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An Ion Generator for Neutralizing Concentrated Aerosols

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ABSTRACT. An ion generator was developed to neutralize concentrated streams of large, highly charged particles in a low-velocity wind tunnel. The aerosol stream tested consisted of 30 μm aluminum oxide particles (aerodynamic diameter 52 μm) at a flow rate of 9.6 m^3/h (160 L/min) and a mass concentration of 43 g/m^3. The average number of excess charges per particle was 240,000 (positive), which corresponds to a neutralizing current requirement of 0.11 μA. Neutralization to $< \pm$ 10,000 charges per particle was necessary to prevent electrostatic sampling artifacts. Neutralization with radioactive sources would have required an impractically large source. The ion generator, constructed from 21 and 32 mm PVC pipe, has 4 peripheral radial electrodes of 0.5 mm tungsten wire and a 2.0 mm diameter central electrode. The aerosol flowed through the ion generator along its axis. The ion generator was powered by an adjustable (0–8.5 kV) power supply. Performance of the ion generator was monitored with an isokinetic Faraday-cup sampler connected to a Keithley Model 6512 electrometer capable of 0.1 fA resolution. The sampler used a stainless steel 47 mm filter holder as the Faraday cup. The cup was insulated with Teflon inside a 90 mm diameter stainless steel enclosure with a 21 mm diameter inlet. This setup gave near real-time measurement of the charge state of the aerosol in the wind tunnel. By adjusting the ion generator power supply, particle charge could be reduced to < 2% of its original charge. Ion generator output was sufficiently stable to maintain the particle charge within ± 2% of the original charge over a 1 h period. These reduced charge levels are comparable to charge levels found on workplace aerosols.

INTRODUCTION

The removal of charge from aerosol particles by neutralization is often needed for aerosol measurement, aerosol processing, or for the production of test aerosols. Solid particles can acquire high charge by passing through flames, by static electrification, or by collisions with ions. There are 2 approaches to reducing the charge on aerosol particles: 1) preventing the buildup of charge, and 2) neutralizing or discharging with bipolar ions. The first approach involves careful selection of materials that the particles contact, providing gentle contact, and using high humidity. The latter allows the charge to bleed away through a surface layer of conductive water molecules. These methods, although relatively simple,

are limited in their effectiveness. With some exceptions for highly charged particles, once charge has been acquired by a particle it can only be removed (neutralized) by contact with a surface or ions of the opposite sign. The most common method of neutralization is by mixing the aerosol with high concentrations of bipolar ions produced by corona discharge or radiation. Methods for discharging aerosol particles with bipolar ions have been reviewed by Liu and Pui (1974), Yeh (1993), and Hinds (1999).

Bipolar ions are created by radioactive decay of isotopes, such as polonium-210 or krypton-85, or by corona discharge, such as an AC corona with a sonic jet or dual electrode corona. For example, the Model 2054 aerosol neutralizer manufactured by TSI, Inc. (St Paul, MN) uses a 10-mCi Kr-85 source to ionize air molecules inside an aluminum cylinder. The design flow rate is 9.0 m^3/h (150 L/min). This provides sufficient residence time for neutralization, approximately 2 s, for an ion concentration of about $8.8 \times 10^{12}/m^3$ $(8.8 \times 10^6/cm^3)$ (Teague 1978). Radiation methods have been reviewed by Cooper and Reist (1973), Zamorini and Ottobori (1978), Adachi et al. (1993), and Romay et al. (1994) and corona methods have been reviewed by Covert et al. (1997).

For highly charged aerosols or when neutralization must be rapid, neutralization is achieved by mixing the aerosol with high concentrations of bipolar ions. These ions must be created continuously to maintain high concentrations within the aerosol. It is difficult to maintain very high concentrations of bipolar ions because at high concentrations the rate of recombination of ions of opposite sign can nearly equal their rate of production. Also, mixing with bipolar ions discharges or neutralizes the particles to a low but not 0 charge level called Boltzmann's equilibrium charge distribution. The rate of neutralization depends on the product of ion concentration and the time during which they are mixed. Generally the requirement for complete neutralization is a value of $N \times t$ that is $\geq 6 \times 10^{12}$ $ion \cdot s/m^3$ $(6 \times 10^6$ $ion \cdot s/cm^3)$, provided that an excess of bipolar ions is maintained.

EXPERIMENTAL

This paper describes an asymmetrical ion generator used to neutralize high concentration aerosols of large highly-charged particles. Such an aerosol was needed for inhalability studies in a large, low-velocity wind tunnel. The basic wind tunnel, its airflow, and its aerosol generation system is described by Hinds and Kuo (1995). The generation system consisted of 3 NBS dust feeders (Hinds 1999), each operated to produce an aerosol output of about 110 mg/s. The particles were found to be highly charged. The charge was believed to be sufficient to affect the inhalability results, so a method to neutralize the test aerosol was needed.

The 3 NBS dust feeders were each operated to produce an output aerosol stream having a concentration of approximately 43 g/m^3 at a flow rate of 9.6 m^3/h (160 L/min). All parts of the aerosol delivery system were grounded. The aerosol streams were carried through 18 mm ID conductive (Carbon filled, EPDM) rubber tubing (Technical Specialities Company, Inc., Odessa, FL) to the 32 mm ID copper output nozzles. In normal operation the nozzles are mounted adjacent to each other and together are scanned back and forth and up and down to provide a uniform average aerosol concentration over the whole cross-sectional area of the wind tunnel.

The test aerosol particles were aluminum oxide (Al_2O_3) optical powders (Norton Company, Worcester, MA and General Abrasives/Treibacher, Inc., Niagra Falls,

NY) having physical diameters from 5–70 μm. Measurement of charge, described below, found that 30 μm particles carried an excess of 240,000 positive charges/particle. At this concentration and charge level 6.6×10^{11} negative charges per second, equivalent to 0.1 μA, are required for each stream to neutralize (discharge) the 30 μm aerosol. This corresponds to a negative ion concentration in the aerosol stream of 2.5×10^{14} /m^3 (2.5×10^8 /cm^3).

To discharge this aerosol using bipolar ions requires a large excess of bipolar ions; a reasonable assumption would be at least 10 times the required negative ion concentration or 2.5×10^{15} /m^3 (2.5×10^9 /cm^3). It would be difficult to achieve this concentration of bipolar ions, either by a radioactive source or by corona discharge, because of the rapid recombination of ions of opposite sign. For comparison, a scale up, based on Teague et al. (1978), of the TSI, Inc. Model 3054 10 mCi Kr-85 aerosol neutralizer (TSI, Inc., St. Paul, MN) would require a Kr-85 source of at least 540 mCi on each stream, an impractically large radioactive source. Furthermore the geometry of the 3054 would cause unacceptable particle losses.

The particular aerosol material used (Al_2O_3) presents another problem in that it has an exceptionally high electrical resistivity, 10^{14} Ω-m. This is so high that it would require hours for a 30-μm particle on a grounded surface to lose its charge by conduction through the particle. Efforts to raise the surface conductivity by raising the relative humidity in the aerosol stream and in the wind tunnel were insufficient to significantly reduce the charge on the particles.

The objective of this study was to develop and test a method for neutralizing the concentrated aerosol described above. This paper describes an asymmetrical 5-electrode, flow-through ion generator, and its evaluation and testing, and the design of a Faraday-cup isokinetic sampler and electrometer monitoring system used to evaluate it.

In order to evaluate different neutralization methods and devices, it was necessary to have a nearly real-time system to monitor the charge on the aerosol particles in the wind tunnel. A Faraday-cup sampler was devised using a stainless steel 47 mm filter holder in a 90 mm diameter stainless steel container as shown in Figure 1. The design is similar to that given by John

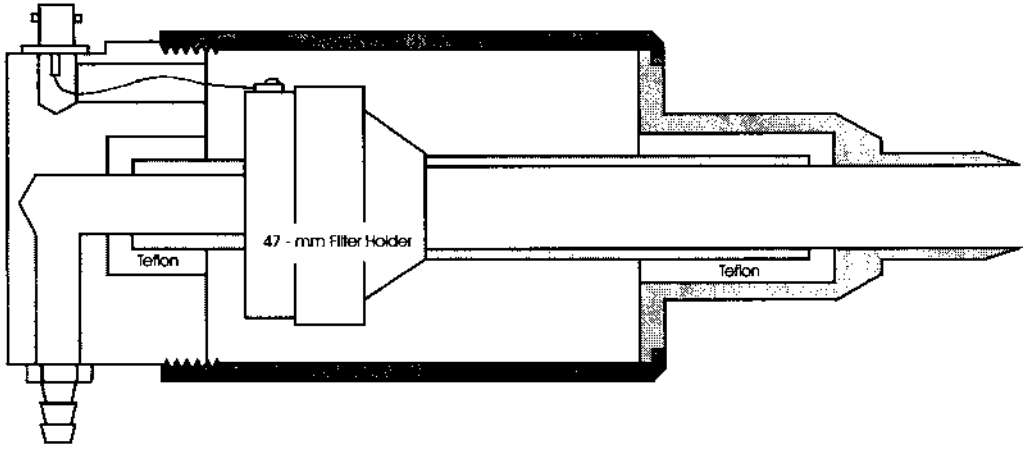

FIGURE 1. Cross-sectional diagram of the Faraday-cup isokinetic sampler.

(1980). The cup is insulated with Teflon and all parts are either stainless steel or Teflon. As shown, the inlet is sharp-edged for isokinetic sampling; a necessity for sampling large particles. The inlet path is straight with a constant internal diameter of 21 mm. The isokinetic sampling flow rate was 1.25 m^3/h (20.8 L/min) for a tunnel velocity of 1.0 m/s. Particles are collected on a glass fiber filter in the 47 mm filter holder, which is connected to an external electrometer by a shielded cable. The charge collected by the filter is detected as a current in the electrometer.

The electrometer, Keithley Model 6512 (Keithley Instruments, Cleveland, OH), is autoranging and has a 0.1 fA resolution. It can be used to measure current in pA or accumulated charge in pC. It has built-in data logging capability and can store 100 measurements. For most measurements we found it convenient to measure and store the accumulated charge every 10 s. The results were read out and differenced with the immediately subsequent reading to get the amount of charge arriving in each 10 s period. This system proved to be a stable and reliable charge measuring system.

Our initial attempt at neutralizing the stream used a Richmond Static Control Services Model AN-2 air ionizing nozzle attached to the dust feeder exit tube. It injects bipolar ions at a flow rate of about 0.6 m^3/h (10 L/min). We found it produced an insufficient concentration of ions and was only able to reduce the average charge slightly.

This led to the design shown in Figure 2, an asymmetrical 5-electrode flow-through ion generator. It is of relatively simple construction, consisting of 3 sizes of PVC pipe and fittings. The axial center electrode is 2 mm in diameter and the 4 peripheral electrodes are 0.5 mm diameter tungsten wire. All 5 electrodes are connected by high voltage connectors and high voltage wire to the power supply. A field is established between the center electrode (positive) and the peripheral electrodes so that there is a negative corona at the 4 peripheral electrodes at the edge of the aerosol stream. The dusty air flows along the axis of the ion generator. The device produces many more negative ions than positive ions and it produces them right at the edge of the aerosol stream where they can quickly contact charged particles. The total number of ions produced is controlled by the power supply setting.

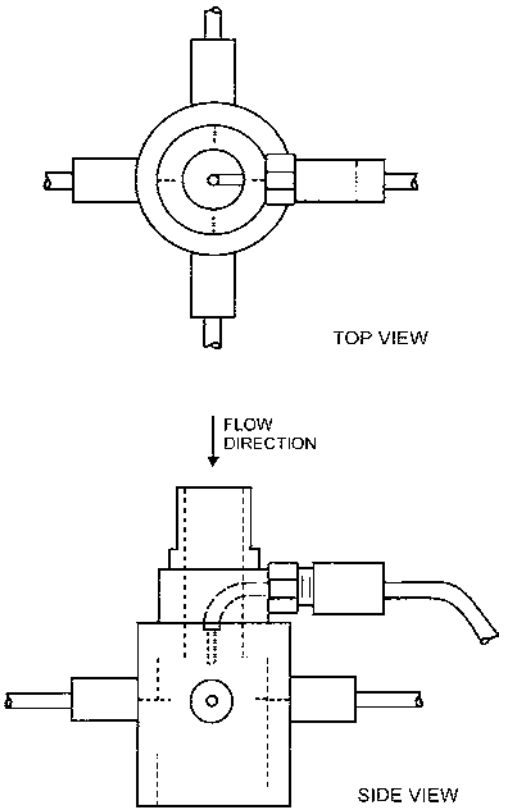

FIGURE 2. Diagram of 5-electrode flow-through ion generator.

The power supply is a Richmond Model AB-250 (Richmond Static Control Services, Palm Springs, CA). It provides precise con-

trol of the output voltage up to 8.5 kV (+/−). Maximum current is 150 μA. It includes solid-state current limiting features for safety. It is sufficient to power 3 ion generators.

RESULTS

Evaluation tests of the ion generator were conducted by fixing the aerosol discharge nozzles in the center of the wind tunnel cross-section. In normal use it is scanned back and forth and up and down, but for these tests it must be fixed. The Faraday-cup isokinetic sampler was positioned about 2 m downstream from the discharge nozzles. A test aerosol of 30 μm Al_2O_3 particles (mass median aerodynamic diameter of 52 μm) was generated at normal exit concentration of about 43 g/m^3.

At the start of each run the power supply output voltage was adjusted to minimize the ion current measured by the Faraday-cup isokinetic sampler. Figure 3 shows average results for a series of 1 min runs. As can be seen in the figure, the ion generator reduces the charge on the test aerosol to about 1% of the original charge, a reduction of approximately a factor of 100. This is still much higher than Boltzmann's equilibrium charge, but was found to be sufficiently low to prevent errors in our measurement of inhalability due to electrostatic effect. Because of variations in the ion generator and aerosol generator output, the charge level shown represents a practical minimum charge for this system.

To evaluate the stability of the ion generator it was adjusted initially to give minimum ion current and operated for 1 h without further adjustment. The wind tunnel and aerosol generators were operated at the constant conditions described above during each test. The results are shown in Figures 4a and 4b. In Figure 4 each point represents a 1 min integration. One second

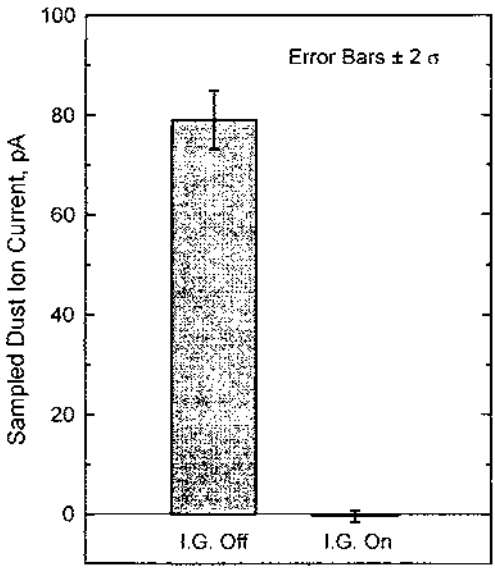

FIGURE 3. Average ion current for a series of 1 min runs with the ion generator off and on.

readings showed much greater variation. Figure 4b shows the same data as Figure 4a, but expressed, with an expanded vertical scale, as a percent of the initial condition. While the ion generator was on, 95% of the ion current measurements were within 1.6 pA of 0. This range corresponds to ± 2% of the current when the generator is off.

DISCUSSION

The power supply has a feedback control that allows automatic adjustment of output voltage to maintain a constant ion current. This was not used for our setup because the dust delivery nozzles are scanned back and forth and up and down to achieve a uniform average concentration in the wind tunnel. For a fixed downstream sampler location the concentration is low most of the time and very high when the aerosol stream passes in front of the sampler and thus precluded automatic control.

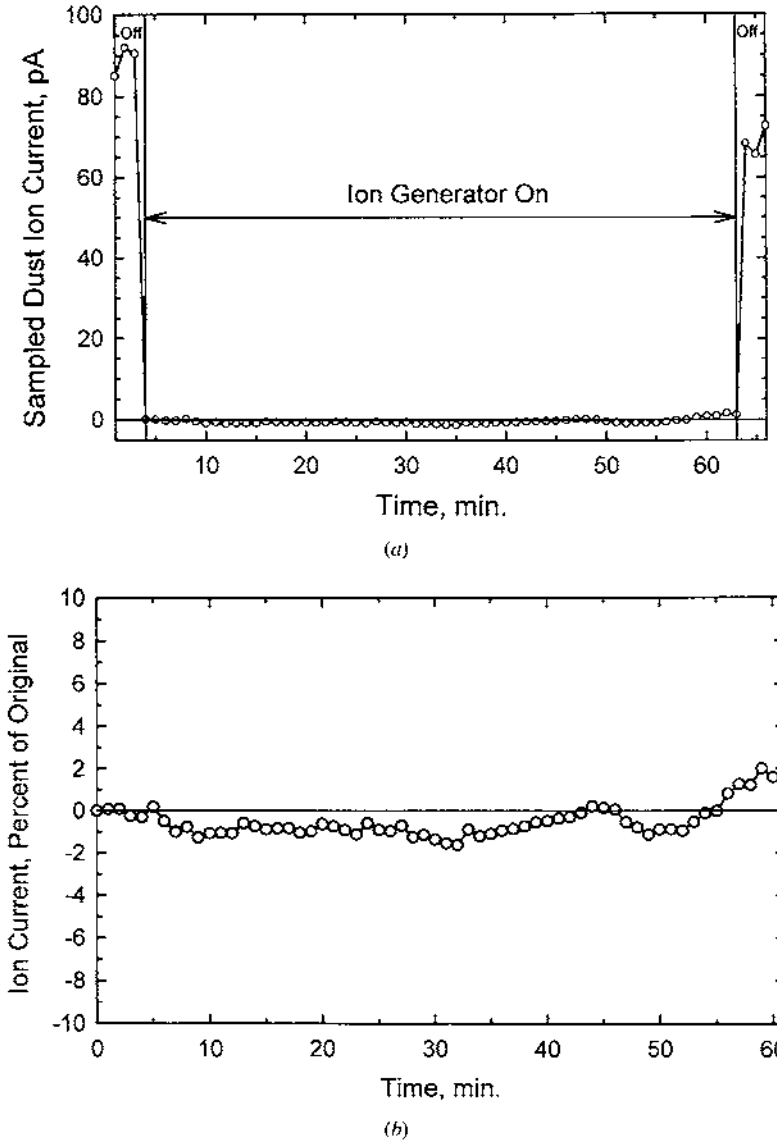

FIGURE 4. (a) Ion current for 1 min intervals with ion generator off and on and off. (b) Variation of ion current over a 1 h period.

In operation there was an occasional arc over between the center electrode and one of the peripheral electrodes. This produced a momentary shift in the aerosol charge conditions that returned to normal in a few seconds. After several hours of operation a small deposit of dust would build up on the electrodes. This was easily removed by increasing the airflow rate through the ion generator and tapping on the ion generator body with the power supply turned off.

The final charge condition for the 30 μm particles was $< 1\%$ of the original charge, or approximately an excess of $< 2{,}400$

charges/particle. This is in the range of data given by Johnston et al. (1986) for workplace aerosols of coal, silica, and mica (1–7.5 μm) extrapolated to 30 μm. They concluded that at these levels electrostatic forces have negligible effect on sampling. This suggests that although the device described here does not reduce charge to Boltzmann equilibrium, it reduces it sufficiently to make electrostatic effects on inhalability and personal sampling negligible.

CONCLUSION

A simple, relatively low cost ion generator for neutralizing a concentrated aerosol stream of large, highly charged particles is described. A Faraday-cup isokinetic sampler design is also described and was used to evaluate the performance of the ion generator.

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