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Technical note

The effect of dielectric constant of materials on unipolar diffusion charging of nanoparticles

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ABSTRACT

We investigated the dependence of unipolar diffusion charging of nanoparticles on the dielectric constant of the particle material experimentally. The examined nanoparticles (10–200 nm) cover a wide range of dielectric constant but have almost the same spherical or compact morphology. Measurements of both intrinsic charged fraction and mean charge per particle show very small differences among different materials. The level of the small difference is consistent with the estimation by Fuchs' [(1963). On the stationary charge distribution on aerosol particles in bipolar ionic atmosphere. *Geofisica Pura e Applicata*, *56*, 185–193] theory.

1. Introduction

Diffusion charging has been widely used in many applications of aerosol science and technology, such as sizing particles in aerosol size spectrometers (Shah & Cocker, 2005), removing toxic particles with electrostatic precipitators (ESPs) (Yang et al., 2007), and measuring surface area of particles (Fissan, Neumann, Trampe, Pui, & Shin, 2007; Shin, Pui, Fissan, Neumann, & Trampe, 2007). Unipolar charging has recently attracted particular attention due to its higher charging efficiency than bipolar diffusion charging for nanoparticles (Chen & Pui, 1999), which are considered as building blocks for nanotechnology.

One of the main advantages of diffusion charging over other charging processes, such as photoionization, is its smaller material dependence, as predicted by diffusion charging theories (Davison & Gentry, 1985; Fuchs, 1963; Marlow & Brock, 1975). The material dependence described in diffusion charging theories is a weak function of the dielectric constant of materials, which functions through the image force due to the interaction between ions and particles. While Fuchs' theory (1963) has been widely used because of its good agreements with various experimental studies (Biskos, Reavell, & Collings, 2005; Pui, Fruin, & McMurry, 1988), very few of them (Pui et al., 1988) explored the material dependence of unipolar diffusion charging. Furthermore, most of these experimental studies focused on the measurement of intrinsic charged fraction only. The intrinsic charged fraction is defined as the possibility of uncharged particles entering the charger to acquire charges in the process independent of their fates (either to penetrate through the charger or to deposit to the wall of the charger). In the transition and continuum regimes, it becomes difficult to study intrinsic charged fraction for unipolar charging because it reaches close to 100% for many unipolar chargers. Some attempts of measuring the mean charge and the charge distribution on monodisperse particles in the transition and continuum regimes were made and showed reasonably good agreements with Fuchs' theory under certain conditions (Biskos et al., 2005). However, no material dependence study has been done for mean charge or charge distribution measurements. In addition, problems of missing the information of the charged particle loss in a unipolar charger and the possible effect of particle

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morphology remain unsolved for these measurements, which make the comparison with Fuchs' theory arguable. Most unipolar chargers have an electrical field in the charging zone which leads to substantial loss of charged particles. Unlike the measurement of intrinsic charged fraction, which can be accurately obtained regardless of the charged particle loss because uncharged particles are actually measured (Romay & Pui, 1992), the measurement of mean charge and charge distribution can be made only for those charged particles that survived through the charger. However, there is no technique available to obtain the charge distributions of the particles lost in the charger. In addition, the presence of an electrical field in the charging zone also involves field charging, which should be avoided if the experimental results need to be compared with Fuchs' theory, which is for diffusion charging only. When testing particles in the transition and continuum regimes, great care needs to be taken of for particle morphology since flame synthesized (Biskos et al., 2005) and furnace generated aerosols (Shin et al., 2007) often contain agglomerates. It was reported that agglomerated particles have larger mean charge than spherical particles with the same mobility diameter for unipolar charging (Oh, Park, & Kim, 2004). Since the Fuchs' theory assumes that the particles are spherical, it is desirable to make these measurements for particles with spherical or compact morphology in a charger with negligible charged particle loss. In this study, we used a unipolar diffusion charger that has been implemented in three commercial instruments (Electrical Aerosol Detector, TSI 3070A; Nanoparticle Surface Area Monitor, TSI 3550 and AeroTrak 9000; UFP Monitor, TSI 3031) and proved to have minimized particles loss by eliminating electrical field in the charging zone (Medved, Dorman, Kaufman, & Poecher, 2000).

The goal of this work is to examine the effect of dielectric constant on unipolar diffusion charging. Intrinsic charged fraction was measured for particles with the electrical mobility diameter $d_m = 10$–$50\,\mathrm{nm}$ and mean charge was measured for particles with $d_m = 50$–$200\,\mathrm{nm}$.

2. Theory

In Fuchs' charging theory, the interaction potential at a distance r from the center of a particle with n elementary charges, i.e., $\phi(r)$, is a key component of the combination coefficient of ions and particles, i.e., β, and it is expressed as

$$\phi(r) = \int_r^\infty F\,dr = K_E\left[\frac{ne^2}{r} - \kappa\frac{e^2a^3}{2r^2(r^2-a^2)}\right], \tag{1}$$

where F is the ion particle interaction force; $K_E = \frac{1}{4\pi\varepsilon_0}$ in the SI unit system with the vacuum permittivity ε_0; $\kappa = (\varepsilon-1)/(\varepsilon+1)$ with the dielectric constant ε; a is the radius of particle, and e is the elementary charge. In Eq. (1), the first term in the parenthesis corresponds to Coulomb force, while the second term corresponds to image force, where material dependence functions. Particles of three different materials were examined: Ag ($\varepsilon = \infty$), NaCl ($\varepsilon = 6.1$), and sucrose ($\varepsilon = 3.3$). Hence, the three test materials cover a wide range of κ, which is 1.00 for Ag, 0.72 for NaCl and 0.53 for sucrose. Particle generation was specially designed to ensure particles' spherical or compact morphology as described in the following section.

3. Experimental methods

The particle generation system is shown in Fig. 1(a). We used a sintering process to generate spherical Ag particles. Ag wire (purity level 99.9%) was placed in a ceramic boat which was placed inside a quartz tube of an electric furnace. Dry nitrogen was used as carrier gas passing through the quartz tube and the flow rate was 1.5 L/min. Silver was vaporized in the furnace operating at 1100 °C and primary particles were formed downstream of the furnace by condensation. The primary particles then grew to larger agglomerates by coagulation in the agglomeration chamber. The agglomerates were subsequently fully sintered at 600 °C (Ku & Maynard, 2006) in the second furnace so that the morphology of the particles turned into spherical. To generate NaCl and sucrose particles, solutions of NaCl and sucrose with 0.1% volume concentration in deionized water were atomized in a home-made collison atomizer and the droplets were passed through a diffusion dryer to evaporate the water and leave only solid particles. Silica gels in the diffusion dryer were replaced frequently with fresh ones to ensure dry particles formation and the same low relative humidity for all the measurements. Silver, NaCl, and sucrose nanoparticles are size-classified by a differential mobility analyzer (DMA, Model 3081, TSI Inc.). The sheath flow and aerosol flow rates for the DMA were 5 and 0.5 L/min, respectively, to ensure high monodispersity. Scanning electron microscopy (SEM) images of sintered silver particle, NaCl particle, and sucrose particle are shown in Fig. 2. The particle morphologies are all compact and almost spherical.

The monodisperse aerosol from the DMA was sent into a ^{210}Po neutralizer followed by the test unipolar charger. The operational flow rate through the test charger was controlled by an aerosol electrometer (model 3068, TSI Inc.) and a UCPC (model 3025A, TSI Inc.) downstream operating at 1.0 and 1.5 L/min, respectively. So the total flow rate through the test charger, i.e., 2.5 L/min, is the same as those used in the corresponding commercial instruments. This charger charges the aerosol particles by diffusion in a chamber with two colliding turbulent jet flows carrying aerosol particles and positive ions, respectively. Downstream of the charger, an ion trap voltage of 20 V was used to completely eliminate the highly mobile residual ions in the aerosol stream but ensure a negligible charged particle loss in the ion trap.

Schematic diagram for experimental setup to obtain intrinsic charged fraction is shown in Fig. 1(b). The intrinsic charged fraction is expressed as

$$\eta = 1 - \frac{N_0}{N_T} = 1 - \exp(-\beta_0 N_i t), \tag{2}$$