are also crucial for corona stability. All parameters need to be carefully determined to achieve a discharge that generates primarily singularly charged particles. The C2000 UCC current stability is shown in Figure 15.



**Figure 15.** Example of the C2000 UCC current stability.

Charging efficiency is another important property of any aerosol particle charging device. In the case of the C2000 UCC, the charging efficiency has been optimized to produce as many charged particles as possible. An example of the charging efficiency is shown in Figure 16. The charging efficiency initially increases rapidly from about 5% at 10 nm up to 83% at 100 nm. For larger particles ( $d_{ip} > 100$  nm) the charging efficiency is almost constant varying slightly between 83% and 96%.

There is a fundamental difference between a radioactive neutralizer and the C2000 UCC. The charging efficiency of a neutralizer is determined by the equilibrium charge distribution and cannot be easily changed. In contrast, the charging efficiency of the C2000 UCC is easy to control and change depending on the application. This makes it more suitable for charging aerosol particles than neutralizers.



**Figure 16.** The charging efficiency of aerosol particles using the C2000 UCC.

## 4. Practical Considerations for the Reliable Corona Charger Operation

Two of the practical considerations associated with the use of corona chargers in scientific instrumentation are the need for frequent maintenance or replacement of the corona tip, and intrinsic particle generation. Both of these issues have been accounted for and resolved in the C2000 UCC.

### User Maintenance

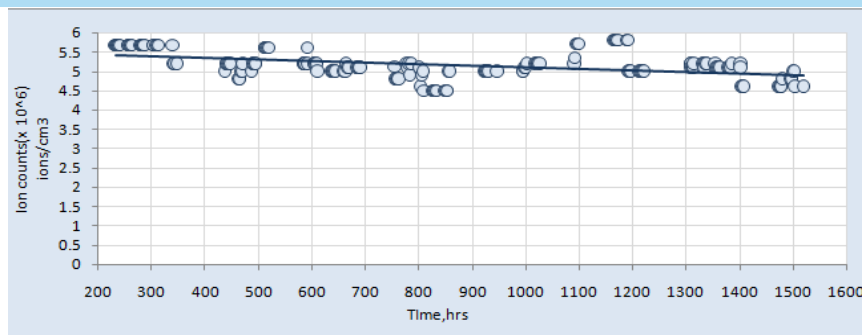
The magnitude and stability of the ion concentration produced by the C2000 UCC is a reliable indicator of its overall condition with respect to its need for maintenance. The unit operates under close-loop control. A variable corona anode voltage is used to hold the corona current to a fixed value (refer to Figure 15). The generated ion concentration will gradually decrease over time as the physical properties of the corona tip change. Allowing for this gradual reduction, long-term testing proves that the C2000 UCC will maintain optimal charging efficiency that virtually eliminates multiple charges on large particles for up to 2,000 hours of use. Preventative maintenance is suggested annually as is common with the calibration of optical particle counters. The long-term ion stability was quantified using an ion counter and the results are shown in Figure 17 on the next page.

### Intrinsic Particle Generation

The C2000 UCC employs a proprietary corona tip design that can operate continuously without generating particles. A simple test was conducted to demonstrate this. An external optical particle counter was used to measure the exhaust from the unit. A zero count filter was placed on the aerosol inlet of the UCC. The measured data shows that 15 particles were generated at 0.3 µm and greater over a 250 hour sample period.

### Conclusion

The C2000 Unipolar Corona Charger allows truly monodisperse nano and sub-micron aerosol to be generated. The primary feature of this technology is the ability to produce a sample aerosol with a single elemental charge over the range of 60 nm to 500 nm. Traditional low-level radioactive neutralizers used in scientific instrumentation such as Differential Mobility Analyzers and Scanning Mobility Analyzers cannot produce the same results. The reason for this is that a neutralizer produces a defined equilibrium charge distribution in an aerosol population. The fraction of multiple charges that are produced is influenced by the size of the particles, and this influence is greater for larger particles than for small particles.



**Figure 17.** The long-term ion concentration produced by C2000 UCC. The data shows ion count stability (precision) of 7% over a period of 1,500 hours.

**References:**

1. ISO 15900:2009 *Determination of particle size distribution – Differential electrical mobility analysis for aerosol particles.*

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