Electrodynamic levitation chamber with parallel double-plate and double-ring electrodes for aerosol investigations

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We present an original design of an electrodynamic levitation chamber (EDLC) with parallel double-plate and double-ring electrodes for investigations of microphysical characteristics of charged aerosol particles. The theory of microparticle motion in the EDLC volume is developed, and analytical equations for the particle oscillation amplitude and displacement of the particle center of oscillation depending on the voltage across the electrodes are obtained. The motion stability boundary for particles of different substances for this EDLC is theoretically determined. Experimental results concerning EDLC characteristics agree well with theoretical predictions. The linear voltage dependence of the amplitude and displacement of the particle oscillation center is found.

Introduction

It is quite convenient to study microphysical properties of atmospheric aerosols under laboratory conditions by use of levitation of individual (or a small group of) particles in a cell under the effect of physical forces of various nature.[1] In particular, this technique is promising for studying the processes of interaction of low-intensity electromagnetic radiation with particles of different substances in a wide range of particle size (1–100 μm) under different pressure of the ambient gas (up to 10^{-2} Torr).

Such experimental conditions obviously model quite completely the behavior of aerosols in the upper atmosphere at different heights in the field of solar radiation not only in the relation to Knudsen number but also to the value of the diffraction parameter.

The most widely used method for levitation of charged microparticles is now their capture in a volume of an electrodynamic levitation chamber (EDLC) under the combined effect of direct and alternating electric fields. Different EDLC design is used for this purpose: from very intricate (bihyperbolic electrodes[2]) to rather a simple (spherical void,[3] coaxial rings,[4] etc.). A comprehensive review on this issue can be found, for example, in Ref. 1.

In this paper, we describe an original EDLC design with double-ring electrodes for alternating electric field and parallel double-plate electrodes for the direct electric field and some results of its tentative test in aerosol studies. This design has some significant merits. First, it provides, for the best conditions of particle observation in a chamber and, second, for a wider set of vertical force effects on the particle as compared with other designs. Third, this design of electrodes allows rather simple calculation of the electric field strengths in the EDLC volume, that is needed for further analysis of experimental results.

Description of the EDLC and experimental technique

Figure 1 shows the arrangement of EDLC electrodes, and Fig. 2 depicts the layout of the experimental setup based on the electrodynamic balance with parallel double-plate and double-ring electrodes. The setup consists of a brass chamber *1*, which houses two parallel copper rings *4* used for generation of the alternating electric field and two aluminum disks *8* used for generation of the direct electric field. The inner diameter of the chamber is 98 mm and its height is 80 mm. The rings with the radius R_0 = 6.7 mm are made of a copper wire with d = 1 mm. The disks have the diameter D_0 = 60 mm and thickness of 3 mm. The separation between the rings $2h$ is 4 mm, and the separation between the disks $2H$ is 30 mm.

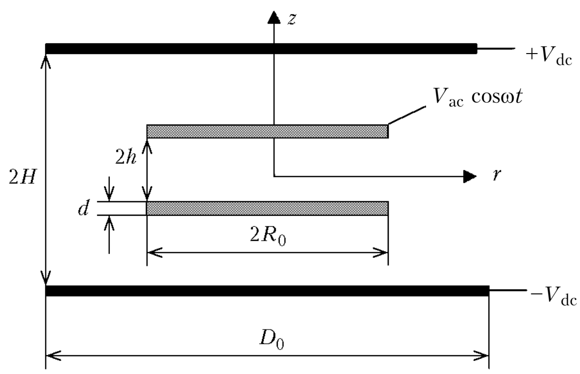

Fig. 1. Arrangement of electrodes in EDLC with parallel electrodes.

The chamber has six inlets, which are used for injection of particles, power points, illumination of the measurement volume, external irradiation, chamber evacuation, and for observations over a particle. It is possible to conduct experiments at low gas pressure, and

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the chamber can be evacuated down to the pressure of 10^{-2} Torr. The upper cover houses the ionizer *10* to charge and inject aerosol particles. The ionizer is made as a glass pipet with a grounded ring electrode at thin end. A needle, to which high negative voltage (− 4.5 kV) is applied, moves inside the pipet. The ionizer contains a small amount of powder of the particles under study. As the needle approaches the pipet end, electric discharge occurs, which charges particles and injects them into the chamber.

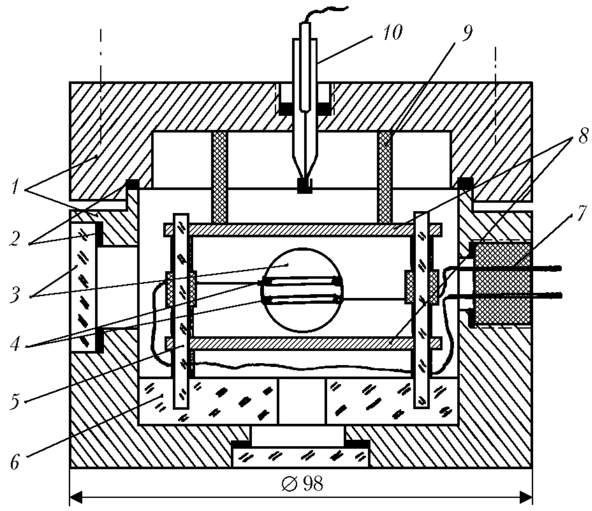

Fig. 2. Working chamber of the experimental setup (vertical cross section): brass body *1*, rubber gaskets *2*, observation windows *3*, ring electrodes for generation of alternating electric field *4*, glass columns *5*, EDLC base *6*, power points *7*, end electrodes (disks) for generation of the static electric field *8*, press-on hush *9*, ionizer *10*.

To confine the charged particle inside the EDLC, the following technique is used. Several particles leave the ionizer and enter the working chamber. Initially, only alternating voltage is applied to the ring electrodes. Some of falling particles are entrapped by the alternating electric field at different points between the rings. Then, decreasing the alternating voltage, we obtain such a situation that all particles but one deposit on the rings or chamber walls. Then the alternating voltage is increased, and the particle occupies a position at the EDLC axis below its geometric center. As this takes place, the particle oscillates along the vertical EDLC axis. Applying the constant voltage to the disks, we can place the particle at the EDLC center, where it stably rests for a long time at certain amplitude of the alternating voltage.

Theory of electrodynamic levitation

To use the EDLC for studying different physical processes with the participation of atmospheric aerosols, we should first solve the problem on motion of a charged particle in electric fields inside the levitation chamber. The equation of motion of a rather large particle for the axial component has the following form:

$$m\frac{\mathrm{d}^2 z}{\mathrm{d}t^2}+6\pi\eta R_\mathrm{p}\frac{\mathrm{d}z}{\mathrm{d}t}-qE_\mathrm{ac}=q[E_\mathrm{dc}-E_\mathrm{dc}(0)]\,. \quad (1)$$

Here m is the particle mass; R_p is the particle radius; η is the dynamic viscosity of a gas; q is the particle charge; E_ac and E_dc are the strength of the alternating and static electric fields; $E_\mathrm{dc}(0)$ is the strength of the static electric field confining the particle at the EDLC center, where the force of gravity is equal to the electrostatic force:

$$qE_\mathrm{dc}(0) = mg. \quad (2)$$

Designating $E_\mathrm{ac} = C_\mathrm{ac} V_\mathrm{ac}$, $E_\mathrm{dc} = C_0 V_\mathrm{dc}$, $\omega t = \tau$ and taking into account the solution of the Laplace equation for electric fields in the EDLC volume, we can write Eq. (1) in the form

$$\frac{\mathrm{d}^2 z}{\mathrm{d}\tau^2}+A\frac{\mathrm{d}z}{\mathrm{d}\tau}-Bz\cos\tau=D\,; \quad (3)$$

$$A=\frac{6\pi\eta R_\mathrm{p}}{m\omega},\ B=\frac{g}{\omega^2}\frac{C_\mathrm{ac}}{C_0}\frac{V_\mathrm{ac}}{V_\mathrm{dc}(0)},\ D=\frac{g}{\omega^2}\left[\frac{V_\mathrm{dc}}{V_\mathrm{dc}(0)}-1\right], \quad (4)$$

where A is the deceleration parameter; B is the parameter of the electric field; D is the parameter of external effects. In Eq. (4) V_ac and V_dc are the ac and dc voltages across the electrodes; $V_\mathrm{dc}(0)$ is constant, at the EDLC center; C_ac and C_0 are the geometric constants determined by the electrode shape and size. For the EDLC design used, $C_\mathrm{ac} = 2.00 \cdot 10^4$ m^{-2} and $C_0 = 77.3$ m^{-1}. The geometric constant C_ac for the ring electrodes was calculated by the technique from Ref. 4, and the constant C_0 was calculated from the estimated capacity of the plane capacitors with the allowance for edge effects.[5]

The nonlinear equation (3) at $D = 0$ can be reduced to the Mathieu equation, which describes nonlinear processes in the electric and mechanic systems. It is known that at certain values of the parameters A and B, a solution to this equation describes unstable motion of a particle in the EDLC.[6] In the plane of the parameters A and B there is a curve called the stability boundary, which separates the areas of stable and unstable particle motion. This curve is a very important characteristic of an EDLC, and its equation in the first approximation has the following form:

$$A^2 = -2 + 2\,(1 + 2B^2)^{1/2}. \quad (5)$$

At a fixed frequency of the alternating electric field, as the ac voltage V_ac increases, an instability point is achieved, at which the amplitude of particle oscillations increases sharply (Fig. 3). The value of this critical voltage can be measured with high accuracy, and this allows Eq. (5) to be used for experimental determination of the EDLC characteristics, as well as of the size of the particle under study.

If a particle is disturbed from the equilibrium at $z = 0$ by changing the static electric field V_dc, then it oscillates along the EDLC vertical axis. In this case, the amplitude of the oscillations, the displacement of the center of oscillations, and their phase can give rich additional information on the physical characteristics of aerosol particles (their mass, density, charge, and so on).

The nonlinear equation (3) in the general case should be solved numerically. At the same time, we have undertaken an attempt to derive an approximate analytical solution of the equation using the Bubenov–Galerkin method of successive approximations. In the first approximation, sinτ and cosτ were taken as basic functions. Then, the sought solution for z should have the form

$$z = A_0 + a \sin \tau + b \cos \tau, \tag{6}$$

where A_0, a and b are unknown coefficients to be determined. Substituting Eq. (6) into Eq. (3), we obtain

$$- a \sin \tau - b \cos \tau + aA \cos \tau - Ab \sin \tau - A_0B \cos \tau +$$
$$+ ab \sin \tau \cos \tau + bB \cos^2 \tau - D = 0. \tag{7}$$

Having multiplied Eq. (7) by the basic functions and integrating it over the whole oscillation period, we obtain equations for the determination of unknown coefficients a and b:

$$-a - Ab = 0, \quad -b - aA - A_0B = 0, \tag{8}$$

wherefrom

$$a = \frac{A_0AB}{1 + A^2}, \quad b = -\frac{A_0B}{1 + A^2}. \tag{9}$$

It follows from Eq. (9) that the oscillation amplitude A_1 and phase Θ are:

$$A_1 = \left(a^2 + b^2\right)^{1/2} = \frac{A_0B}{\left(1 + A^2\right)^{1/2}},$$

$$\Theta = \arctan\frac{a}{b} = \arctan(-A). \tag{10}$$

The displacement of the oscillation center of the particle (center displacement) A_0 can be found from the following reasoning. Let us write Eq. (6) in the form

$$z = A_0 + A_1 \cos (\tau - \theta), \quad \sin \theta = \frac{a}{A_0}, \quad \cos \theta = \frac{b}{A_0}. \tag{11}$$

Substituting Eq. (11) into Eq. (3) and using the known trigonometric equations, we obtain

$$A_0 = (1 + A^2)\, D/B^2. \tag{12}$$

Equations (10) and (12) with the allowance for designations introduced in Eq. (4) describe the motion of a charged aerosol particle in the EDLC of a given design in the first approximation and therefore they can be used for experimental determination of particle characteristics. In Ref. 7, where the theory of particle motion in a double-ring EDLC is described as well, an error or misprint is likely present (the results differ from those described above exactly twice).

Experimental results

By changing the magnitude and frequency of the ac voltage, as well as the value of the dc voltage in the EDLC, we can check the adequacy of the above theory to the experiment. Below we present briefly the results of this comparison.

Figure 3 depicts a theoretical curve of the stability boundary and experimental values for particles of different substances and different size. Licopodium particles as well as nickel particles produced in explosive dispersion of wires had spherical shape, and this allowed their radius to be determined correctly. For other, nonspherical particles, the effective aerodynamic radius was determined. It should be noted that the experimental data agree well with the theoretical curve for various particles.

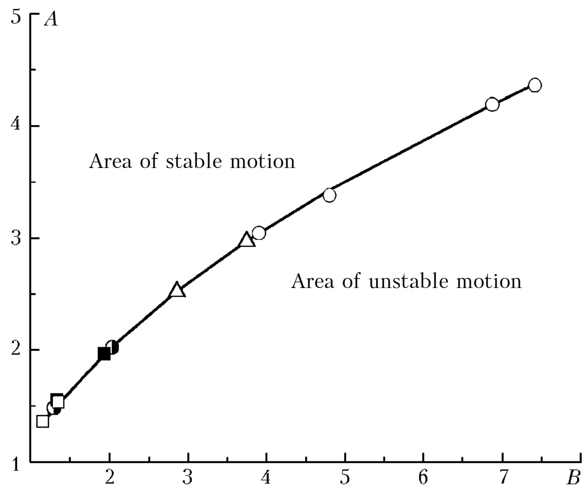

Fig. 3. Stability diagram of particle motion in the EDLC (theory and experiment): licopodium particles (○), nickel (△), iron (□), titanium (■), copper (◐), and theory (curve).

Theoretical and experimental values of the parameters A_0, A_1, and ratios A_0/A_1, A_0/A_1^2 are tabulated below for different values of the ac voltage V_{ac} for a licopodium particle.

Oscillation characteristics of licopodium particle (a = 16.1 μm) for different ac voltage V_{ac} at $V_{dc}(0)$ = 29.8 V, f = 50 Hz

V_{ac}, V	A_1, μm (exp.)	A_0, μm (exp.)	$(A_0/A_1^2)\cdot 10^4$, m^{-1} (exp.)	$(A_0/A_1^2)\cdot 10^4$, m^{-1} (theory)
468	169	514	1.77	1.77
595	140	319	1.67	1.77
738	112	226	1.80	1.77
919	96.1	164	1.77	1.77
1108	85.4	124	1.71	1.77
1203	80.4	94.9	1.53	1.77

Figure 4 illustrates the dependence of the ratio A_0/A_1 on V_{ac}. For the whole range of experimental values of this characteristic, we can see a good agreement with the theoretical predictions.

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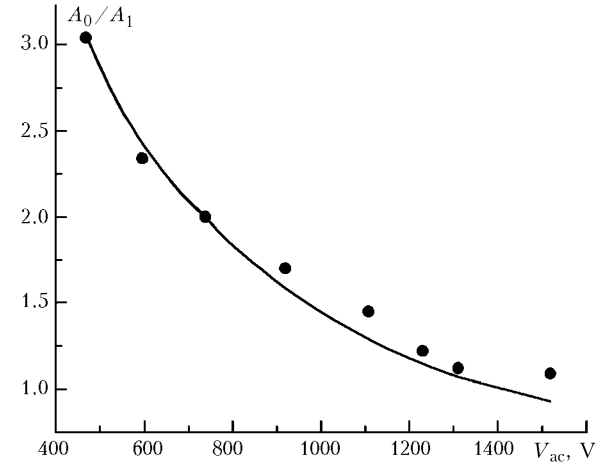

Fig. 4. The ratio A_0/A_1 as a function of the ac voltage V_{ac} for licopodium particle (a = 16.1 μm, $V_{dc}(0)$ = 29.8 V, f = 50 Hz), theory (curve).

Figure 5 shows the dependence of the ratio A_0/A_1^2 on the ac frequency f at the constant V_{ac} and V_{dc} voltages across the electrodes.

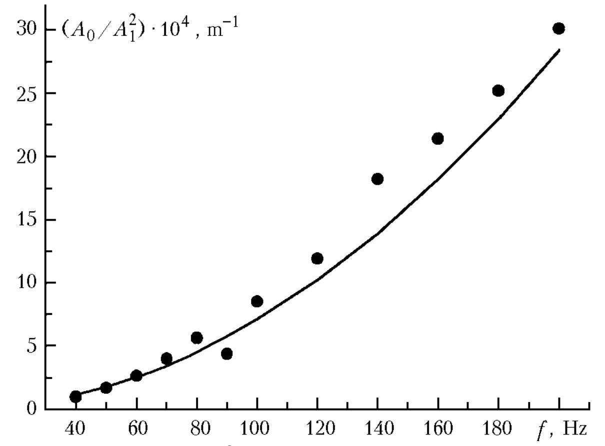

Fig. 5. The ratio A_0/A_1^2 as a function of the ac frequency f for licopodium particle ($V_{dc}(0)$ = 29.8 V, V_{ac} = 1365 V), theory (curve).

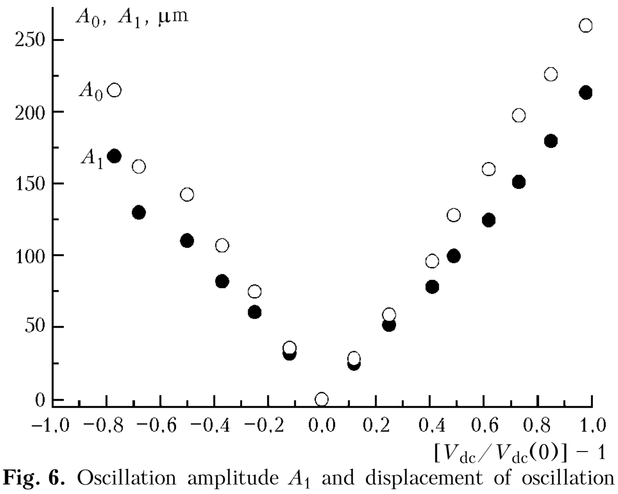

Fig. 6. Oscillation amplitude A_1 and displacement of oscillation center A_0 of a licopodium particle as functions of the strength of static electric field V_{dc} ($V_{dc}(0)$ = 26 V, V_{ac} = 809 V, f = 50 Hz).

Theoretically, this ratio depends only on the frequency of the ac voltage f and is proportional to its square. Experiment confirms this theoretical conclusion within the experimental accuracy. Figure 6 shows the dependence of the oscillation amplitude A_1 and the displacement of the particle oscillation center A_0 on the direct voltage V_{dc} at a fixed ac voltage V_{ac}. It can be seen that this dependence is almost linear, as was predicted theoretically.

This fact can be used to measure the forces acting on the microparticle along the vertical direction.

Conclusion

In this paper, we have described a particular design of the electrodynamic levitation chamber with parallel double-plate and double-ring electrodes, which possesses some advantages over similar chamber we used earlier[8] (in particular, it provides for more stable trapping of particles in the measurement volume). The theory of the EDLC has been presented, which includes calculation of electric fields in the levitation volume and prediction of the oscillation amplitude, the displacement of the oscillation center, and the oscillation phase for a particle as it is disturbed from the equilibrium.

This technique allows simultaneous determination of different microphysical characteristics of a particle in one series of experimental measurements. Test measurements confirm the adequacy of the developed theory to the experiment. In the future, this setup is planned to be used for experimentally modeling the dynamics of atmospheric aerosols in the field of solar radiation at different heights in the upper atmosphere.

Acknowledgments

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