Regions of the nanoparticle confinement by the electrodynamic linear Paul trap

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Abstract. The possibility of the nanoparticles confinement by the electrodynamic Paul trap is shown. The areas of a nanoparticle confinement in gas flow are found. The electric potential of a nanoparticle for its capturing in the Paul trap should be of order 0.5 V to 150 V for particle sizes from 0.03 nm to 1 μm.

1. Introduction
Nanosized particles are present in atmospheric aerosols and astrophysical dusty plasmas [1, 2, 3]. Recent investigations have demonstrated a strong correlation between the presence of aerosols in the atmosphere and their effect on climate parameters and the quality of life [4, 5]. Therefore, a removal of charged particles is a very important issue. One way of filtering is a particle charging by the corona discharge and their deposition on the precipitation electrodes. For example, in electrostatic filters particles gain charge in the corona discharge and then are accumulated by the electrodes [6]. However, electrostatic filters are not efficient in capturing particles with sizes of 0.6–1.6 microns. Unfortunately, the problems of a selective particles removal cannot be solved by the corona discharge precipitators.

The other possibility of charged particles capturing is their confinement in alternating electric fields generated by electrodynamic traps [7]. The observation of dynamic traps for the charged particles confinement is presented in [8]. The analysis of charged particle motion in alternating electric fields is presented in [9].

In previous works [10, 11, 12, 13] the confinement of micron sized particles by the alternating electric fields has been studied in static gas media and in gas flows.

The goal of this work is a theoretical study of charged nanoparticles confinement by the electrodynamic Paul trap [7] in gas flows. The regions of the nanoparticle and trap parameters necessary for the particles confinement are investigated at normal conditions.

2. Mathematical simulation of charged nanoparticle dynamics in Paul trap in gas flows
The sketch of a linear Paul trap is presented in Figure 1a. The trap consists of four cylindrical electrodes with radius $R_1 = 1.5$ mm and length $L_m = 6$ cm. The alternating voltage is applied to electrodes: $U_\omega \sin(\omega t + \pi)$ to pair electrodes with number 1 and $U_\omega \sin(\omega t)$ to those with number 2, where $U_\omega$ is the alternating voltage magnitude, $\omega = 2\pi f$ and $f$ is the alternating voltage frequency. The distance between the axes of the neighboring electrodes varies from $L = 8$ mm to 28 mm. To simulate the charged nanoparticle dynamics in the trap and to find the regions of nanoparticle confinement the Brownian dynamics has been used. The simulations took into account stochastic forces of random collisions with

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neutral particles, viscosity of the gas medium, regular forces of the trap electrodes and the gravitational force. Thus, the particle dynamics was described by the following Langevin equation [14]:

$$m_p \frac{d^2 r}{dt^2} = F_t(r) - 6\pi \eta r_p \left( \frac{dr}{dt} - v_f \right) + F_b + F_g$$

where $r$ is the radius-vector of particle, $r_p$ is the particle radius, $m_p$ is the particle mass in the assumption of spherical particles ($m_p = \frac{4}{3}\pi r_p^3 \rho_p$), in simulations $\rho_p = 3700$ kg/m$^3$, $\eta$ is the dynamic viscosity of gas medium (18.2 μPa•s [15]), $C_x$ is the Cunningham factor [16], $v_f$ is the gas flow velocity, $F_t(r)$ 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. To solve the stochastic differential equation (1) the numerical method developed in [17] was used.

To simulate nanoparticle dynamics in the air at the normal conditions the Cunningham correction factor $C_x$ was taken into account as the dependency on particle size. In Figure 1b the dependence of $\eta/C_x$ on the particle size is presented obtained from the data in [16]. For the micron sized particles the Cunningham factor is close to 1.

To simulate the interaction of the electric field of the trap with a charged nanoparticle the model of point charges distributed along each electrode [14] was used.

Figure 2 presents the lower bounds of the regions of nanoparticle confinement for the charged nanoparticle for gas flow velocities 1, 5 and 10 cm/s at different interelectrode distances $L$. As the $F_t(r)$ depends on the $\frac{q_p U}{L}$ ($U = 2U_\omega$) [14], the lower bounds of confinement regions are presented as the dependencies of the expression $\frac{q_p U}{L}$ on $f$, where $U = 2U_\omega$. From Figure 2 one can see that at increasing of the gas flow velocity the minimum frequency of alternating voltage for particle catching increases. To catch nanoparticles in the gas flow with the velocity of 1 cm/s the frequency of the alternating voltage should be higher than 150 Hz (Figure 2a). In gas flows with the velocity of 5 cm/s the lowest frequency should be 400 Hz and for the velocity of 10 cm/s the frequency should be higher than 700 Hz. To catch micronsized particles the frequency $f$ should be one and a half times lower. Also from Figures 2a–c one can see that at increasing the interelectrode distance $L$ the frequency $f$ for particle cathing becomes lower.

From Figure 2 it is possible to find the potentials of nanoparticle needed for its confinement in the Paul trap for a given magnitude of the electric field strength ($2U_\omega/L$). For example, for the electric field strength of 20 kV/cm in Figure 3 the lower bounds of particle potentials $U_p$ are presented.
The lower bounds of the nanoparticle confinement for different particle sizes and gas flow velocities in trap with (a) $L = 8$ mm, (b) $L = 14$ mm and (c) $L = 28$ mm.

Figure 4 shows that at increasing the interelectrode distance the particle electric potential for its confinement rises despite of the same value of electric field strength in trap $2U_{\omega}/L = 20$ kV/cm.

3. Conclusion
The possibility of the nanoparticle confinement by the electrodynamic Paul trap was shown. The areas of the nanoparticle confinement in gas flow were found. The electric potential of the nanoparticle for its capturing in the Paul trap should be of order $0.5$ V to $150$ V for particle sizes from $0.03$ nm to $1$ μm and electric field potential up to $20$ kV/cm. As the interelectrode distance increases the particle electric potential for its confinement rises. Also as the gas flow velocity increases, the frequency of alternating voltage needed for particle capturing grows as well. To catch particles in gas flow with $1$ cm/s the frequency of alternating voltage should be higher than $100$ Hz, gas flows $2$ cm/s the lowest frequency should be $200$ Hz and for $10$ cm/s – $400$ Hz.

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Figure 3. The lower bounds of the electric potentials of the nanoparticle for different particle sizes and gas flow velocities in trap with (a) $L = 8$ mm, (b) $L = 14$ mm and (c) $L = 28$ mm.

Figure 4. The lower bounds of the electric potentials of the nanoparticle for different interelectrode distances.

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