Particle separation by alternating electric fields of quadrupole type

D S Lapitsky
Joint Institute for High Temperatures of the Russian Academy of Sciences, Izhorskaya 13
Bldg 2, Moscow 125412, Russia
E-mail: dmitrucho@yandex.ru

Abstract. In this article, the possibility of particle separation by alternating electric fields of quadrupole type was demonstrated. It was shown that by varying the parameters of the trap (the distance between electrodes, the magnitude and frequency of alternating voltage) it is possible to separate both specific types of particles from the polydisperse powder as well as spatially separate them inside the trap.

1. Introduction

Powders of micron- and submicron-sized monodisperse particles with known physical parameters are used in physics of low-temperature plasma [1–4], in the particle image velocimetry research methods [5, 6], in nanotechnology [7]. Thus the task of producing powders of monodisperse particles is a very important problem.

There are several ways to obtain monodisperse powders. In work [8], particle separation is provided by their organizing in standing surface acoustic waves. Different-sized particles are separated into multiple collection outlets due to the space distribution of the acoustic force which magnitude differs in different areas of the device.

In [9] particle separation is provided by dielectrophoresis.

Methods of cyclone particle separation are often used to separate solid and liquid particles from gases [10, 11].

Particle separations by rf and glow discharges are presented in [12, 13].

Theoretical and experimental works have shown the possibility of nanoparticle and ion separation by mass-spectrometers [14, 15]. This approach is facing number of difficulties when it is used for micron- and nano-sized particles in gas medium. In vacuum an ion or a particle motion is described by the Mathieu equation. To study particle dynamics in a gaseous medium computer simulation are needed [16]. In previous works [17–20] the confinement of micron sized particles by the alternating electric fields has been studied in static gas media and in gas flows.

The aim of this work is theoretical investigation on the possibility of charged particle separation by alternating electric fields.

2. Mathematical simulation of charged particle dynamics in alternating electric fields of quadrupole type

To generate alternating electric field of a quadrupole type the linear Paul trap is used. The sketch of the trap is presented in figure 1 [21]. The trap consists of four cylindrical electrodes...
Figure 1. The sketch of the linear Paul trap.

with radius \( R_1 = 1.5 \) mm and length \( L_m = 10 \) cm. The alternating voltages \( U_\omega \sin(\omega t) \) and \( -U_\omega \sin(\omega t + \pi) \) were applied to electrodes as it shown in figure 1. In simulation the distance between the axes of the neighboring electrodes \( L_b \) varied from 0.13 cm to 0.28 cm, the amplitude of the alternating voltage varied from 2 to 5 kV and the frequency \( f = 2\pi \omega \) varied from 25 to 100 Hz. The gravity force was directed opposite to the direction of the \( z \) axis (figure 1).

To simulate the charged particle dynamics in the trap and to find the regions of particle confinement the Brownian dynamics has been used. The simulations took into account stochastic forces of random collisions with neutral particles, viscosity of the gas medium, regular forces of the trap electrodes and the gravitational force. Thus, the microparticle dynamics was described by the following Langevin equation [22]:

\[
m_p \frac{d^2r}{dt^2} = F_t(r) - 6\pi \eta r_p \frac{dr}{dt} + F_b + F_g + F_{int},
\]

(1)

where \( m_p \) and \( r_p \) are the particle mass and radius, \( \eta \) is a dynamic viscosity of gas medium (it is \( \approx 18.2 \) \( \mu \)Pas [23]), \( F_t(r) \) is the force of trap electrodes, \( F_b \) are stochastic delta-correlated forces accounting for stochastic collisions with neutral particles, \( F_g \) is the gravitational force, \( F_{int} \) is the interparticle force of the Coulomb interaction. To solve the stochastic differential equation (1) we used the numerical method developed in [24].

To simulate the interaction of the electric field of the trap with charged particle the model of point charges distributed along each electrode [16] was used. In paper [16], the confinement regions of a particle in the trap were presented as the dependencies of frequency \( f \) on the ratio \( q_p/m_p \), where \( q_p \) is particle charge. Particle mass was calculated in assumption of spherical particles with density \( \rho = 3990 \) kg/cm\(^3\). In this paper the confinement regions for single particle in figures 2 are presented as the dependencies of frequency \( f \) on charge density \( \sigma_p = q_p/s_p \). It was assumed that particles gain charges in corona discharge [17, 25]. The confinement regions in figures 2 are presented by filled areas.

In corona discharge the ratio \( q_p/s_p \) depends on the magnitude of the electric field strength \( E_c \) [17] and the charge \( q_p \) gained in the corona discharge is close to its maximum value \( Q_p(E_c) = 4\pi \varepsilon_0 r_p^2 E_c (1 + 2(\varepsilon - 1)/(\varepsilon + 2)) \) [25] where \( \varepsilon \) is the inductive capacity of the particles (in simulation \( \varepsilon = 10 \)). In figures 2 right borders of particle confinement are limited by charge density \( \sigma_{\text{max}}(E_c) = Q_p(E_c)/s_p \) (vertical lines in figures 2).
Figure 2. The regions of single particle confinement as the dependence of the frequency $f$ of alternating voltage on charge density $\sigma_p$ in air for different traps with (a) $L_b = 1.3 \text{ cm}$ and (b) $L_b = 2.8 \text{ cm}$. Vertical lines correspond to maximum charge density gained in corona discharge with $E_c; U_\omega = 5 \text{ kV}$.

In figure 2, one can see that the smaller trap is used the smaller particle charge is needed for its confinement. Also for different particles with different radii the confinement regions are different. Since particle confinement depends on the product of particle charge on voltage amplitude [16] the confinement regions can be shifted left or right by increasing or decreasing $U_\omega$ accordingly. To explain the possibility of particle separation let us consider figure 2b. The confinement region for $20 \mu m$ particle is located to the right-hand of the vertical line that corresponds to maximum $\sigma_{\text{max}}$. It means that $20 \mu m$ particles will not be confined by the trap. Decreasing the $E_c$ the $\sigma_{\text{max}}$ will also decreases and vertical line will shift to the left and for $E_c \sim 14 \text{ kV/cm}$ the confinement region for $1 \mu m$ will appear at the right-hand of the vertical line that means that $1 \mu m$ particles will not be caught by the trap.

In addition, the confinement regions are bordered not only by the charge density but by the frequency $f$. In figure 2a, the confinement region for $20 \mu m$ particle is limited by the frequency $f \sim 50 \text{ Hz}$. In figure 2b, the confinement regions for 10 and $20 \mu m$ are also limited by the frequency $f \sim 50 \text{ Hz}$.

Figure 3. The confinement of particles of particular type in traps with (a) $L_b = 1.3 \text{ cm}$ and $f = 50 \text{ Hz}$, (b) $L_b = 1.3 \text{ cm}$ and $f = 100 \text{ Hz}$ and (c) $L_b = 1.6 \text{ cm}$ and $f = 0 \text{ Hz}$. $U_\omega = 5 \text{ kV}$. Particles 1: $r_p = 5 \mu m$ and $q_p = 25000e$; particles 2: $r_p = 4 \mu m$ and $q_p = 16000e$; particles 3: $r_p = 1 \mu m$ and $q_p = 1000e$. 
In [16], it was mentioned that the force $F(t)$ is in an order of magnitude greater that the gravity force and the greater particle charge the closer particle to the central axis of the trap. It means that it is possible to achieve spatial separation of particles of different sizes by varying the parameters of the trap. To study spatial separation inside the traps with $L_b = 1.3$ and 1.6 cm polydisperse powder of 500 particles was injected. The powder consisted of particles of 5 types that differed with radius and charge: the radii and charges of the particles of the first type were $r_1 = 1 \, \mu m$ and $q_1 = 1000e$, for the 2nd type: $r_2 = 2 \, \mu m$ and $q_2 = 4000e$, 3rd type: $r_3 = 3 \, \mu m$ and $q_3 = 9000e$, 4th type: $r_4 = 4 \, \mu m$ and $q_4 = 16000e$, 5th type: $r_5 = 5 \, \mu m$ and $q_5 = 5000e$. Figure 3 presents the separation of the trapped particles in traps. At $f = 50$ Hz inside the trap with $L_b = 1.3$ cm the particles of 1st, 4th and 5th types were confined. Increasing the frequency $f$ up to 100 Hz leads to depositing of the small particles of type 1 from the trap while increasing $L_b$ to 1.6 cm leads to depositing particles of the 1st and 2nd types.

3. Conclusion
In this article the possibility of particle separation by alternating electric fields of quadrupole type was demonstrated. It was shown that varying the parameters of the trap (the distance between electrodes, the magnitude and frequency of alternating voltage) it is possible to separate both specific type of particles from the polydisperse powder as well as spatial separate them inside the trap.

Acknowledgments
The work was done under financial support from the Russian Foundation for Basic Research (grant No. 16-32-00031).

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