

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 as 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 2%, which compares favorably with similar commercial instruments.

High-Stability Unipolar Corona Charger System (UCC)

Low-level radioactive sources such as ^{85}Kr , ^{210}Po and ^{241}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.

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 rather 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 μm 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 using a laboratory nebulizer and classified with a

commercially-available DMA. An aerosol of Cr_2O_3 particles was generated for all challenges < 50 nm using a Naneum aerosol generator (model NG100) 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) showed excellent agreement.

Table 1

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

Reference Instrument <i>dp, nm</i>	NPS500 <i>dp, nm</i>	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

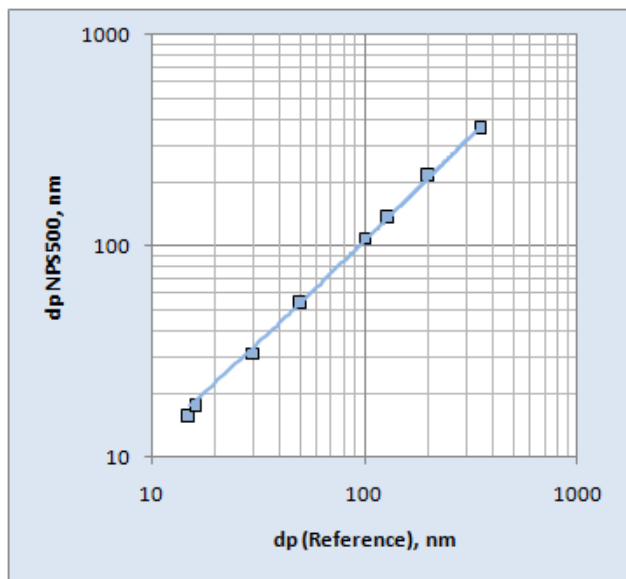


Figure 1. Comparison of NPS500 aerosol particle size data with the Reference Instrument

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

The NPS500 was challenged with a Cr_2O_3 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.

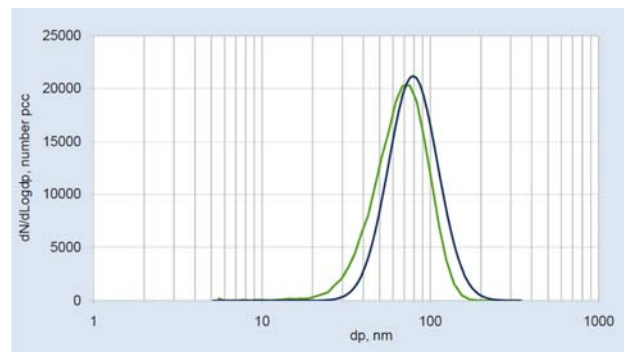


Figure 2. PSD comparison of a Cr_2O_3 challenge. The maximum of the size distribution for NPS500 is 79 nm (Blue) and the Reference Instrument is 73 nm (Green). The vertical axis shows number concentration per cm^{-3} . This data shows sizing agreement between the two instruments is 8%.

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.

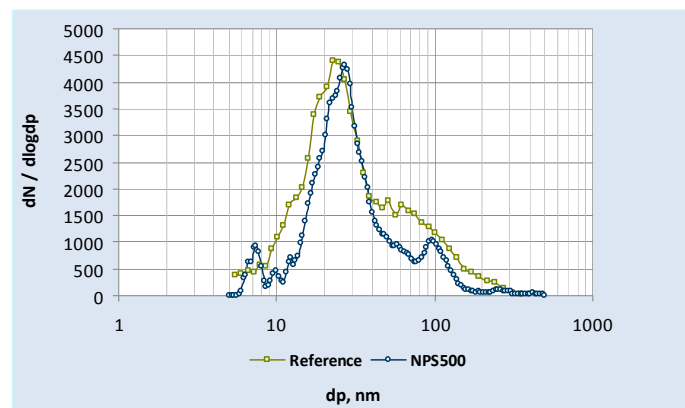


Figure 3. PSD comparison of an atmospheric aerosol challenge. The vertical axis shows number concentration per cm^{-3} . The NPS500 shows higher resolution than the Reference Instrument.

A second series of tests was conducted using a Zn and a ZnO aerosol. A Naneum generator (model NG100) was used to generate the nanoparticle challenge. Figure 4 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.

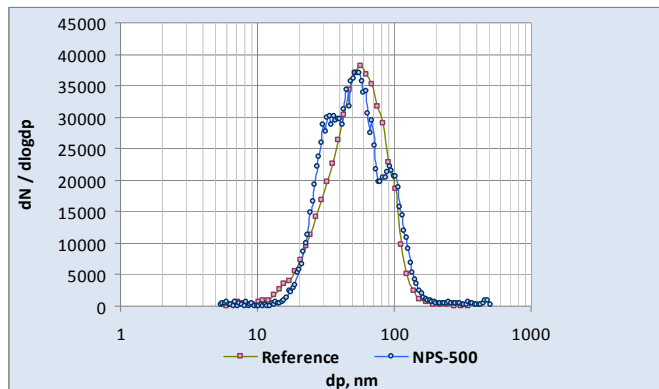


Figure 4. PSD comparison for a ZnO challenge. The vertical axis shows number concentration per cm^{-3} . Three distinct modes are observed in the test and are clearly resolved better by the NPS500.

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 σ_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 σ_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}Kr bi-polar charger used especially to generate multiple charges. 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 σ_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.

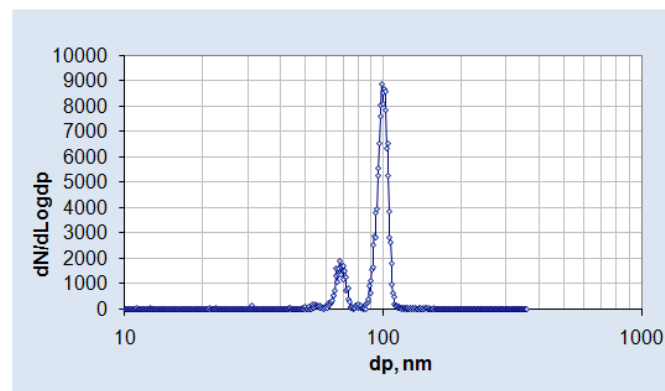


Figure 5. Example of resolution obtained with the NPS500 for a 100 nm PSL particle challenge. The double-charged particle peak is at 68 nm. This peak appears from the NPS500 adding a single charge to a small percentage of the 100 nm classified particles from the upstream DMA.

A more structured size distribution measurement is shown in Figure 6. Here, the upstream DMA with ^{85}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.

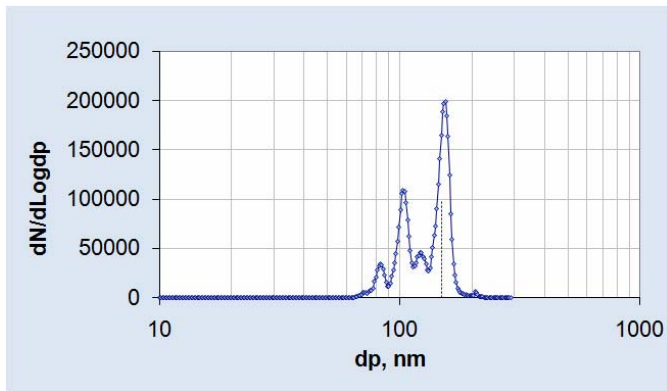


Figure 6. Example of a complex aerosol distribution obtained with the NPS500 for a NaCl particle challenge. The structure in the figure is a result of multiple charging effects.

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 report 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.

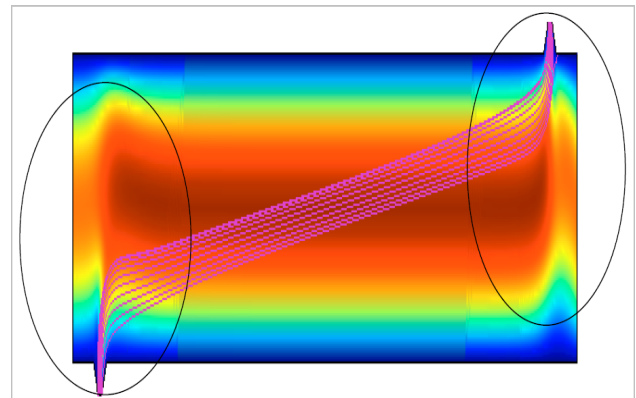


Figure 7. A side-view profile of the DMA used in the NPS500. The aerosol (sample) flow trajectory is shown in pink. Regions of red, yellow, green, and blue color represent the velocity field profile. The flow velocity is greatest in the region of dark red and gradually decreasing to the lowest region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

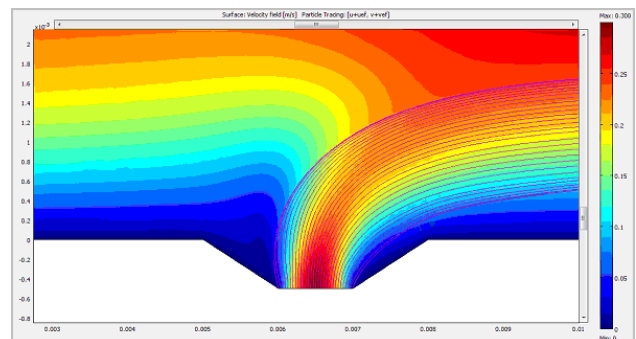


Figure 8. A close-up of the aerosol inlet from Figure 7. The air flow trajectory is uniquely controlled by the special design of the inlet and outlet flow geometries to optimize the effects of the electric and velocity fields.

Particle Concentration Measurement using the NPS500

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

A test aerosol of Cr_2O_3 nanoparticles was generated with a Naneum model NG100 aerosol generator 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 points between several hundred particles per cm^3 and 10^5 particles per 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.

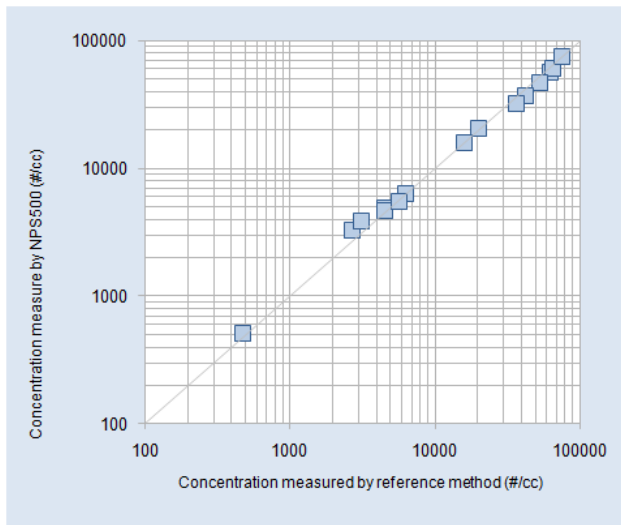


Figure 9. Comparison of aerosol number concentration data obtained with a NPS-500 operating in CPC mode compared to the US-based Reference Instrument.

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.

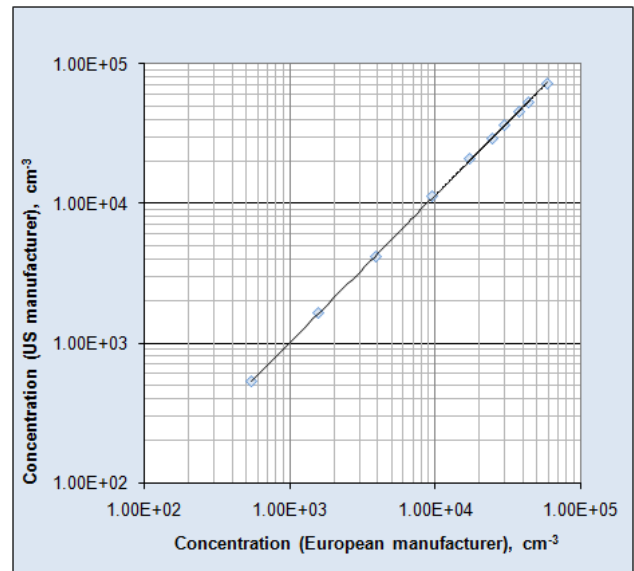


Figure 10. Comparison of aerosol number concentration data obtained with Reference CPC instruments from the US and European-based manufacturers.

Maximum Concentration in SMPS Mode

A test aerosol of ZnO particles was generated with a Naneum model NG100 aerosol generator 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 cm^3 . The peak of the PSD at 20 nm measures a concentration density of 8.27×10^6 particles per 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.

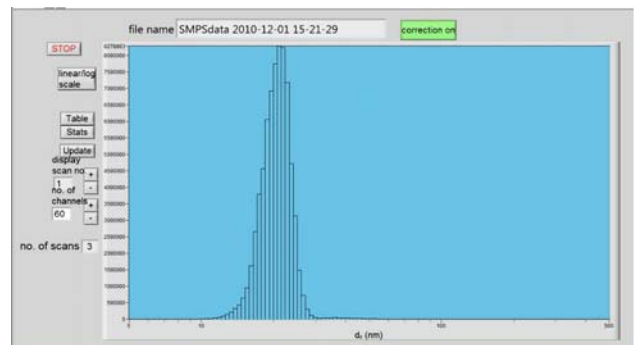


Figure 11. The ZnO distribution as measured with the NPS500. Combining the counts from all channels demonstrates that the instrument exceeds the particle concentration specification of 10^7 counts per cm^3 .

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}Kr , ^{210}Po and ^{241}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.

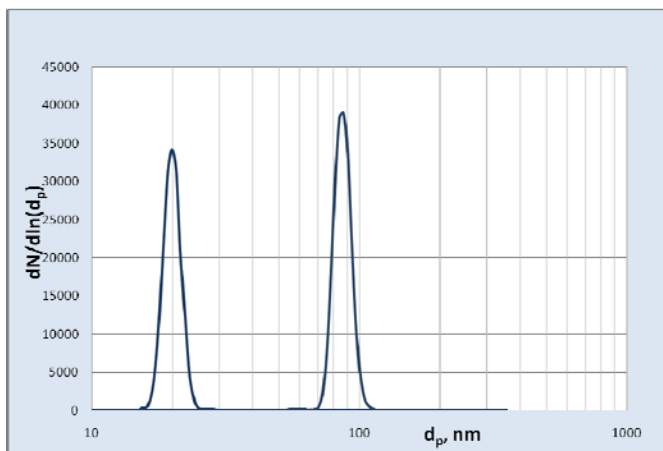


Figure 12. An example of two aerosol size distributions obtained with the NPS500 for Cr_2O_3 nanoparticles fractionated with the PMC500 Particle Mobility Classifier.

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 with a Naneum NG100 generator and charged with a Naneum 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.

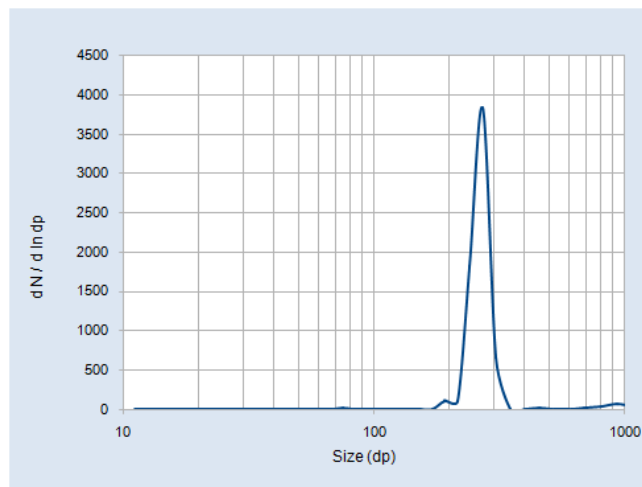


Figure 13. A monodisperse aerosol size distribution with a peak at 270 nm charged with the Naneum UCC and measured with the NPS500.

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.

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 Naneum UCC. The long-term ion/charge stability of the UCC was quantified using an ion counter and the results are shown in Figure 14.

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.

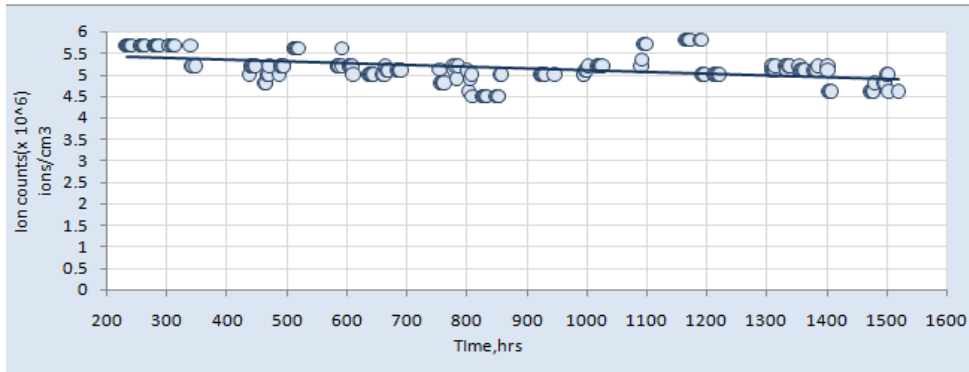


Figure 14. The long-term ion concentration produced by the Naneum UCC showing ion count stability (precision) of 7% over a period of 1,500 hours.

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