Confinement of charged microparticles in a gas flow by the linear Paul trap

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Abstract. In this paper, we present the experimental results demonstrating the charged microparticles confinement in an electrodynamic trap in a gas flow and prove the selective possibility of these traps to capture charged microparticles in gas flows in a wide range of microparticle and trap parameters.

1. Introduction
Charged dust particles are often present in air of the nuclear plants or in many energy devices, for example, in etching and fusion installations. The removal of microparticles from these devices is a very important problem. One of the ways to improve the efficiency of filtration is to affect the microparticles by various physical factors in order to change their physical properties. For example, in electrostatic filters microparticles gain charge in the corona discharge and then are accumulated by the electrodes [1]. Unfortunately, the problems of a selective particles removal can not be solved by the electrostatic filters.

The idea of traps for charged particles often appears in the literature [2, 3]. Firstly, the idea of electrodynamic traps has been developed in mass spectrometry, molecular beam physics and physics of accelerators [4]. The description of dynamic traps for microparticles capture is described in [5].

The motion of charged particles in alternating electric fields [6] was analyzed and the results have been applied for treatment of experimental shock excitation of He atoms [7].

The charged microparticles confinement by the electrodynamic trap at normal conditions in stationary gas media [8, 9] have been studied in a wide range of parameters such as microparticle charge and radius, electric field strength and its frequency. The improved electrodynamic trap allowing more effective capturing of microparticles has been suggested in [10]. The interparticle distances in the linear Coulomb structures in the linear Paul trap were measured in [11, 12].

2. The experimental setup
The sketch of the experimental setup for charged microparticles confinement by the electrodynamic trap in a gas flow is presented in figure 1a. The experimental setup consisted of three separate modules located in a gas channel: 1 is the corona discharge module of microparticles charging, 2 is the trap module, 3 is the air-exhauster module. The gas channel was presented by the pipe of a square section with sides of length $L = 6$ cm.
Figure 1. The sketch of the experimental setup for charged microparticles confinement in a gas flow. The gas channel consists of 3 modules: a) 1 and b) are the corona discharge modules, a) 2 and c) are the trap modules, a) 3 is the air-exhauster module. The scheme of the single linear Paul trap is presented by the figure (d).

The corona discharge module (figure 1b) consisted of one row of the discharge electrodes and two rows of grounded ones. Two rows of the grounded electrodes were located above and below of the discharge electrodes at the distance of 12 mm. The discharge electrodes were made of wires with a diameter of 70 µm and were arranged at a distance 1 cm from each other. The positive DC potential $U_c = 15$ kV was applied to the discharge electrodes. The grounded electrodes were made of metal rods of the diameter $d = 3$ mm and the distance between their axes was $L_g = 12$ mm. This design generates an ion wind in two opposite directions compensating its effect on air inside the channel.

The trap module (figure 1c) consisted of four linear Paul traps [4] combined together to overlap the gas channel. The sketch of the single linear Paul trap is presented in figure 1d. The trap consisted of four cylindrical electrodes with radius $R_1 = 1.5$ mm and length $L = 6$ cm. The alternating voltage was applied to electrodes: $U_\omega \sin(\omega t)$ to pair electrodes with number 1 and $U_\omega \sin(\omega t + \pi)$ to pair ones with number 2, where $\omega = 2\pi f$, $f$ is voltage frequency, $U_\omega$ is AC voltage amplitude, $U_\omega = 840$ V and $f = 50$ Hz. The distance between the axes of the neighboring electrodes was $L_b = 1.4$ cm.

The diagnostics and registration of microparticles were made by 1 cm sheet of laser light (figure 1c). The sheet was oriented along the trap electrodes. The sheet height allowed watching microparticles both in the trap and out of it. The parameters of the sheet of laser light were: wavelength of 532 nm and power up to 230 mW. The registration of microparticles was done by the camera HiSpec Fastec Imaging with the resolution of 1280x1024 pixels located along the sheet of laser light.

The air-exhauster module was located at the end of the gas channel. The exhaust fan blows out a gas and allowed to provide the gas flow velocities up to $v_f = 50 \pm 11$ cm/s.

The polydisperse aluminum oxide $\text{Al}_2\text{O}_3$ powder was used in our experiments. The microparticle density was $\rho_p = 3990$ kg/m$^3$, and typical size $d_p$ was in the range from 4 to 80 µm.

To start the experiment we turned off the exhaust fan and applied the positive DC potential $U_c$. Then particles were injected in the corona module. Passing through the corona, particles
got a positive charge $q_p$ and fall inside the trap module, where they were captured between the electrodes. Figure 2a shows an example of the stable Coulomb structure of charged microparticles captured in the trap. The captured microparticles oscillated with frequency of 50 Hz around equilibrium positions. The most of the microparticles were captured inside the trap below the central axis.

To study the effect of the gas flow on the ensemble of captured microparticles the exhaust fan was turned on. Most of captured microparticles were blown out from the trap and only a few particles remained inside it (see figure 2b). The particle structure was shifted below the central axis of the trap while interparticle distances were enlarged.

To measure sizes of the captured microparticles we turned off the exhaust fan and analyzed the particles remained in the trap by two methods are presented in figure 3.

In the first method (figure 3a) there was a hole in the wall of the gas channel between the trap electrodes. During the experiment on microparticle capturing the hole was closed. After microparticles capture the exhaust fan was turned off, the hole was opened and the ebony electrified wand was inserted inside the trap to get particles captured by the trap.

In the second method (figure 3b) there was a slit in the wall of the gas channel under the trap. During the experiment on microparticle capturing the hole was closed. When the exhaust fan was turned off the slit was opened and the subject glass was inserted in the trap. Then the electrodynamic trap was turned off and microparticles fell down on the subject glass. In both cases microparticle sizes were measured by the microscope.

In our experiments we have used a powder of polydisperse microparticles of complex shape. To define the effective particle size of each microparticle we selected the smallest particle size $d_{min}$ and the largest one $d_{max}$. The effective microparticle diameter was defined as $d_p = \frac{d_{min} + d_{max}}{2}$.

Figure 4 presents the initial distribution of microparticles on sizes in the powder ($P_i(d_p)$), the distribution of microparticles on sizes obtained by the ebonite wand ($P_e(d_p)$) and the distribution of microparticles on sizes obtained by the subject glass slide ($P_g(d_p)$). The average diameter of the microparticles in the experiment (curves 1 and 2) was $d_p = 32 \mu m$.

Figure 5 presents the function $P(d_p)$ obtained according to the ratio $P(d_p) = \frac{P_e(d_p) + P_g(d_p)}{2P_i(d_p)}$. This function is the relative distribution of particles on sizes.

Figure 5 demonstrates that maximum of the distribution is shifted to small particles with respect to the initial powder. The second maxima at $d_p = 54 \mu m$ can be explained by the shape of particles that varied from spherical up to plates. This result indicates selectivity of the trap as the capture is more efficient for smaller particles.
3. Conclusion

Our experimental studies proved the possibility of the linear Paul trap to capture charged microparticles in gas flows in a wide range of microparticle and trap parameters, such as microparticle charges, electrode voltages, electric field frequencies and velocities of gas flows. For the first time it was experimentally validated the capturing of the charged microparticles ensemble with strong Coulomb interaction by the linear Paul trap in gas flows.

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