

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 classification¹. 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 ⁸⁵Kr, ²¹⁰Po, and ²⁴¹Am. 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 corona technology. 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 (σ_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 $2,600,000 \text{ cm}^{-3}$).

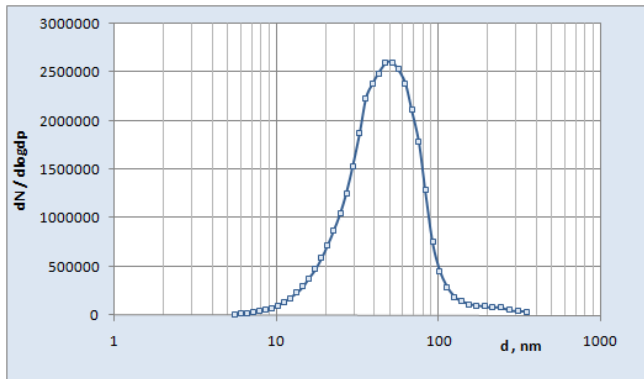


Figure 1. A typical PSD (Particle Size Distribution) of Cr_2O_3 particles generated by the Naneum model NG100 particle generator and recorded with the NPS500 Nanoparticle Spectrometer. The concentration is in particles per cm^{-3} .

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).

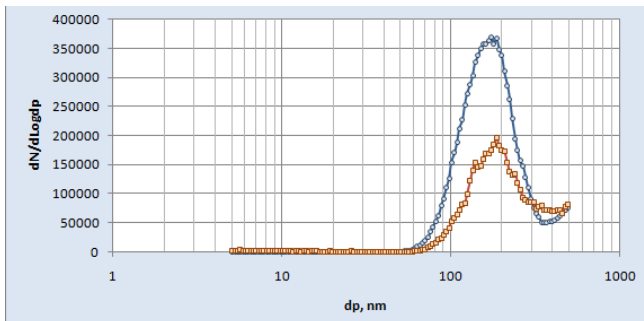


Figure 2. A typical PSD of dimethyl sebacate (DMS) particles generated by the Naneum model MG100 particle generator and recorded with the NPS500 Nanoparticle Spectrometer. The concentration is in particles per cm^{-3} .

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.

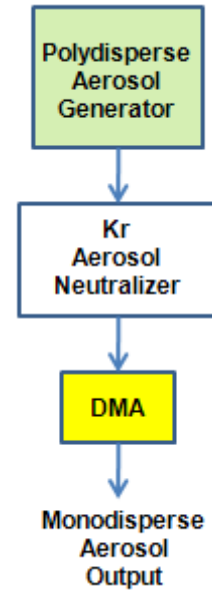


Figure 3. A typical setup for using a DMA and a radioactive source neutralizer to produce monodisperse aerosols.

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).

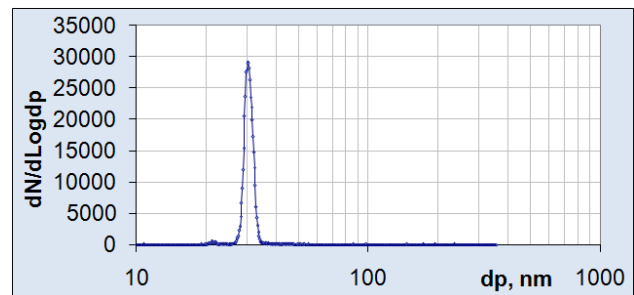


Figure 4. A typical aerosol PSD obtained with NaCl particles fractionated at 30 nm using the Naneum DMA model PMC500 with an external Kr source neutralizer and recorded with the NPS500 Nanoparticle Spectrometer.

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 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.

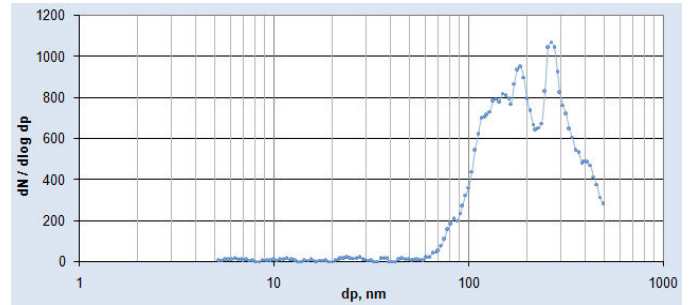


Figure 6. A DMS aerosol fractionated at 270 nm with the Naneum DMA model PMC500 and neutralized using an external K_r source.

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.

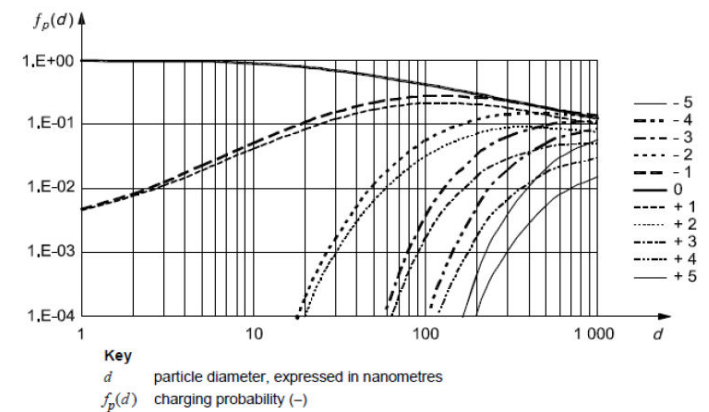


Figure 7. An aerosol particle charge distribution calculated for various particle diameters. The different lines indicate a different number of elemental charges on particles. The diagram is taken from International Standard ISO 15900 (2009-05-15).

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

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 σ_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.

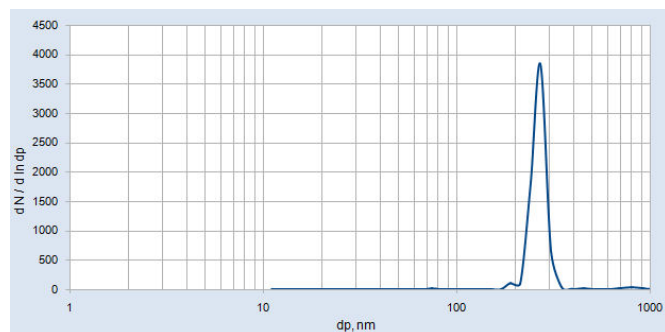


Figure 8. Monodisperse aerosol distribution obtained using the Naneum DMA model PMC50 and charged with the C2000 UCC.

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.

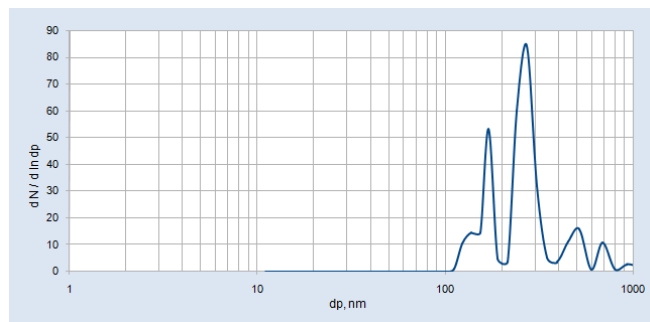


Figure 9. PSD when the particles were charged with a commercially available K_r neutralizer.

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.

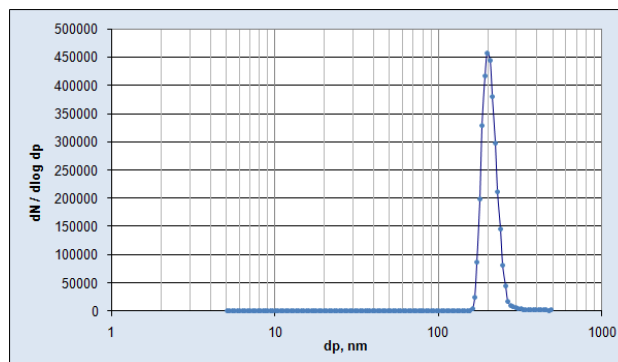


Figure 10. Monodisperse aerosols produced over a size range where traditional neutralizers produced unwanted effects caused by multiple charges.

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.

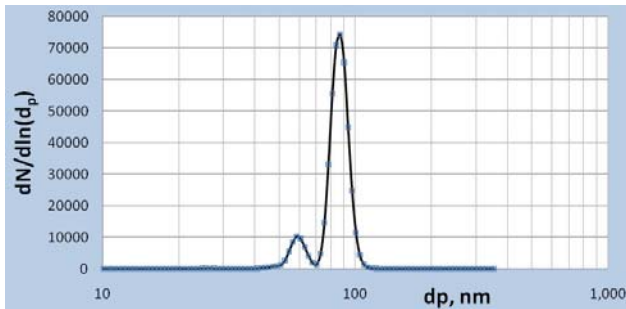


Figure 11. A monodisperse Cr_2O_3 aerosol using a neutralizer.

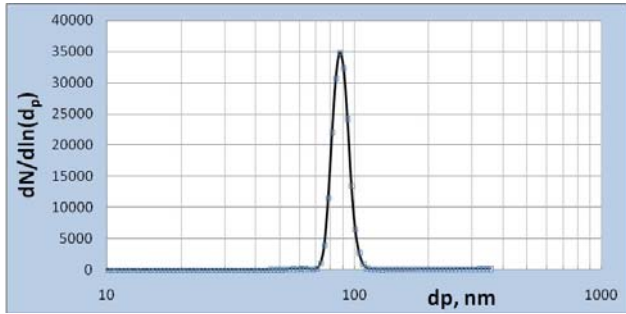


Figure 12. A monodisperse Cr_2O_3 aerosol using the C2000 UCC.

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.

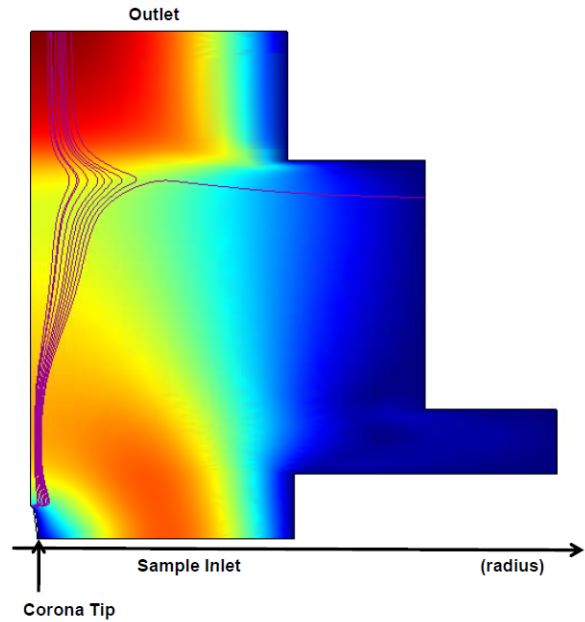


Figure 13. Ion trajectories the C2000 UCC

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).

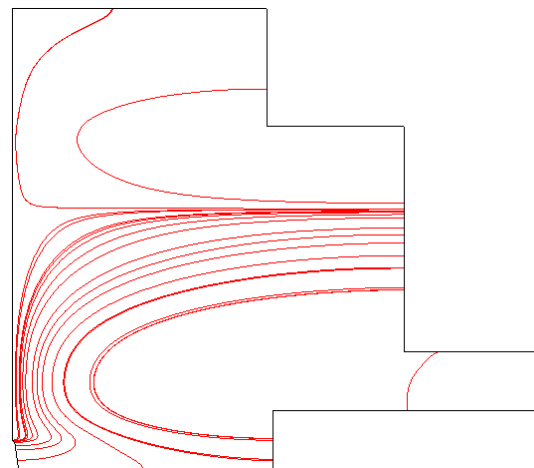


Figure 14. Electric strength field line in a corona for an applied high voltage of 3,000 V and a corona tip diameter of 55 μm .

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.

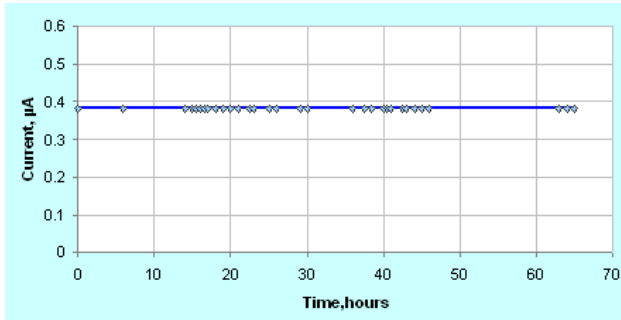


Figure 15. Example of the C2000 UCC current stability.

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.

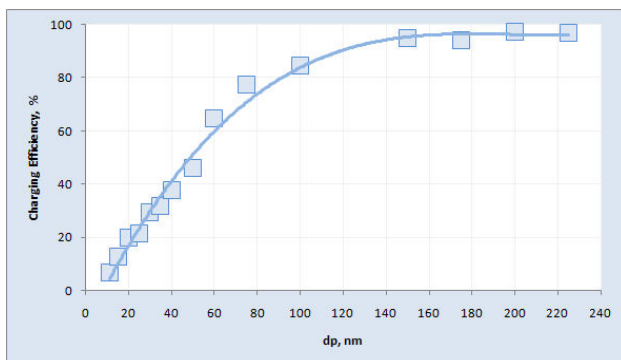


Figure 16. The charging efficiency of aerosol particles using the C2000 UCC.

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.

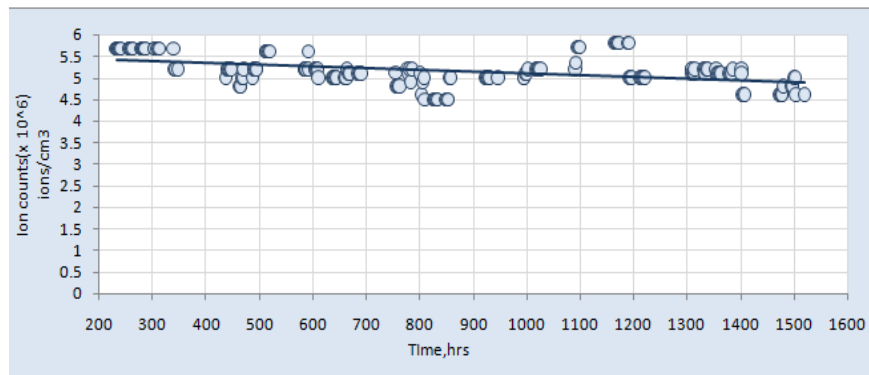


Figure 17. The long-term ion concentration produced by C2000 UCC. The data shows ion count stability (precision) of 7% over a period of 1,500 hours.

References:

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

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