Limit charge of particulates at their ejection from plane electrode

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Abstract. Laboratory experiments on both metal and dielectric polarized solid particle levitation between plane electrodes at static electric field are performed. The dependence of particles charge on their mass is studied. The particle charge is found to increase with particle mass. The method to obtain extremely high electric charge on particles at atmospheric pressure is introduced. The maximum electric charge $2.8 \times 10^7 e$ is achieved in experiments with heavy metal particles.

1. Introduction
Charged dust particles are used in a variety of manufacturing techniques and laboratory equipment [1–4], such as dust-gas mixtures cleaning, filtering, electric separation, sedimentation, as well as surface coating. Efficiency of these methods depends directly on dust particles charge. The number of papers on dust particle behavior in non-equilibrium non-thermal plasma are published for the last decade concerning Coulomb crystal producing [5–7]. Charged macro particles of micron scale could be found in the Earth’s atmosphere, ionosphere, as well as in the outer space [5, 8] where they play a significant role in physical and chemical processes. Macroparticles with extremely high electric charge are quite a promising material for production of heavy-duty coatings and strong Coulomb interaction structures, surface reactions catalysis, minerals separation, and unique nanostructure objects.

The maximum particle charge depends on particles size, conductivity, permittivity, as well as on the way of charging and ambient medium properties [1, 2]. At present, exposure of dust particles to electron or ion beams is the most common way of charging [5]. The particles charge is determined by floating potential which depends on temperature of electrons in low pressure non-equilibrium plasma with typical value of several eV. Electric charge of micro scale particles in plasma could reach $(10^3 - 10^4)e$ [5], where $e$ means absolute value of electron charge. Extremely high electric charge of $10^7 e$ could be obtained only under a high energy electron beam or in an electron cyclotron discharge in the presence of hot electrons with energy of tens eV [9, 10]. A corona discharge at atmospheric pressure is usually used to charge particles in electrofilters for gaseous filtering and particles separation [11]. In this case dust particles charge depends on electric field and surface area of the particles. However, it is difficult to gain sufficient electric charge for the particles at a distance from the electrode where electric field decreases rapidly.

A particle charging in the absence of plasma is of importance for several applications such as gas filtering and surface cleaning and modification [2–4], experimental simulation of a dust storm,
mixture fractioning [3], creation of strong Coulomb stable structures of charged particles [12],
and nuclear energy conversion systems [13, 14].

At atmospheric pressure, particles could be charged while being in contact with electrode in
high electric field with following levitation over the electrode surface. Despite such plasma-less
method is known for years [1–4,15], specific conditions to reach maximum charge on the particles
of micron sizes are not clear yet and comparison of the magnitude of the charges with other
methods of charging such as electron beam or corona discharge still have not been carried.

In this paper, we present the results of the experimental study on limiting charge of the
particles detaching in uniform electric field from the plane electrode of capacitor.

2. Experimental

The principal scheme of the experimental setup is shown in figure 1. The experiments are
performed at atmospheric pressure in ambient air. The electric field was near threshold value
for electric breakdown of capacitor. Two polished 150-mm-diameter copper disks are placed
concentrically at a distance $d$ of 24 mm. They are connected to a DC HV power supply through
a 100 MΩ ballast resistance. The voltage could be adjusted in the range of (0–40) kV and has
a positive polarity. A static kilovoltmeter is used to measure the voltage. The upper disk has
a 25-mm-diameter orifice at the center to provide the charge measurements with the method
described below. The orifice is covered by brass gauze with $0.7 \times 0.7$ mm cells to provide
the field distribution like there is no orifice. A vertically oriented 100-mm-height glass tube is placed
in the orifice.

Thin layer of metal and dielectric particles are placed on the surface of the bottom electrode
before starting the experiments. The electric field between the electrodes then increases till the
particles start to take off and levitate toward the top electrode. The particles being accelerated
by the field enter the tube through the gauze cells and then are caught by the transparent sticky
tape on the inner surface of the tube.

Trajectories of the particles are captured by a high-speed HiSpec camera at full resolution
of $1280 \times 1024$ px. To make the particles observable they are illuminated by the 650 nm laser
with adjustable power 10–100 mW. Depending on the aims cylindrical laser beam and 2-mm-
Table 1. The types of used particles.

| Material | Al | Brass | W | Diamond | Al₂O₃ | SiO₂ |
|----------|----|-------|---|---------|-------|------|
| 2r₀, µm  | 20–60 | 50–150 | 50–150 | 5–7 | 20–40 | 40–60 |
| M, 10⁻⁹ kg | 0.16 | 9.6 | 19 | 4⁻¹⁰⁹ | 5.7 10⁻² | 0.12 |
| ε        | 16.5 | 8.5 | 6 | | | |

thickness laser sheet are used. Several types of polydisperse metal and dielectric particles are used. Types, sizes, mean mass $\overline{M}$, and permittivity $\varepsilon$ for used materials are summarized in table 1.

3. Results and discussion
For each type of particles, there is a threshold voltage, at which the first particle takes off. When the voltage increases by 5–7%, the number of moving particles increases sharply. After contact the top electrode the particles change, their charge and move back towards the bottom electrode. Reflected particles oscillate in such manner until leave inter-electrode space through the orifice. The particle fluxes in both directions are approximately equal. The trajectories are recorded at 40, 400, and 1200 fps. From the image analysis, it was revealed that the particles move with constant acceleration in both directions. The particles are divided into three groups along the measured acceleration: the first group fast particles with (10–20)g acceleration, the second group—with acceleration of (5–10)g, and the last one—slow particles with (1–3)g acceleration ($g$ means gravitational acceleration).

A specific charge $q/M$ is determined from the equation (1) basing on the measured acceleration $a$. In interelectrode gap at the speed and size of particle 1 m/s and 100 µm correspondingly, an air viscous drag could be neglected compared to electric force:

$$a = \frac{q}{M} E₀ - g.$$

The charge of particle depends on its size and electric field intensity. The distribution of polydisperse particles over the specific charge has a specific form, which is different from that over the particles mass. The distribution of specific charge at 5.6 kV/cm is shown in figure 2. It is calculated for 60 observed particles. Their acceleration is calculated from $d = at₀²/2$, where $t₀$ is the time for particle to cross the gap.

One should know a particle mass to determine a certain charge of a particle with known specific charge. Initial distribution of the brass particles over the mass is shown in figure 3. This distribution is different from the one for moving particles because only a fraction of particles is involved in motion. The given electric field $E₀$ is able to lift the particles if the mass is below a certain value. The charge to mass ratio is determined by dynamics of the moving particles in a capacitor gap. Using particle shift at two successive images, one could easily calculate particle velocity and acceleration. The same method is applied to determine the mass $M$ of particles entering the glass tube through the brass gauze in the top plate of the capacitor. Correspondence between the distributions shown in figures 2 and 4 could be established if separation of the particles is performed. For this purpose the particles are released into the glass tube with sticky inner surface so they are depositing on the wall. The separation takes place outside the capacitor in the presence of electric field from two plates considered as a dipole, as well as in gravity field. While retarding the particles are also influenced by viscous drag from the ambient air. Electric field over the top plate of the capacitor is much weaker, than in area between capacitor plates.
therefore in this case it is necessary to consider a viscous friction from the ambient air. Initial particle velocity $\nu_0 = \sqrt{2ad}$ also depends on the specific charge $q/M$. The dipole field is defined as $E_0d/2R$ near the top plate surface where $d \ll z \ll R$, where $z$—a particle position above the top plate. The maximum lift $H$ could be calculated from the second Newton’s law:

$$M \frac{d\nu}{dt} = -Mg - qE_0 \frac{d}{2R} - kv.$$  

The initial conditions are $z(0) = 0$ and $\nu(0) = \nu_0$. The coefficient $k$ could be written as $k = 6\pi r_0 \eta \beta$, where $\beta = 1 + Re^{2/3}/6$ according to [1].

The equation (2) can be integrated analytically at $\beta = const$. This allows one to calculate $H$ with known initial velocity $\nu_0$. The calculated $H$ for the polydisperse brass particles is 4 cm. The number of particles at different altitudes is counted as to determine the distribution of particles over the mass and the specific charge in each of four 1-cm-height sections above the plate. The fractions of heavy and light particles decrease in the distribution over the mass, while the fraction of middle weight particles increases corresponding to the maximum of the initial distribution (figure 3). The mean mass of particles in each section is equal to each other and to
the mean mass in the initial distribution. The specific charge is calculated for each section and then the mean charge of particles is rated as $q = \overline{M} \times \bar{q} / \bar{M}$.

The charge distribution for the particles inside the capacitor almost repeat the specific charge distribution (figure 2) because the mean mass remains constant. The mean charge $4 \times 10^6 e$ is calculated for the particle in the fourth section. Extremely high charge $2.8 \times 10^7 e$ is gained by 8% of the particle from the forth section. Proposed method for charge definition of polydisperse particles has an inaccuracy of not more than 25%.

A microparticle polarizes and charge separation occurs once electric field is on. Induced
charge on the surface facing the electrode disappears after the contact while the rest of the charge remains on the particle. The force $F$ exerted on a spherical particle in electric filed is given in [16]:

$$F = 17.2\varepsilon_0 E_0^2 r_0^2.$$

An expression for the particle charge is given in [17]:

$$q = \frac{2}{3} \pi^3 \varepsilon_0 E_0^2 r_0^2.$$

The charging process depends on a particle conductivity as well as on environment conditions according to [16–19]. The dielectric particle charge and the exerted force can be calculated in the same way as for metal particles if its conductivity is higher than that of ambient air. The dependence of the minimal particles reduced charge $q/(er_0)$ required for levitation on the particles mass is shown in figure 5. 

The solid line states for the results from equations (3) and (4), single points—the results of experimental measurements of mean charge of the materials from table 1 with error bars. The maximum charge of particle grows along with particle mass according to equations (3) and (4). This is one of the most notable features of described charging technique.

The maximum particle charge for different charging technique is shown in figure 6 including non-equilibrium plasma and electron beam techniques.

It is clear from the figure that particle charging in high static electric field has an advantage over other charging techniques and can be compared with charging in 10 keV electron beam.

4. Conclusion

The experiments on particles charging in static electric field are performed. An effective method for measuring the charge of polydisperse particles with an accuracy of less than 25% is proposed. The maximum gained particle charge is $2.8 \times 10^7 e$ at 100 µm particle diameter.

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