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Electrostatic Charge Measurement and Charge Neutralization of Fine Aerosol Particles during the Generation Process

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Abstract

An aerosol charge analyzer has been constructed to measure the charge distribution of NaCl particles generated in the laboratory. A radioactive electrostatic charge neutralizer utilizing Po-210 was used to neutralize the electrostatic charge of the particles. The atomization technique was used to generate NaCl particles with diameters of 0.2 to 0.8 µm, while the evaporation and condensation method was adopted to generate particles of 0.01 to 0.2 µm in diameter. The experimental data demonstrates that the absolute average particle charge depends on the particle diameter, and is higher than that calculated by the Boltzmann charge equilibrium for particles within the range of 0.2 to 0.8 µm. The charge increases with decreasing NaCl concentration. When these particles are neutralized using the Po-210 neutralizer, it is found that the electrostatic charge reaches the Boltzmann charge equilibrium. For 0.01 to 0.2 µm NaCl particles generated using the evaporation and condensation method, test results show that the absolute average particle charge is higher than that calculated by the Boltzmann charge equilibrium for particles larger than 0.03 to 0.05 µm in diameter, while it is lower than that predicted by the Fuchs theory [1], for particles smaller than 0.03 to 0.05 µm. However, after charge neutralization, particles with diameter above 0.05 µm reach the Boltzmann charge equilibrium condition, and the charges for particles with diameters of 0.010 to 0.05 µm, agree well with Fuchs' theory.

Keywords: aerosol charge analyzer, charge equilibrium, charge neutralizer, condensation aerosols, electrostatic charge, evaporation aerosols

1 Intruduction

The electrical properties of charged aerosol particles are of vital importance to aerosol sampling, measurement instrumentation and air cleaning equipment. The dispersion and deposition of electrically charged particles has been studied in the literature, e.g., deposition of charged particles in duct/channel flows [2–4], micro-contamination control [5], and deposition of charged particles in the human lung [6]. Aerosol particles can be electrically charged by different techniques and the number of charges on a particle depends on the charging mechanisms. Accurate information concerning the magnitude and distribution of the particle charge is essential to investigate the electrostatic effects in aerosol studies.

Kousaka et al. [7] studied the charge of aerosols of different materials generated by a variety of methods: evaporation-condensation, chemical reaction, atomization and mechanical dispersion. The study found that both the type of aerosol particles and the generation method have a significant effect on the magnitude of the particle charge. For example, di-octyol sebacate (DOS) particles are almost entirely uncharged while sodium chloride particles are highly charged, and polystyrene latex particles possess the highest charge among the aerosols generated by the atomization method.

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The particle electrostatic charge can be neutralized by mixing the particles with a high concentration of bipolar ions, produced either by corona discharge or radiation [8]. A $N_i t$ value (N_i: ion concentration; t: contact time) of 6×10^6 ions-sec/cm^3 is required for complete neutralization of highly charged particles [8]. Polonium-210 and krypton-85 are the two most commonly used radioactive isotopes. AC corona with a sonic jet or dual electrode corona is also used for bipolar ion generation.

For an aerosol in charge equilibrium, the Boltzmann charge distribution assumes that the fraction of particles carrying either N positive or N negative elementary units of charge, is the same. However, since the mobility of an electron is greater than that of a positive ion, the fraction of particles carrying N negative charges is greater than that of particles carrying N positive charges, and the Fuchs theory [1] can be used to calculate the charge distribution. Wiedensohler [9] developed an approximate equation for the Fuchs theory [1]. The fraction of particles carrying N elementary charges can be calculated from the following expression as

$$ f(N) = 10^{\left[\sum_{i=0}^{5} a_i(N) \left(\log \frac{d_p}{nm} \right)^i \right]} \tag{1} $$

where N is the number of elementary charges on a particle, d_p is the particle diameter (nm), the approximation coefficients $a_i(N)$ can be obtained from Table 1 in Wiedensohler [9]. Eq. (1) is valid for particles carrying at most, two elementary charges. For particles carrying three or more charges, the following equation developed by Gunn is valid for particles with diameters greater than 0.05 μm [10]:

$$ f(N) = \frac{e}{\sqrt{(4\pi^2 \varepsilon_0 d_p kT)}} \exp \frac{-\left[N - \frac{2\pi\varepsilon_0 d_p kT}{e^2} \ln\left(\frac{c_{NI+} Z_{I+}}{c_{NI-} Z_{I-}} \right) \right]^2}{2 \frac{2\pi\varepsilon_0 d_p kT}{e^2}} \tag{2} $$

where e is the elementary unit of charge, ε_0 is the dielectric constant, k is the Boltzmann constant, T is temperature, $c_{NI\pm}$ is the ion concentration and $Z_{I\pm}$ is the ion mobility. The concentration of positive and negative ions is assumed to be equal and the ratio of the ion mobility, Z_{I+}/Z_{I-}, is 0.875.

In recent years, research interests have shifted from micrometer to nanometer particles. Thus, the objective of this study is to measure the electrostatic charge for laboratory generated nanometer particles, in particular for particles that are less than 0.1 μm, which have not

been measured by Forsyth et al. [11]. In this study, an aerosol charge analyzer was constructed in the laboratory to examine the amount of electrostatic charges carried by NaCl particles. A radioactive electrostatic charge neutralizer using Po-210 as a radioactive source was also built, to neutralize freshly generated NaCl particles. Its effectiveness was compared with the TSI Kr-85 radioactive neutralizer.

2 Aerosol Charge Analyzer

The design of the aerosol charge analyzer in this study originated from the paper of Forsyth et al. [11]. The significant advantage of this analyzer is that it is efficient and simple to use for simultaneous measurement of the aerosol charge for particles of different diameters. Figure 1 shows the schematic diagram of the analyzer,
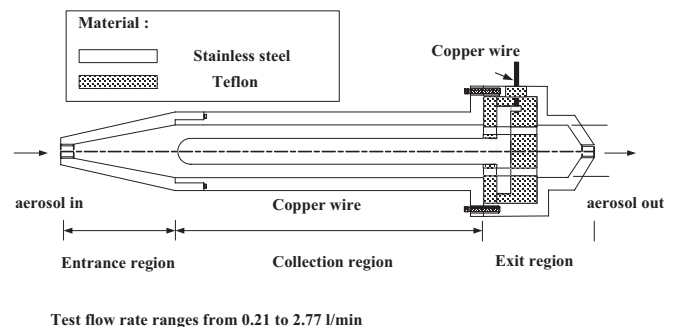

Fig. 1: Aerosol charge analyzer.

which is constructed mostly from stainless steel. It has three sections: an entrance region, a collection region and an exit region. At the entrance region, a 7.5 degree cone brings the input aerosol in the collection region to a state of low probability of recirculation and turbulent transition [12]. The current design enables a fully developed laminar flow, with volumetric flow rates up to 30 liters per min. The collection section of the charge analyzer consists of a concentric cylindrical assembly with a long circular rod at the center. The inner rod is supported by a teflon insulator. A 30 degree converging nozzle is used in the exit region of the analyzer. A highly positive voltage ranging from 0 to 10,000 V was applied on the inner collection rod using a high voltage power supply. The penetration of particles with different applied voltages was obtained experimentally, in order to calculate the charge carried by particles. The principle used to calculate the particle charge, follows that described by Forsyth et al. [11].

3 Neutralizer

In this study, a radioactive electrostatic charge neutralizer was built in order to neutralize the charged particles. Aerosols were neutralized by using a Po-210 (NRD, Model 2U500) radioactive source with a maximum energy of 5.3 MeV and a half-life of 138.4 days. In the radioactive source, Polonium (Po-210) radiation material is incorporated into small ceramic beads, which are cemented onto a flat substrate and mounted inside a protective assembly [13], as shown in Figure 2. The distance that the alpha particles radiate in the air can be up to 3.8 cm. It is a relatively inexpensive source, and in
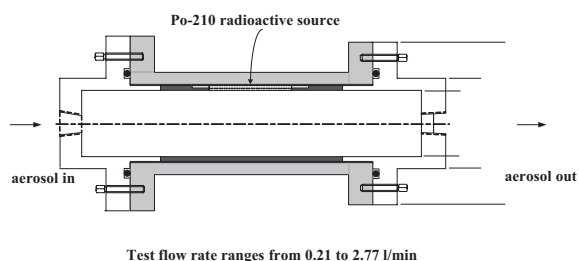
Fig. 2: Radioactive charge neutralizer.

addition, it is not necessary to obtain a license for its use. A commercial TSI Kr-85 radioactive source (Model 3077) with β energy of 0.695 MeV and a half-life of 10.7 years was also used, to allow a comparison of the effectiveness of charge neutralization with that of the self-designed Po-210 neutralizer.

4 Experimental Method

The two experimental setups used in this study are shown in Figures 3(a) and 3(b), respectively. The aerosols were generated via a constant output atomizer (TSI Model 3076), and then passed through a silica gel diffusion dryer. After drying, the aerosols were then passed through a mixing tank to stabilize the aerosol concentration (see Figure 3(a)). However, the neutralizer shown after the mixing tank in Figure 3(a) was not used initially in the experiment. The neutralizer was added after the mixing tank in the latter part of the experiment, in order to test the performance of the self-designed Po-210 neutralizer and allow a comparison between it, and the commercially available TSI Kr-85 neutralizer. In all other instances, the test aerosols were introduced directly into the aerosol charge analyzer, to measure the charges. The particle size distribution and concentration were measured by an optical particle counter (Grimm, Model 1:108) connected to the system after the analyzer.
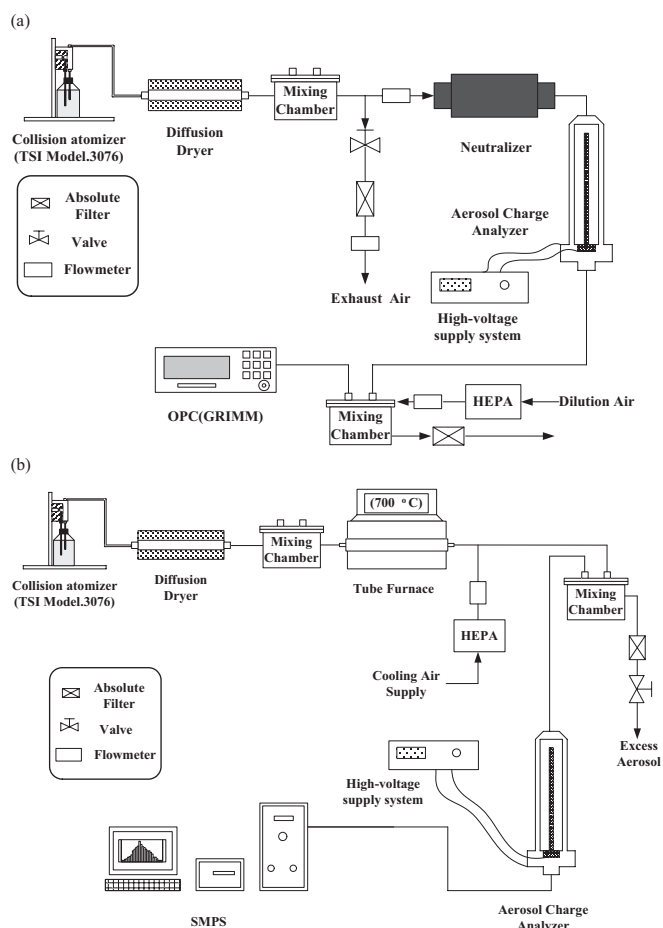
Fig. 3: The schematic diagram of the experimental setup for particles generated from: (a) an atomizer only, (b) an atomizer together with a tube furnace.

The lower limits of the optical particle counters fifteen channels are: 0.3, 0.4, 0.5, 0.65, 0.8, 1, 1.6, 2, 3, 4, 5, 7.5, 10, 15, and 20 μm. At first, the polydisperse aerosol size distribution was measured without a voltage being applied to the inner rod of the analyzer. A high positive voltage was then applied to the inner rod by a high voltage power supply (Knight Power Model MR10-3). The voltage was increased in a step-wise mode, while the particle size distribution was measured simultaneously, at each applied voltage. After a series of measurements, the relationship between the particle collection efficiency, η, and the applied voltage of the inner rod, V, was fitted using an exponential expression. By differentiating the exponential equation with respect to V, $d\eta/dV$ can be obtained and therefore, the mobility distribution function and number of particle charges can be obtained. This procedure is detailed in Forsyth et al. [11]. 0.05%, 0.1%, 0.5% and 1.0% NaCl aqueous solutions were used as the source of particle material in the study.

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In the second experiment, a tube furnace was added after the atomizer to generate ultrafine aerosol particles (Figure 3(b)). In this setup the aerosols generated by the atomizer were evaporated by a tube furnace and subsequently cooled by mixing with filtered ambient air [14]. The tube furnace (Lindberg/Blue, Model HTF55342C) was operated at 700 °C to evaporate the aerosols, which had a residence time in the furnace of about 2.82 s. This evaporation-condensation method is able to produce the desired ultrafine particle distribution. A scanning mobility particle sizer (SMPS, TSI Model 3934) was used for measuring particle size distribution. The same procedure described in the previous section was followed to determine the electrostatic charge on the particles. In this part of the experiment, 0.05% and 1.0% NaCl aqueous solutions were used.

5 Result and Discussion

5.1 Particles Generated by an Atomizer

Figure 4 shows the experimental results for the absolute average charge on NaCl particles generated by the atomizer, with different initial aqueous concentrations versus the particle diameter It shows that the absolute average charge of the NaCl particles increases as the concentration of the NaCl solution decreases. The abso-
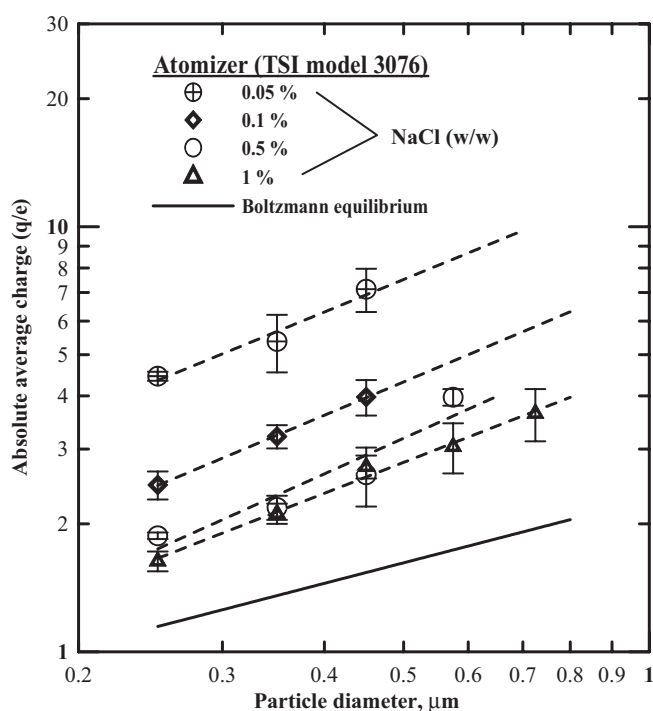
lute number of elementary units of charge on particles with diameters ranging from 0.25 to 0.45 μm is about 4.5 to 7.1 (q/e) for 0.05% w/w NaCl solution and is about 1.6 to 2.2 (q/e) for 1.0% w/w NaCl solution. As the concentration of NaCl solution increases, it approaches the Boltzmann charge equilibrium condition. This experimental observation confirms the earlier results of Forsyth et al. [11], who used NaCl solutions of different concentrations to generate particle diameter ranging from 0.1 to 1.0 μm. The increase in the absolute average charge of NaCl particles with decreasing salt concentration, observed in the current work, is due to the effect of dissolved ions on the dipole charge layer at the liquid gas interface [11].

Figure 5 shows the plot of the absolute average charge level for NaCl aerosols generated from different NaCl solutions versus the particle diameter, following neutra-
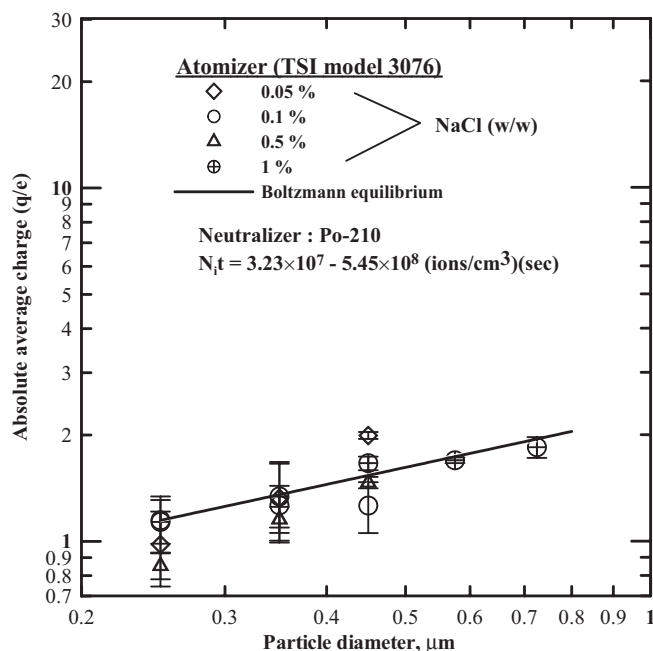
Fig. 5: Particle charge distribution for NaCl particles from the atomizer in Figure 4, and neutralized by a Po-210 neutralizer.

lization using the new Po-210 bipolar neutralizer. In the experiment, the $N_i t$ product ranged from 3.23×10^7 to 5.45×10^8 ions-sec/cm³. The absolute charge level measured for particles of 0.25 to 1.0 μm diameter, almost coincides with the Boltzmann charge equilibrium, for each concentration of NaCl solution used. These observations are comparable with earlier measurements by Forsyth et al. undertaken using NaCl particles after atomization and Po-210 neutralization [11]. The results suggest that the Po-210 neutralizer is effective in neutralizing the charge on particles produced by the atomizer technique.

Fig. 4: Particle charge distribution for NaCl particles generated from a constant output atomizer.

5.2 Particles Generated by the Evaporation and Condensation Process

The absolute charge of NaCl particles of 0.01 to 0.2 μm diameter, generated by the evaporation and condensation technique, is discussed in this section. The absolute average charge level of 0.05% and 1.0% w/w NaCl solutions versus the particle diameter, is plotted in Figures 6 and 7, respectively. In the case of 0.05% w/w NaCl solution without neutralization, the results show that the absolute charge level is higher than that calculated by
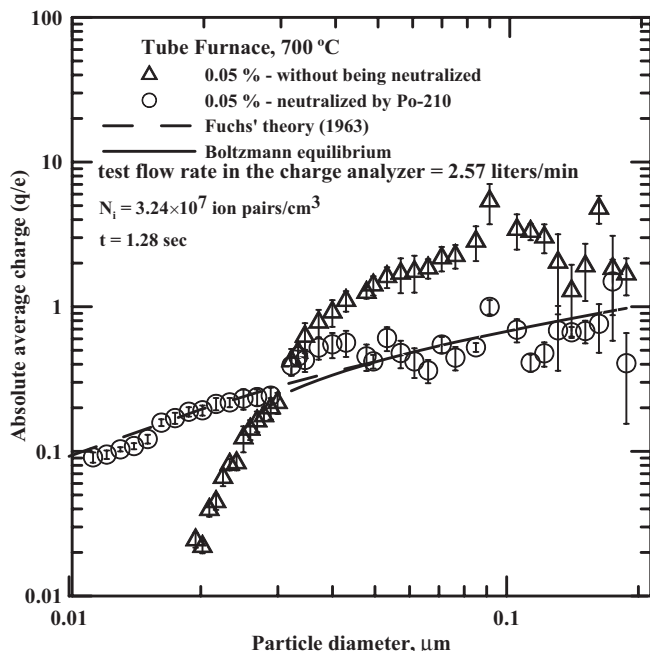
Fig. 6: Particle charge distribution for NaCl particles generated from the atomizer in Figure 4, together with a tube furnace (0.05%, w/w NaCl).

the Boltzmann charge equilibrium, for particles larger than 0.03 to 0.05 μm, and is lower than that predicted by Fuchs' theory (1) when the particle size is smaller than 0.03 to 0.05 μm (Figure 6). By using the Po-210 neutralizer and the results in Figures 6 and 7 indicate that the charge of particles above 0.05 μm follows the Boltzmann charge equilibrium, while the charge of 0.01 to 0.05 μm particles is as predicted by Fuchs' theory (1).

The comparison of the neutralization effectiveness of the Po-210 neutralizer with the commercial TSI neutralizer, is also shown in Figure 7. The total aerosol concentration in this study was about 10^6 particles/cm^3. In case of the Po-210 source, two residence times of 1.28 and 0.067 s were used, which corresponds to a $N_i t$ product of 4.15×10^7, and 2.17×10^6 ions-sec/cm^3, respectively. The results show that both the Po-210 source with a 1.28 s. residence time ($N_i t = 4.15 \times 10^7$ ions-sec/cm^3) and the TSI
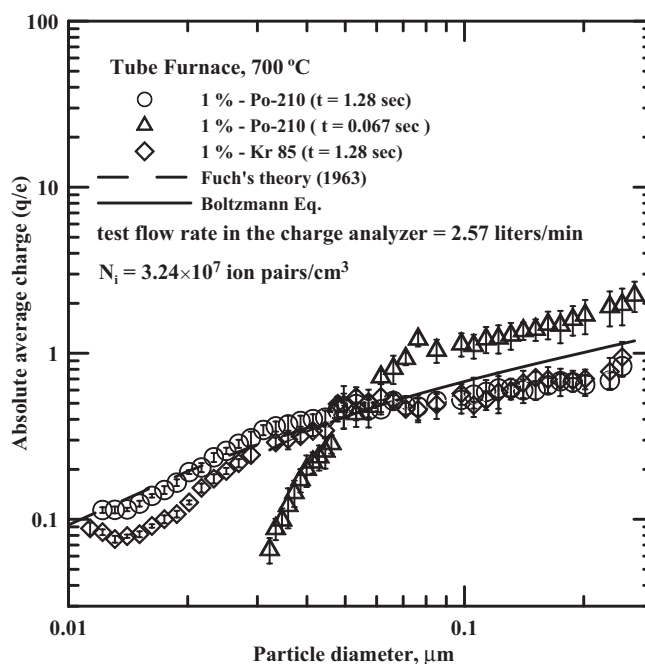
Fig. 7: Particle charge distribution for NaCl particles generated from the atomizer in Figure 4, together with a tube furnace (1.0%, w/w NaCl).

neutralizer, can be used to effectively neutralize the charge of particles greater than 0.03 μm. The measured particle charge for particles smaller than 0.03 μm and neutralized by the TSI neutralizer is only slightly lower than the Boltzmann charge equilibrium. This TSI neutralizer has been used for about ten years and is still effective in neutralizing charged particles. Results for the two residence times of the Po-210 source show that a residence time of 1.28 s (or $N_i t = 4.15 \times 10^7$ ions-sec/cm^3) is required to bring the charged particles to the Boltzmann charge equilibrium, while a residence time of 0.067 sec (or $N_i t = 2.17 \times 10^6$ ions-sec/cm^3) is not sufficient to completely neutralize the charged particles.

6 Conclusions

An experiment was conducted to study the electrostatic charge and charge neutralization of aerosol particles with diameters ranging from 0.01 to 0.8 μm. The results suggest that the charge on NaCl particles generated by the atomizer increases with a decrease in NaCl solution concentration. The formation of an electrical double layer on the surface of the liquid solution and the dependence of its thickness on the solution concentration, contribute to this effect. In most instances, the charge on the NaCl particles after Po-210 neutralization follows the Boltzmann charge equilibrium, regardless of the concentration level of the NaCl solution. The test aero-

sols generated by the evaporation and condensation method carry an electrostatic charge that is higher than that calculated by the Boltzmann charge equilibrium, for particles larger than 0.03 to 0.05 μm, while it is lower than that predicted by Fuchs' theory (1) when the particles are smaller than 0.03 to 0.05 μm. When the particles are neutralized by a radioactive Po-210 source with a sufficiently high $N_i t$ value (N_i: ion concentration, t: residence time), the charge distribution almost follows the Boltzmann charge equilibrium for particles greater than 0.05 μm in diameter, and agrees with Fuchs' theory [1] for particles smaller than 0.05 μm in diameter.

7 Acknowledgments

8 References

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