Response of an Electrical Aerosol Detector based on a Corona Jet Charger

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Abstract

This paper describes a new particle instrument, the electrical aerosol detector (EAD) that is based on a corona-jet charger and an aerosol electrometer. In the device, ions are generated in particle free air by a positive corona discharge through an orifice, forming a turbulent jet of unipolar ions in a mixing chamber. A stream of aerosol enters the same chamber in a second jet opposing the ion jet, and the turbulent mixing of these two jets promotes efficient transfer of charge to the incoming aerosol particles. The charged aerosol and the remaining ions enter a coaxial precipitator where a weak electric field removes the highly mobile ions while allowing the aerosol particles to pass through. Finally, the charged aerosol particles are collected on a conductive filter connected to the input of a sensitive, thermally-stabilized electrometer. The electrometer output is measured and the values are displayed and made available externally via a serial interface.

The EAD response is evaluated with monodisperse aerosols as a function of particle diameter and concentration. From this preliminary study the overall instrument response is determined linear in the range from 10 to 500 nm. Comparisons were also made of the EAD response to the first moment response from SMPS data on combustion aerosols.

Introduction

The combination of an aerosol filter and a sensitive electrometer, known as the aerosol electrometer, is used to measure charged aerosol. The charged particles in a gas flow are collected by the filter, resulting in a current whose magnitude is proportional to the mean charge per particle, the particle concentration, and the volumetric flow rate.

TSI's Model 3068A Aerosol Electrometer has been used for many years to measure the total net charge on aerosol particles from 0.002 to 5 micrometers. When paired with a TSI Electrostatic Classifier, the aerosol electrometer measures the number concentration of monodisperse aerosol. This system is called a "primary" method of generating precisely known monodisperse aerosols because it depends only on basic measurements such as flow rate, voltage, and amperage. This configuration has been used primarily for calibrating and testing other particle instruments like CPC's.

It is advantageous to provide a well characterized way of charging the sample aerosol by a known amount. This has been done in various ways, using ionizing

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radiation or ions generated in a corona discharge. The overall response of such a device is determined by the mean charge per particle versus particle diameter.

The "corona-jet" charger (Medved et al., 2000) differs in several aspects from other corona-based chargers. The chamber where the corona discharge generates ions is isolated from a field-free mixing chamber where the aerosol is exposed to the ions. An air flow transfers the ions into the mixing chamber, and an opposing aerosol flow promotes mixing of the aerosol and the ions. The design creates turbulent conditions in the mixing chamber. Since the aerosol-ion mixture is not subjected to an applied electric field, the only field being a negligible one from the ion space charge itself. Hence, diffusion charging may be shifted somewhat compared with other chargers in which even a small field is applied.

Instrument Design

Charger

Ions are generated at a Pt needle tip located in a small ion-generation chamber which is connected to a mixing chamber via an orifice. A 1 liter/min flow of filtered air passes through the orifice, sweeping ions through and forming a jet. Turbulence develops in such a jet within a few aperture diameters.

The needle has a voltage with respect to the chamber wall of approximately 2 kV. The current is held at 1 microampere by actively controlling the supply voltage. To retard the deposit formation on the ionizer needle, an active charcoal filter was inserted into the air path prior to the corona chamber. With the charcoal filter in place particle formation on the ionizer needle was insignificant.

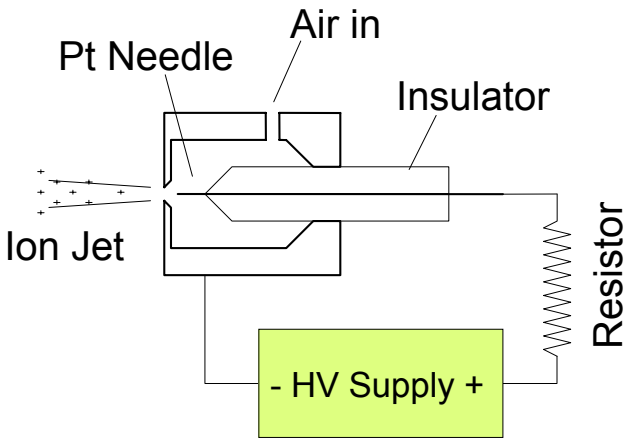


Figure 1 Corona Jet Charger

Mixing Chamber

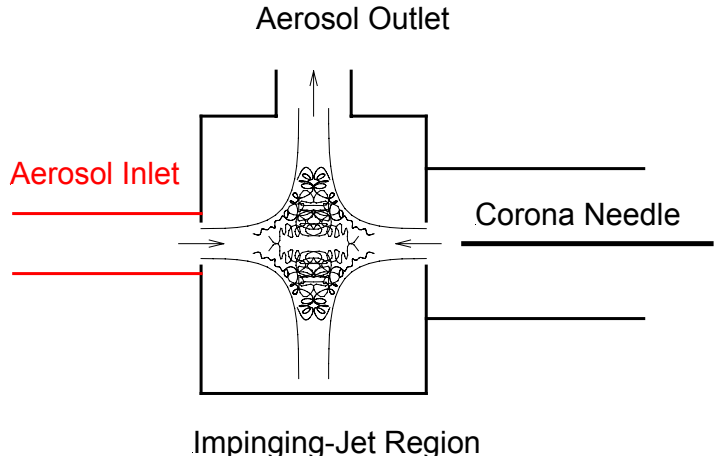


Figure 2 Mixing Chamber

The aerosol sample (1.5 liter/min) enters the mixing chamber through an orifice, likewise forming a turbulent jet. The aerosol and corona jets face each other so the two turbulent jets collide, promoting the mixing of aerosol particles with the ions from the corona.

Ion Trap

On leaving the mixing chamber, the aerosol-ion mixture flows through an ion precipitator or "ion trap" designed to remove the high-mobility corona ions while allowing small charged particles to pass through towards the aerosol electrometer. The ion trap is coaxial, with a central electrode and an applied voltage of 20 volts and the total flow of 2.5 liters/min. The Reynolds' number for the coaxial trap is about 270, suggesting that the turbulent flow entering the trap will be somewhat smoothed before reaching the exit.

Aerosol Electrometer

On leaving the ion precipitator, the aerosol flows to the filter in the aerosol electrometer. The filter is a standard glass-fiber unit, modified by adding a wire mesh to increase the response speed by shortening the conductive path along which the charge must flow to reach the electrometer. System response to a chopped aerosol source was used to verify the improvement provided by the mesh.

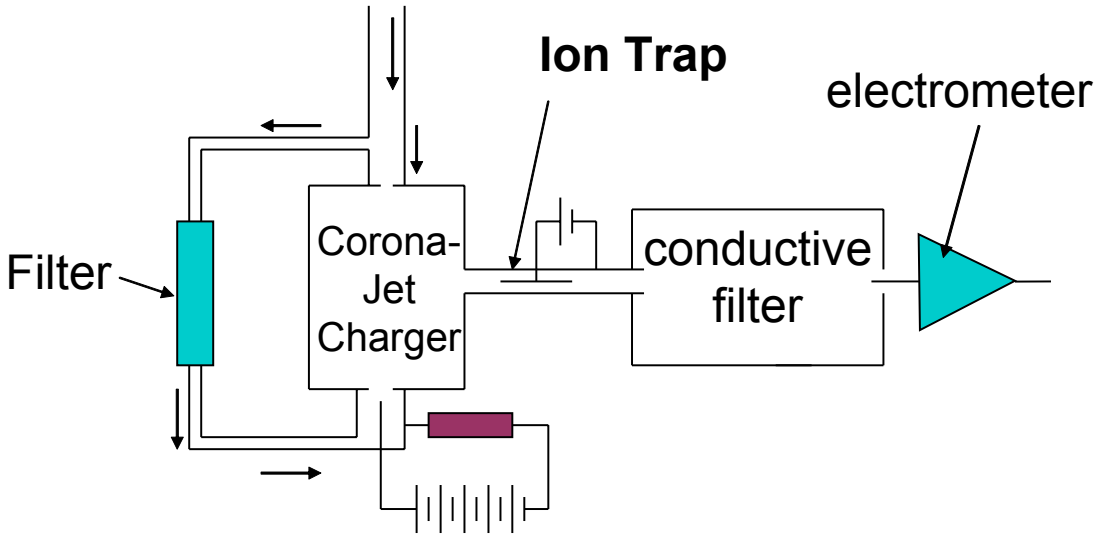
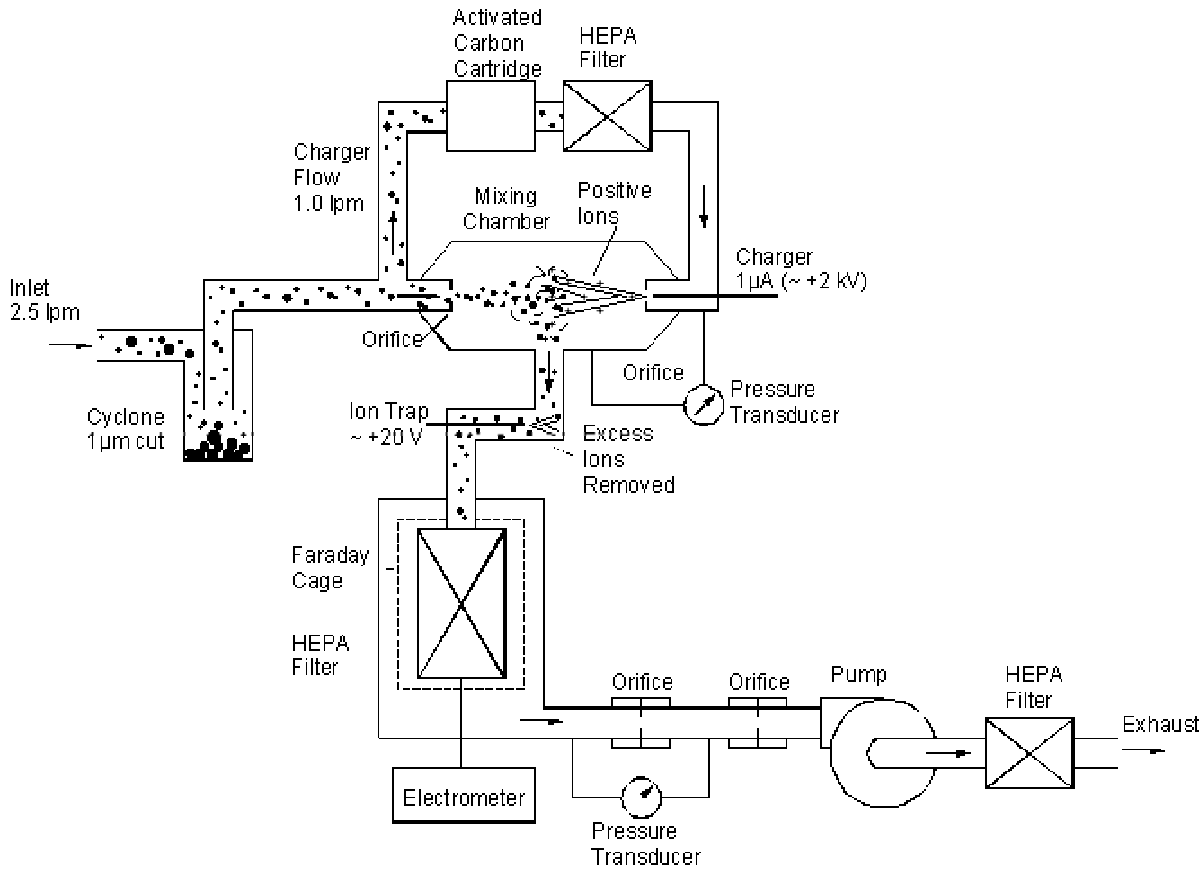


Figure 3 EAD Charger and Ion Trap

Internal connections, packaging and interface

The ion generator, aerosol inlet, mixing chamber, ion trap, filter, and electrometer are integrated into a single aluminum block, with ports for gas flow and flow measurement. A schematic diagram of the interconnections is shown below.

A pump draws air through the system. The pressure drop across an orifice between the electrometer exhaust and the pump inlet is used in a feedback system to maintain the total flow at 2.5 liter/min. A portion (1 liter/min) of the inlet aerosol flow is routed through the active-charcoal and particle-filter cartridges to the corona chamber to generate the ion jet. The jet flow is adjusted by means of a small valve, and is monitored using the pressure drop across the jet orifice. The remainder (1.5 liter/min) of the aerosol flow enters the mixing chamber as the sample.



Characterization of Losses and Instrument Performance

Characterization with Test Aerosols

Measurements were conducted using monodisperse test aerosols to determine the behavior of the charger alone, and also of the complete instrument including losses.

The following methods were used to obtain the monodisperse aerosols needed for the experiments described below. Model numbers refer to TSI Inc. products except where otherwise stated.

(1) Electrically neutral, monodisperse sucrose test aerosols in the range of electrical-mobility diameters (EMD) from 3 to 15 nm were generated using an Electrospray Aerosol Generator (model 3480) spraying solutions of these compounds. The solution concentration was chosen to place the size distribution peak at the desired EMD. A nano-DMA (model 3085) was used to select singly charged particles and reject large and small outliers. Subsequently, the aerosols were passed through a Kr-85 neutralizer (Model 3077) followed by a simple coaxial precipitator to remove all charged particles.

(2) NaCl aerosols between 10 and 400 nm EMD were generated by spraying solutions in a collision nebulizer, followed by the Kr-85 neutralizer and a long DMA (model 3081) to select a narrow EMD distribution from the broad spectrum produced by the nebulizer. The charged aerosol from the DMA outlet was passed through a

second Kr-85 neutralizer, followed by the coaxial precipitator. The DMA selects for mobility only, and the broad distribution from the NaCl nebulizer means that the DMA output will include some physically larger particles of the same electrical mobility carrying more than one charge. An attempt was made to correct for this based on the NaCl distributions measured when generating these aerosols.

(3) Aerosols between 300 and 1000 nm EMD were generated by a Condensation Monodisperse Aerosol Generator (model 3745), passed through the Kr-85 neutralizer and a long DMA (model 3081), and finally through a second Kr-85 neutralizer. The precipitator could not fully eliminate singly-charged particles at the top of this range, and was omitted.

(4) Polystyrene Latex (PSL) particle size standards in ultrapure water were dispersed using an electrospray aerosol generator with a modified capillary to generate aerosols from 500 to 1,000 nm EMD. To obtain sufficient concentrations the use of a DMA was avoided. Instead a series of diffusion screens was used to remove the small residue particles resulting from "empty" droplets.

A prototype charger of the same dimensions as the EAD charger was characterized using somewhat different flow rates than those used in the EAD (Medved, A. et al. 2000). For this characterization, the corona flow was 0.3 liter/min and the aerosol flow was 1.2 liter/min.

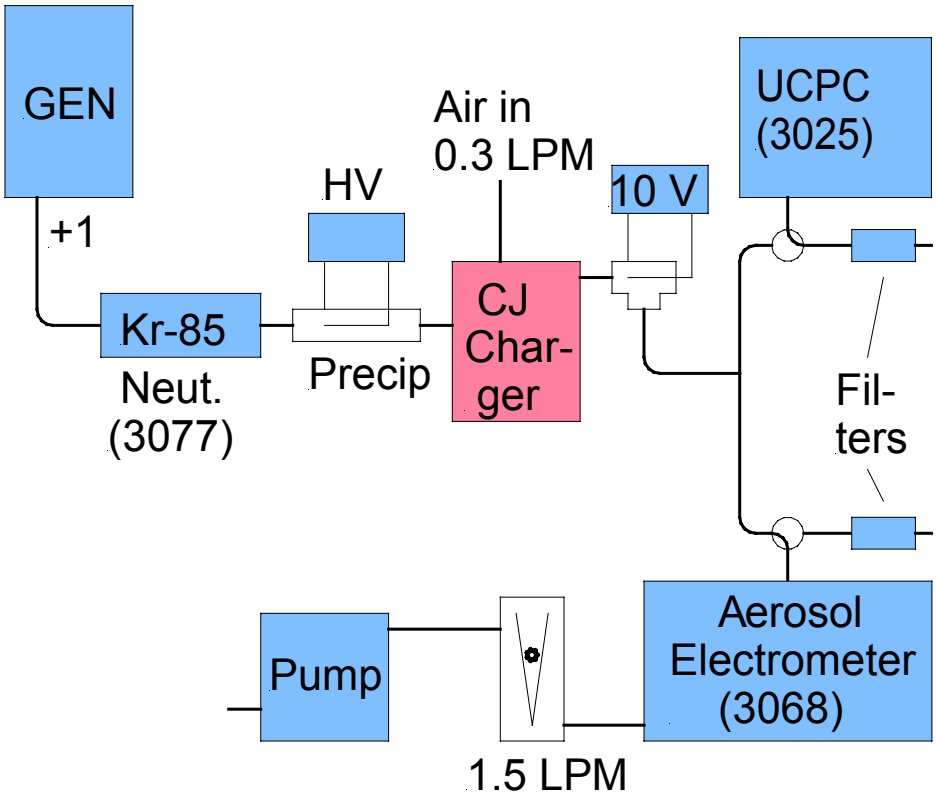


Figure 4 Instrument for measurement of Mean Charge per Particle of Charger

Figure 6 shows the setup used to determine the mean charge per particle at the outlet of the charger, as a function of particle EMD. Monodisperse uncharged aerosol passes through the charger. The aerosol concentration in the output stream is measured by a UCPC (model 3025A), and the total aerosol current is measured

by a Aerosol Electrometer (model 3068A). The two instruments were connected alternately to the charger outlet. Care was taken to provide equal tubing lengths and equal sample flows to the two alternate detectors.

For electrometer current I [amperes], particle concentration N [particles per cm^3] and a flow rate Q [cm^3/sec], the mean number of electronic elementary charges per particle is

$$n_{charger} = \left(\frac{I}{eNQ} \right)$$

Figure 7 shows how $n_{charger}$ depends on the test aerosol EMD. The measured dependence was fitted consistently over the range from 10 to 1000 nm by a single-coefficient linear expression

$$n_{charger}(D) = \left(\frac{n_0}{D_0} \right) D$$

With the coefficient (n_0/D_0) = 0.0444 electronic elementary charges per nanometer and a fit correlation coefficient r^2 = 0.9976.

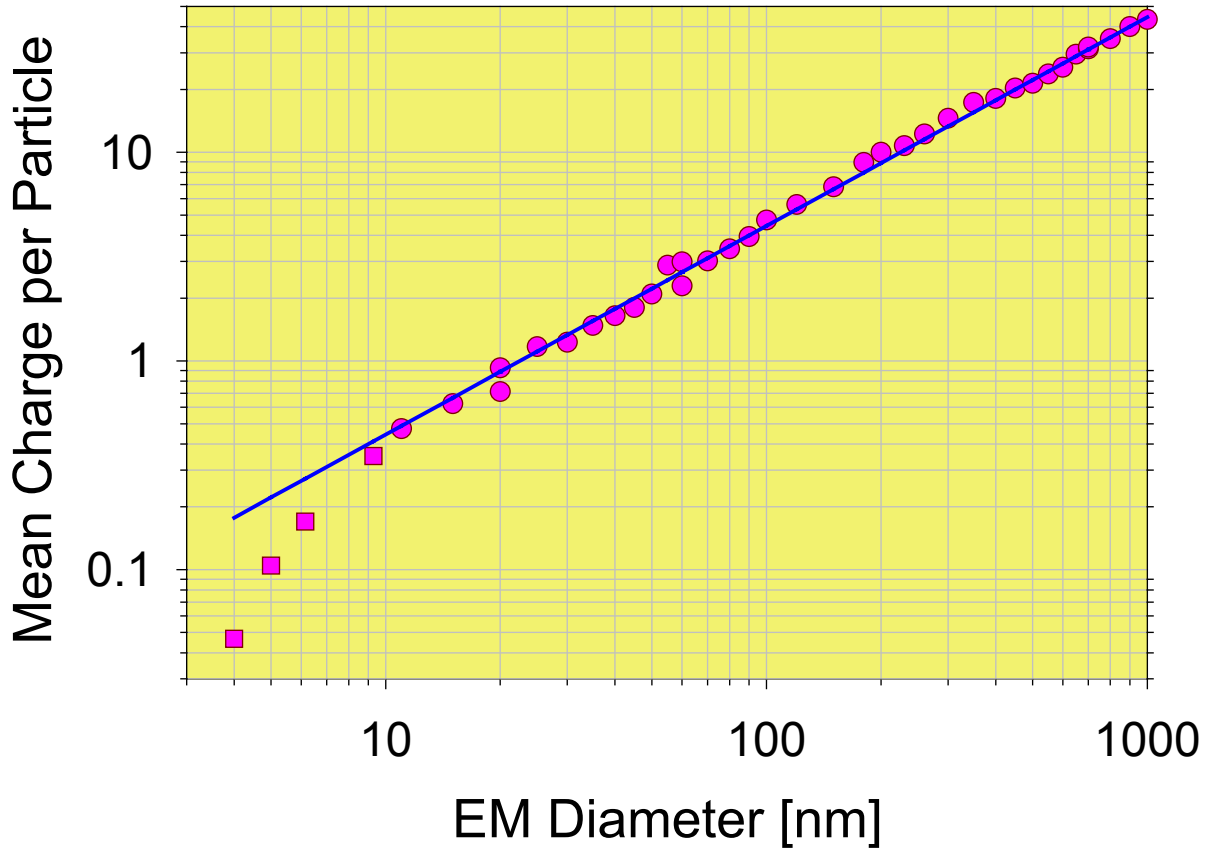


Figure 5 Measured Charge per Particle verses Electrical Mobility Diameter for Charger

The measured response and the fit are shown in Figure 7. The linear response from 10 through 1000 nm was initially surprising in view of the transition expected in passing from the molecular-flow to the continuum regime at particle dimensions of

the order of the mean free path. However, it has been pointed out (Pui, D 1976) that because the "air ions" carrying the charge are clusters, they have a shorter mean free path than air molecules. His estimate of the mean free path of air ions is 14.5 nm. It is likely that the transition from linear to square-law behavior would occur at about that particle size. Later studies have determined values of the mean free path of ions in the range of 13 and 14 nm (Pui, et. all 1988).

Overall response of the complete EAD instrument

In the above study of the fundamental charging law, effects of particle loss were eliminated by taking the ratio of charge to concentration at the charger exit. Size-dependent losses occur in the charger, the electrometer, and the interconnecting internal paths. Thus a quantity of greater practical interest is the dependence of the electrometer current on the particle size and concentration at the instrument inlet. This was studied and the results for the EAD are shown in Figure 8. In the range from 10 to 500 nm, the result is well represented by a power law with the current proportional to the 1.133 ± 0.012 power of the diameter, which may be expressed as

$$y = n_{ref}\left(\frac{d}{d_{ref}}\right)^{\alpha},$$

Hereby, d is the particle EMD, n_{ref} the charge at a reference diameter d_{ref}, and α the exponent 1.133. This result is also supported by recent work that is being done by Heejung Jung and D. Kittelson, but still unpublished (2002). The best power-law fit to the charger prototype data gives α = 1.133(± 0.012), and choosing d_{ref} = 100 nm results in n_{ref} = 3.908.

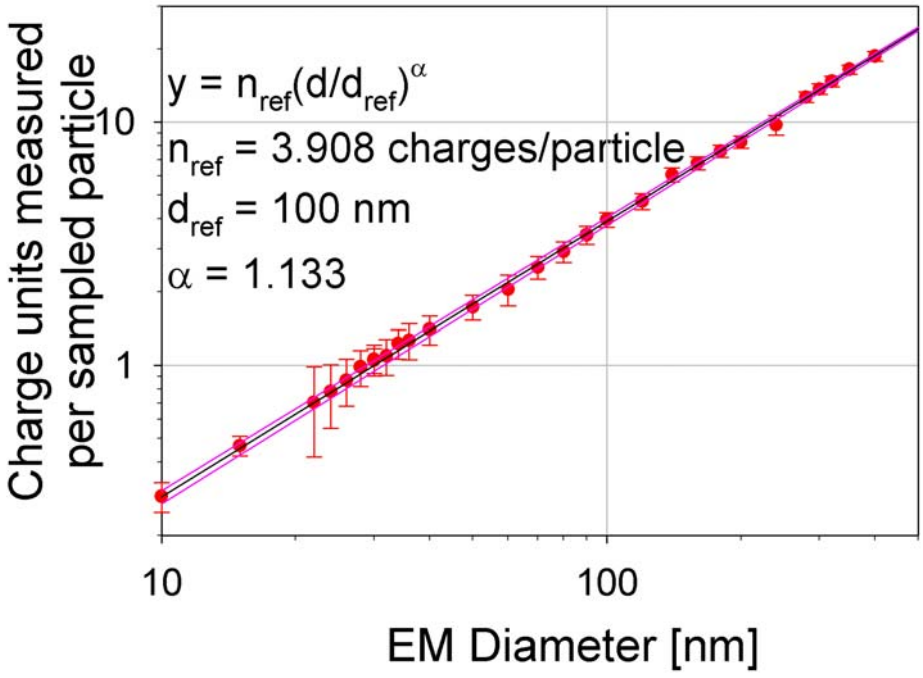


Figure 6 Electrical Aerosol Detector overall response

Response to “Real-world" Aerosols

The EAD has been used on a number of real-world aerosols. A series of measurements was conducted as part of the GRPE Particulate Measuring Program (PMP) Phase 2 in June 2002. During the PMP testing, an EAD, a CPC (model 3022A) and a SMPS system (model 3936L25) were all sampling from the same dilution system (see figure 9).

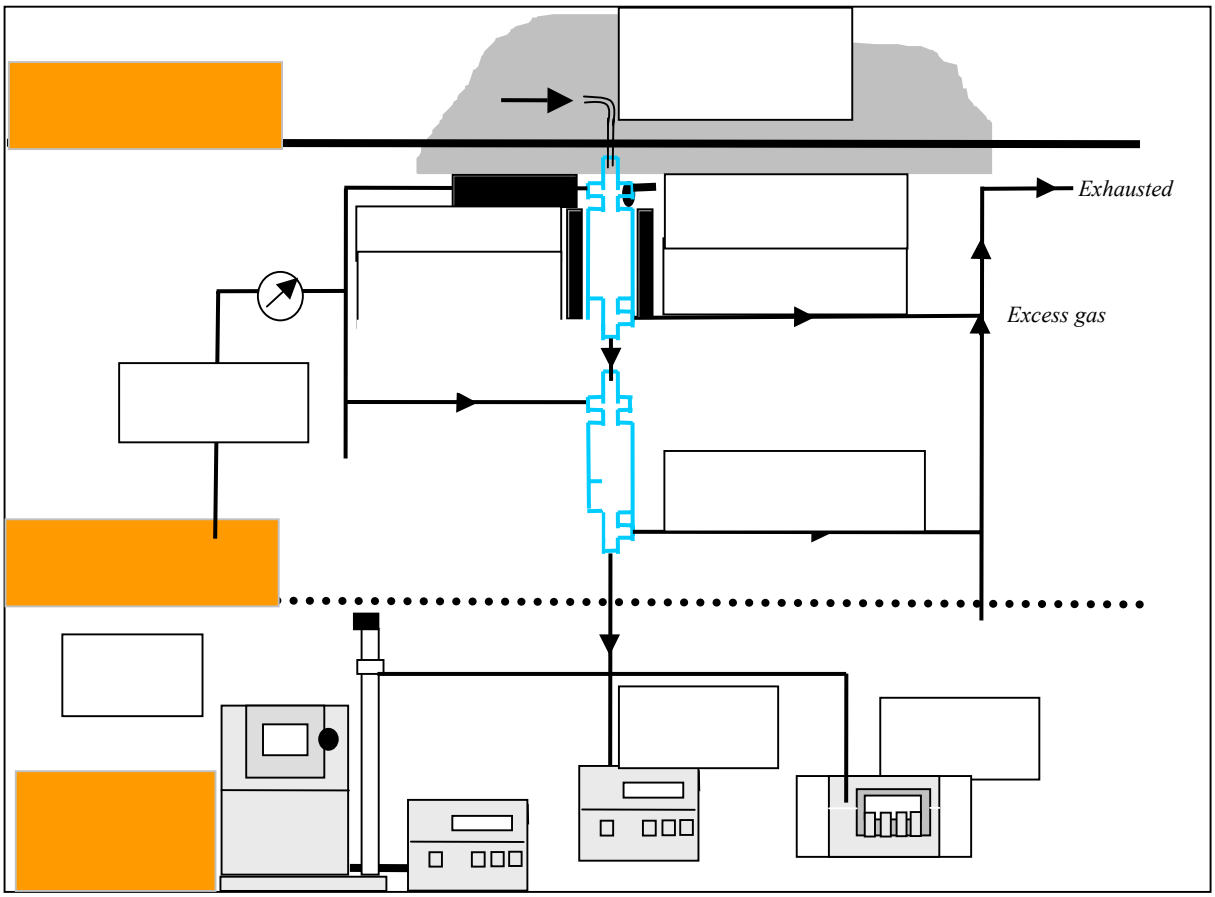


Figure 7 Two-stage Ejector Dilution System used for PMP Phase 2 testing from engine

Due to a minimum scan time of 30 s, the SMPS was not used on transient cycles. However, both the EAD and the CPC measured from an engine dynamometer and from a combustion aerosol soot generator (CAST, Matter Engineering). Figure 10 shows data from the EAD and the CPC (model 3022A) on a portion of one of the transient cycles. Note that the responses are different in magnitude between the two instruments to the change in engine conditions. Due to the fast response of both instruments the large spikes in particle production and particle size change can be detected during engine transients. The EAD was in general more sensitive and its response to transients was superior to that of the CPC.

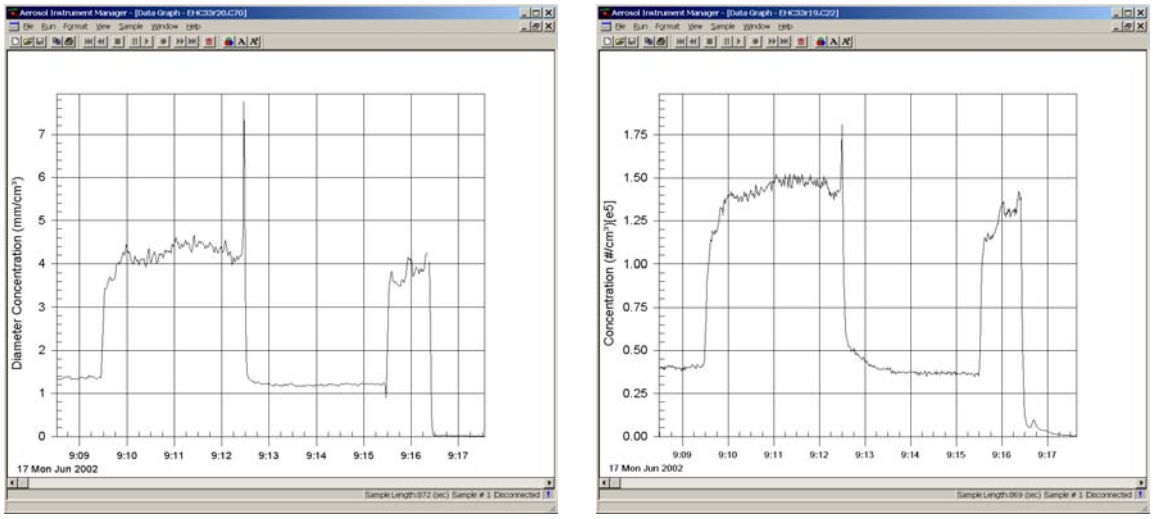


Figure 8 Instrument Response of EAD (left) and TSI model 3022A CPC (right) at GRPE Particulate Measurement Program Phase 2

During steady-state engine conditions within the same PMP test program, all three instruments were able to collect data. Moreover, tests were also done on the CAST generator as part of the PMP testing program. All of these tests were at stable aerosol conditions. An example of test results are shown if figure 11. From that same test 10 minutes of data was taken. For the EAD and the CPC these were 10 subsequent one minute samples. The SMPS took 7 subsequent one minute samples (with 15 second downscans). When the EAD and CPC data are combined information about the diameter of average mean can be determined as follows:

$$D_{Average\ Mean} = \left(\frac{EAD_{lenth}}{CPC_{count}} \right)$$

This can be compared by the mean diameter determined by SMPS statistics. The results are shown if figure 12. The EAD and CPC data points used were one minute averages. The CPC model 3022A has a size range of 7 to 3,000 nm while the SMPS was doing a scan of the range from 11.5 to 437 nm. This difference in size range contributed to the differences between in mean diameters.

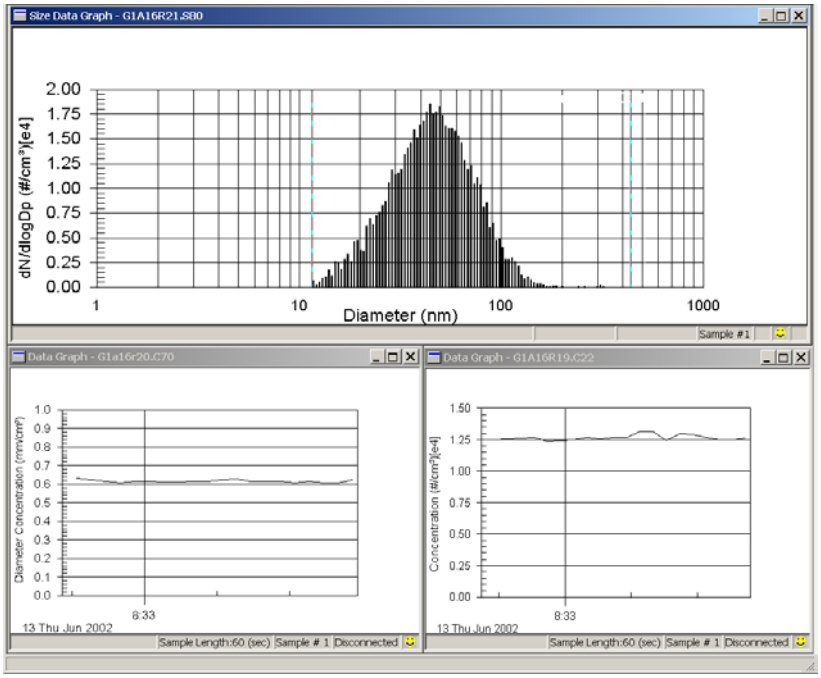


Figure 9 Measurements from CAST aerosol source on SMPS, EAD and CPC

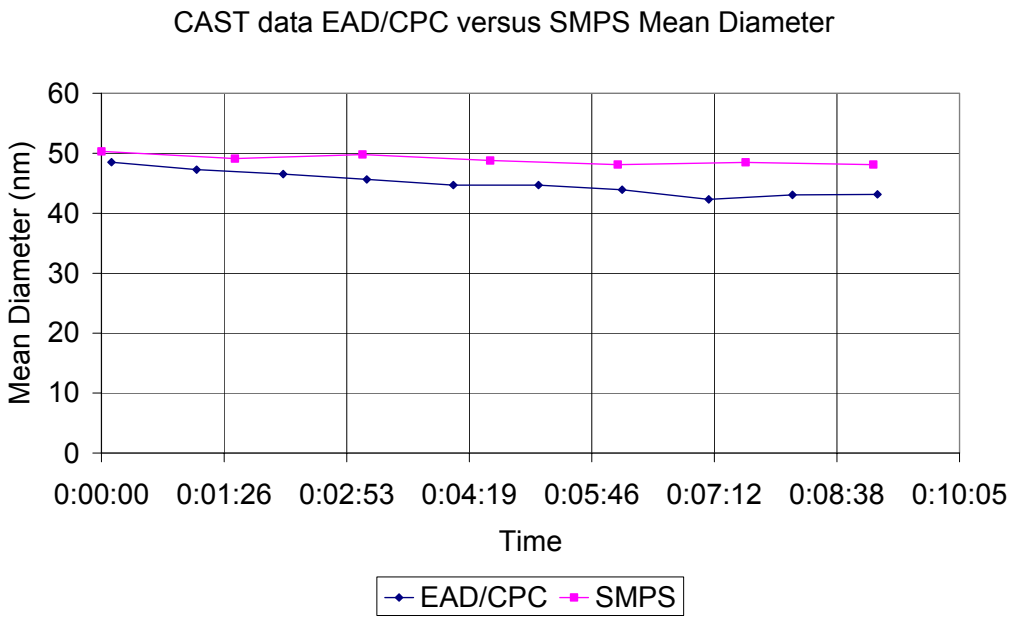


Figure 10 Comparison of EAD/CPC and SMPS Mean Diameters

Another data example is from a diesel train plume measured from the atmospheric monitoring station located on the rooftop of TSI headquarters in Shoreview, MN (USA). When a train passed the building, EAD data showed an immediate response with a large spike. The EAD signal increased by approximately a factor of 80. The total time for the spike and the signal completely returning to background level was about one minute.

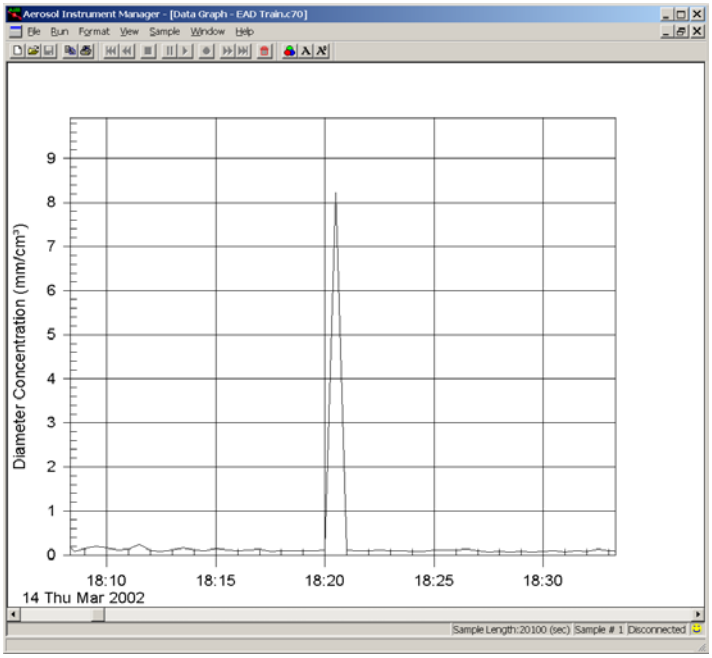


Figure 11 Diesel train passes TSI monitoring station - EAD data

Figure 14 shows aerosol sampled at the same sampling station at TSI, measured simultaneously with an SMPS (model 3936) and two EAD instruments (model 3070A), for a period of 2 and ½ days. The parameter reported here is the first moment's response calculated from the SMPS and the data from the two EAD's. The difference in results is most likely due to the different size ranges (integration

limits for the SMPS calculations) for the different instrument types. Note the excellent agreement between the two EAD's.

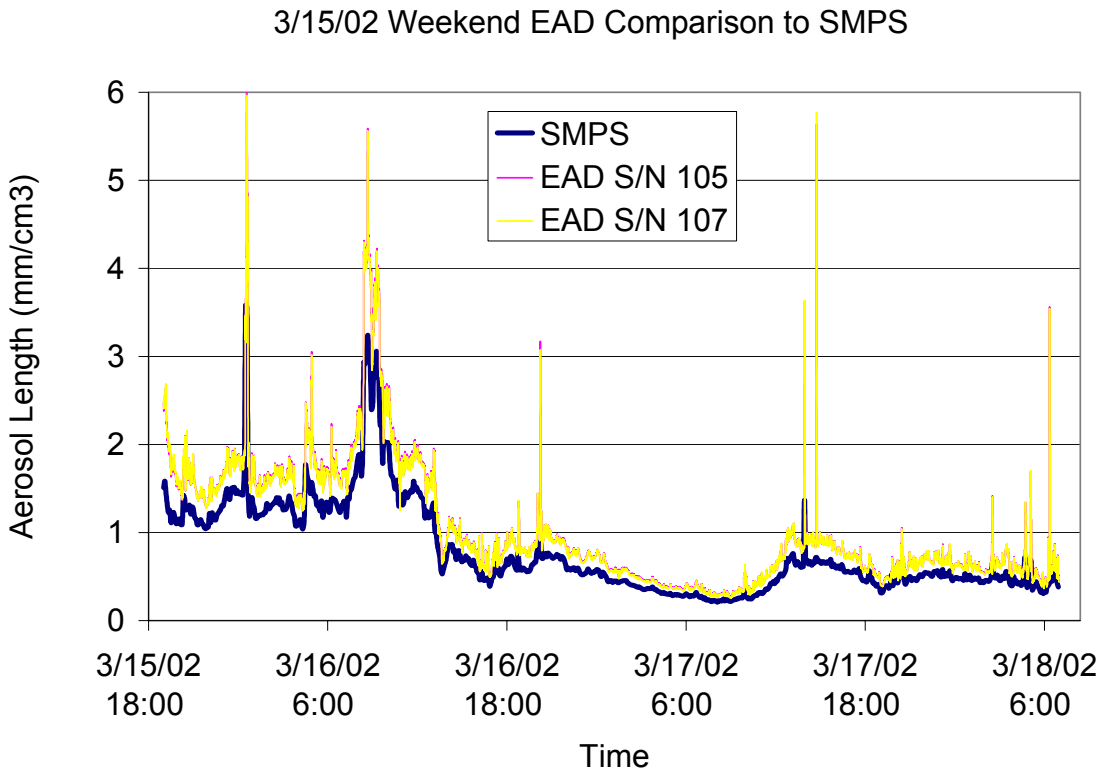


Figure 12 Atmospheric Aerosol comparing SMPS and EAD length data

Additional tests on atmospheric aerosol are ongoing at the EPA super site in St. Louis, MO (USA). Two EAD's are taking data on the same aerosol sampling source and have agreed within about 1% for a period of approximately 6 months. This agreement between aerosol instruments is extremely good for any aerosol instrument where variability in the tens of percent is common.

Summary & Conclusions

The EAD measures a parameter that is effectively the first moment (diameter or length) of the particle size distribution. This linear dependence is consistent with expectations that the mean free path of ions is assumed to be on the order of 0.01 microns.

The results depend on concentration and diameter of the particles so changes of either parameter give a response change. Some engine cycle changes make small changes in concentration (CPC data) but significant changes in the aerosol length measurement.

When EAD length is divided by CPC count the result is mean diameter. Since both instruments have fast response to aerosol changes the mean diameter can be determined for transient aerosols like those that occur during engine test cycles.

This new instrument is quite rugged and can yields stable results over a wide range of concentrations. The EAD covers the size range of interest for engine exhaust measurements. While the measurement units are new it is an easy to operate instrument that would work well for routine measurements. Its rapid response and unmatched reproducibility make it a candidate for many types of engine testing.

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