Charged particle capturing in air flow by linear Paul trap

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Abstract. The paper presents the simulation results of micro- and nanoparticle capturing in an air flows by linear Paul traps in assumption that particles gain their charges in corona discharge, its electric field strength is restricted by Paschen equation and spherical shape of particles.

1. Introduction
For air filtering from suspended particles fibrous filters and devices based on the coagulation effect are used, for example, scrubbers and electrostatic filters based on the corona discharge unit, where particles gain electric charges and removed from gas flow to the precipitating electrode [1–3].

Another approach is using additional traps based on electrodynamic particle capturing that allow non-contact particle filtering. These traps are presented in [4–8]. The charged microparticles confinement by the electrodynamic trap has been studied in static gas media at normal conditions [5, 7], where the regions of capturing have been studied in a wide range of parameters such as microparticle charge, mass and radius, electric field strength and frequency. The interparticle distances in the linear Coulomb structures in the linear Paul trap were measured in [9, 10]. Improved electrodynamic trap allowing a more effective microparticle capturing has been suggested in [8, 11, 12]. In these works theoretical and experimental studies of filtering of aluminum oxide particles Al₂O₃ with radii 0.2–140 µm by the linear Paul trap from the air flow by the complex influence of ac and dc electric fields were provided.

The aim of the work is simulation of particle motion by Brownian dynamic methods in alternating electric fields and in air flow. Particle capturing in the linear Paul trap have been analyzed with the following restrictions: spherical shape of particles, particles supposed to get their charges in the corona discharge and maximum prebreakdown electric field strength in linear Paul trap is restricted by Paschen equation.

2. Mathematical simulation of charged particles capturing in air flows
The sketch of the setup for charged particles capturing in air flows is presented in figure 1(a). Particle gets charge in the unipolar corona discharge, the charge magnitude defined by the
**Figure 1.** (a) The sketch of the setup for charged particles capturing in air flow: 1—-the corona discharge module for particles charging; 2—the trap module. (b) Scheme of Paul trap.

equation [13]:

\[ q_p = 3\pi \varepsilon_0 E_c r_p^2 \left( 1 + 2 \frac{\varepsilon - 1}{\varepsilon + 2} \right), \]  
where \( q_p \) is particle charge, \( \varepsilon_0 \) is vacuum permittivity (electric constant), \( E_c \) is the average electric field strength in corona discharge module, \( r_p \) is radius of particle and \( \varepsilon \) is the relative permittivity of the particle (\( \varepsilon \sim 10 \) for \( \text{Al}_2\text{O}_3 \)). In simulations \( E_c = 16 \text{ kV/cm} \) according our previous works [8]. Also in this work attention is paid to particles with \( r_p \sim 1 \mu\text{m} \) and the results will be presented for particles with \( r_p = 0.5, 1 \) and \( 2 \mu\text{m} \). According to (1) maximum particle charges that particles can gain in corona discharge will be 690, 2800 and 11 100 \( e \) accordingly, where \( e \) is the elementary charge.

The trap module is presented by the linear Paul trap the scheme of which is presented in figure 1(b) [8]. The trap consists of four cylindrical electrodes with radius \( r_1 = 1.5 \text{ mm} \) and length \( L_m = 10 \text{ cm} \). The alternating voltage is applied to electrodes: \( U_\omega \sin(\omega t) \) to pair electrodes with number 1 and \( U_\omega \sin(\omega t + \pi) \) to those with number 2, where \( \omega = 2\pi f \), \( f \) is the voltage frequency, \( U_\omega \) is the ac voltage amplitude. The distances between neighboring electrodes \( X \) in simulations were \( (X = L_b - 2r_1): 3, 5, 7, 17, 27 \) and 37 mm.

According to Paschen’s equation [14] the minimum electric strength for all these \( X \) at atmospheric pressure is 30.4 \( \text{kV/cm} \) so in simulations the interelectrode electric field strength was \( U_\omega /X = 10 \) and 20 \( \text{kV/cm} \).

To simulate the charged particle dynamics in the trap the Brownian dynamics has been used. The simulations also took into account regular forces of the trap electrodes, the gravitational force and Stokes force of air flow drag. Thus, the particle dynamics was described by the Langevin equation [11]

\[ m_p \frac{d^2 r}{dt^2} = F_t(r) - 6\pi \frac{\eta}{C_x} r_p \left( \frac{dr}{dt} - v_f \right) + F_b + F_g, \]  
where \( m_p \) and \( d_r \) are the particle mass and radius in assumption of spherical particle, \( \eta \) and \( C_x \) are the dynamic viscosity of the gas medium and Cunningham factor [15] \( (\eta = 12.5 \mu\text{Pa s} \) for \( r_p = 0.5 \mu\text{m}, \eta = 16.5 \mu\text{Pa s} \) for \( r_p = 1 \mu\text{m} \) and \( \eta = 18.2 \mu\text{Pa s} \) for \( r_p = 2 \mu\text{m} \) ), \( F_t(r) \) is the
Increasing the interelectrode distance the maximum air flow speed for particle capturing electric charges they can carry and thus they can be captured at a higher air flow speed. Also the bigger particles the higher force of the trap electrodes, $F_\text{b}$, are stochastic delta-correlated forces accounting for stochastic collisions with neutral particles, $F_\text{g}$ is the gravitational force, $v_f$ is the velocity of the gas flow. For solving the stochastic differential equation (2) we used the numerical method developed in [16].

Figure 2 presents the maximum air flow speed for particle confinement at different interelectrode distances $X$. In figure 2(a) one can see that at increasing the frequency of alternating voltage the maximum flow speed decreases. Also the bigger particles the higher electric charges they can carry and thus they can be captured at a higher air flow speed. Increasing the interelectrode distance the maximum air flow speed for particle capturing decreases despite the same electric field strength (figure 2(b), $U_\omega/X = 10$ kV/cm).

Increasing electric field strength the air flow speed increases too, that is presented in figure 3 at $U_\omega/X = 20$ kV/cm.
3. Conclusion
The paper presents the results of simulation of Brownian dynamics of charged micro- and nano-particles motion in alternating electric fields of the Paul trap in air flow. Particle capturing in the trap was studied in assumption of spherical shape of particles, particles gain their charges in corona discharge and maximum prebreakdown electric field strength in linear Paul trap is restricted by Paschen equation. It was shown that decreasing the interelectrode distances as well as increasing the electric field strength in the linear Paul trap the air flow speed at which particle can be captured increases. Also bigger particles can be captured at a higher air flow speed.

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