Capturing of a structure of charged micron-sized particles in the gas flow by the linear Paul trap

D. S. Lapitsky[1], L. V. Deputatova[1], V. S. Filinov[1], V. Ya. Pecherkin[1], R. A. Syrovatka[1], L. M. Vasilyak[1], V. I. Vladimirov[1]

[1]*Joint Institute for High Temperatures of the Russian Academy of Sciences (JIHT RAS), Bd.2, Izhorskaya st. 13, Moscow 125412, Russia*

In the paper simulation and experimental results of charged micron-sized particles capturing by the dynamic electric fields generated by the linear Paul trap in a gas flow at atmospheric pressure are presented. The regions of the micron-sized particle, linear Paul trap and gas flow parameters needed for particle capture have been obtained and experimentally tested.

1. Introduction.

Dynamic stabilisation of a charged particle motion demands a field that will confine a particle in a certain position.

For an example a particle may move in the parabolic electric potential $\Phi = \Phi_0(\alpha x^2 + \beta y^2 + \gamma z^2)/r_0$, where r_0 is the characteristic size of a studied volume. However, according to the Laplace equation $\Delta\Phi = 0$ and coefficients α, β, γ have to satisfy the condition $\alpha + \beta + \gamma = 0$, so at least one of them have to be negative: $\alpha = 1 = -\beta$, $\gamma = 0$. In this case the field will be of the two dimensional type and the potential electric field will be $\Phi = \Phi_0(x^2 - z^2)/r_0$. A particle in this field will make harmonic oscillations in x-y plane while its shifts along z-axis will exponentially increase. To prevent this effect the dynamic electric field can be used and the electric field will be of a type $\Phi = (V+U_\omega\cos(\omega t))(x^2 - z^2)/r_0$, where V and U_ω are DC and AC voltages amplitudes correspondingly, $\omega = 2\pi f$, f is the voltage frequency. A particle motion in this electric field is described by the Mathieu equation that has two types of the solutions that describe stable and unstable particle motions.

The viscous medium and gravity can significantly affect particle motion by the dissipation of particle energy by the gas medium and the solutions of the Mathieu equation will no longer be correct. To study dynamic stabilisation of a charged micron-sized particle motion by alternating electric fields in a gas medium the numerical simulation should be carried out.

The charged micron-sized particles confinement by the electrodynamic trap have been studied in static gas media at normal conditions [1,2], where the regions of capturing have been studied in a wide range of particle and trap parameters.

The goals of this work are theoretical and experimental studies of charged particle capturing in the linear Paul trap in a gas flow.

2. The setup for the charged particle capturing.

For the studies of particle capturing the charged particles have to be moved by the gas flow through the trap. The sketch of the experimental setup is presented in fig. 1a. The experimental setup consisted of three separate modules located in a gas channel: 1 was the corona discharge module for particles charging, 2 and 3 were detail structures of the corona discharge module and trap module respectively.

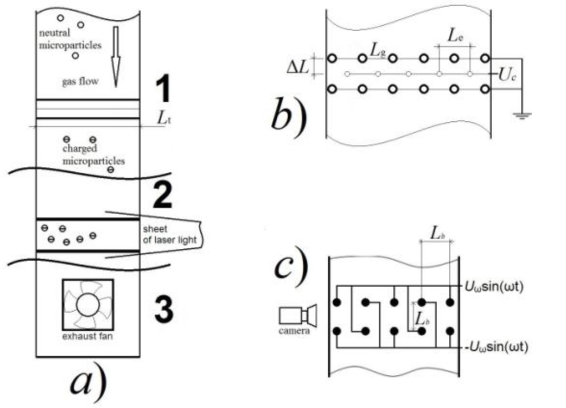

Fig. 1. The sketch of the setup for particles capturing by the linear Paul trap in the gas flow: a) gas channel of the experimental setup with 3 modules: 1 is the corona discharge module; 2 is the trap module; 3 is the gas flow module; b) corona discharge module; c) trap module.

In fig. 1b the sketch of the corona module is shown. Two rows of the grounded electrodes were located above and below of the discharge electrodes at the distance of ΔL = 12 mm. The discharge electrodes were made of wires with a diameter of 70 μm and were arranged at a distance L_e = 1 cm apart 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 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.

Figure 1c shows the sketch of the trap module. The two rows of electrodes were mounted across the air channel forming one trap consisted of 4 meshes (wide trap). Each mesh was presented by the single linear Paul trap that is presented in fig. 2 [3]. The trap consisted of four cylindrical electrodes with radius R_1 = 1.5 mm and length L_m = 6 cm. The alternating voltage was applied to electrodes: $U_\omega \sin(\omega t)$ to pair electrodes with number 1 and -$U_\omega \sin(\omega t)$ to pair ones with number 2. The distance between the axes of the neighbouring electrodes was 1.4 cm.

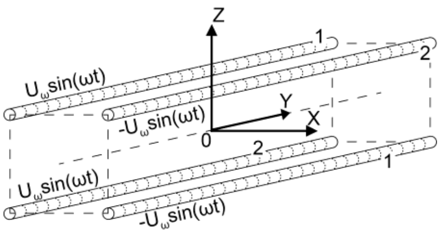

Fig. 2. The sketch of the linear Paul trap.

The diagnostics and registration of particles were made by 1 cm sheet of laser light. The sheet was oriented along the trap electrodes. The sheet height allowed watching particles both in the trap and out of it. The registration of particles 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 = 10 ~ 50 cm/s.

3. Numerical simulation of charged particle capturing in the linear Paul trap in the gas flow.

To simulate the charged particle dynamics in the trap and to find the regions of particle capturing 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 particle dynamics was described by the following Langevin equation [4]:

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

where m_p and r_p are the particle mass and diameter, r is particle radius-vector, η is the dynamic viscosity of gas medium (17.2 μPa∗sec), $F_t(r)$ 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, v_f is a velocity of a gas flow. For solving the stochastic differential equation we used the numerical method developed in [5].

The Coulomb forces acting on the particle from each electrode were presented as the sum of forces of point–like charges uniformly distributed along the electrode [2].

To study particle capturing we used the following parameters of the trap: U_ω = 8 kV, R_2 = 25 cm. For simulation we have used the particle with mass density ρ_p = 3990 kg/cm^3.

Figure 3 presents the difference of regions of charged particle capturing in case of the single linear Paul trap and the wide trap. The regions of particle capturing in case of the wide trap were wider.

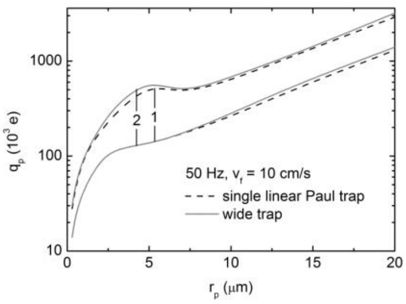

Fig. 3. The regions of charged particle capturing in case of single linear Paul trap and the wide trap.

Figure 4 presents the capturing regions for the charged particle (areas 1, 2, 3, 4) for a velocity 5 cm/sec of the gas flow for the wide trap.

The lower and upper bounds of particle capturing regions are shown by related lines. Above the upper bound the trap field is strong enough to push particle out of the trap. Below the lower bound particle cannot be captured as the trap field cannot compensate the gravity and Stokes forces.

The analogous regions of capturing versus particle diameter at frequency f = 80 Hz for gas flow velocities (v_f = 5, 10 and 15 cm/s) are presented in fig. 5.

Figure 5 shows that the capturing region becomes narrower with increasing the gas flow velocity due to the lower border shifting upwards at practically the same position of the upper bound.

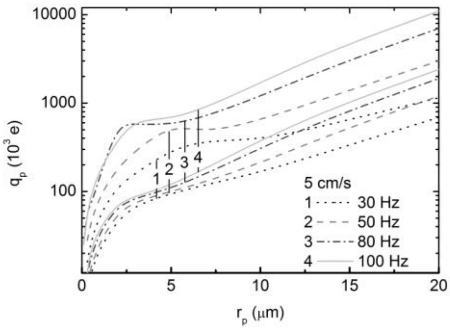

Fig. 4. Regions of capturing (between corresponding lines) versus particle radius r_p. Regions are located between the upper and lower bounds presented by corresponding lines for different electric field frequencies: 1 – f = 30 Hz, 2 – f = 50 Hz, 3 – f = 80 Hz, 4 – f = 100 Hz.

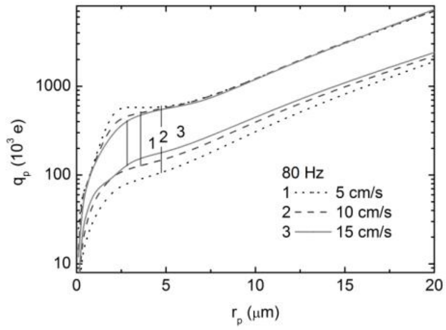

Fig. 5. Regions of capturing (between corresponding lines) versus particle radius r_p for different gas flow velocities: 1 – v_f = 5 cm/s, 2 – v_f = 10 cm/s, 3 – v_f = 15 cm/s.

4. Experiment.

The polydisperse aluminium oxide Al_2O_3 powder was used in our experiments. The particle density was ρ_p = 3990 kg/m^3, and typical size r_p was in the range from 2 to 40 μm.

Figure 6a shows an example of the stable Coulomb structure of charged micron-sized particles captured in the trap without the gas flow. The captured particles oscillated with frequency of 50 Hz around equilibrium positions. The most of the particles were captured inside the trap below the central axis, while others were trapped above of it.

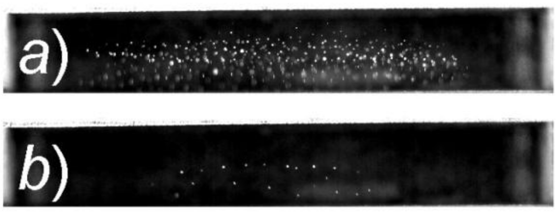

Fig. 6 The structure of charged particles captured by the trap (a) in a static gas media (v_f = 0 cm/s) and (b) in the gas flow (v_f = 50 cm/s)

To study the effect of the gas flow on the ensemble of captured particles the exhaust fan was turned on. Most of captured particles were blown out from the trap and only a few particles remained inside it (see fig. 6b). The particle structure was shifted below the central axis of the trap while interparticle distances were enlarged.

To measure sizes of the captured particles we turned off the exhaust fan and analyzed the particles remained in the trap by method shown in fig. 7. Withdrawal of particles was carried out when the exhaust fan was turned off to prevent the ingress of dust into the trap from outside.

In this method we used a closed slit. 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 particles fell down on the subject glass. In both cases particle sizes were measured by microscope.

The effective particle radius was defined as $r_p = (r_{min}+r_{max})/2$. The accuracy of particle radius measurements was 2 μm. Figure 8 presents the three distributions of particles versus the effective sizes. The first one is the distribution of particles on sizes obtained by the subject glass slide. The second one is the initial distribution of particles introduced in the flow.

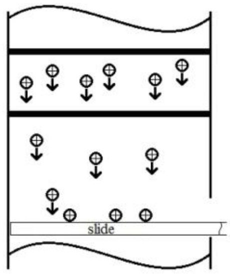

Fig. 7 The sketch of the captured particles taking by the subject glass slide.

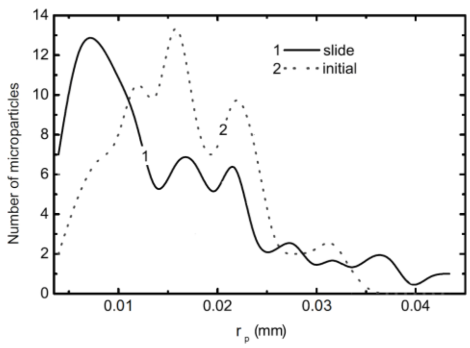

Fig. 8 The initial and captured particle distributions:
1 is the distribution of particles on the subject glass;
2 is the initial distribution.
The average diameter of the particles in the experiment was r_p = 16 μm with rms deviations σ = 0.02.

4. Conclusion

The simulations and experimental studies prove the possibility of a linear trap to capture charged micron-sized particles in gas flows. For the first time it was experimentally confirmed the capturing of the charged micron-sized particles ensemble with strong Coulomb interaction by the linear Paul trap in gas flows.

5. References

[1] Filinov V.S., Lapitsky D.S., Deputatova L.V., Vasilyak L.M., Vladimirov V. I., Pecherkin V.Ya. *Contrib. Plasma Phys*. **53** (2013) 450 - 456.

[2]Vasilyak L.M., Vladimirov V.I., Deputatova L.V., Lapitsky D.S., Molotkov V.I., Pecherkin V.Ya., Filinov V.S. \and Fortov V.E. *New Journal of Physics* **15** (2013) 43 – 47.

[3] Paul W. *UFN* **160** (1990) 109.

[4] Filinov V.S., Lapitsky D.S., Deputatova L.V., Vasilyak L.M., Vladimirov V. I., Sinkevich O.A. *Contrib. Plasma Phys.* **52** (2012) 66 – 69.

[5] Skeel R.D., Izaguirre J.A. *Molecular Physics* **100** (2002) 3885 – 3891.