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Dust particles selection in plasma-forming gases with different ionization potentials

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The sizes of dust particles capable of levitating in dust traps in striations in a glow discharge in all inert gases are quantitatively determined for the same discharge parameters. A more than twofold decrease in the particle size was established upon passing from the gas with the maximum ionization potential (He) to Xe. The dependence found in the experiment is interpreted from the point of view of the conditions of particle levitation. It is shown that in gases with a low ionization potential in the balance of forces, the ion drag force exceeds the force of gravity, while the absolute values of the forces decrease with decreasing particle size. The discovered effect can be used for fine trapping of dust particles in plasma traps.

Keywords: Dusty plasma, glow discharge, polydisperse particles, inert gases, ion drag force.

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Introduction

The main features of the dust plasma are the self-organization of the dust component into an ordered structure capable of forming different types of spatial crystal packing [1,2], the occurrence of new types of waves [3], as well as extreme properties of an ordinary matter — mechanical, thermodynamic, magnetic [1,4,5]. Dust granules capable of levitating in a plasma trap are selected during the formation of dust plasma. A number of particle parameters are used for selection: mass (size and density), electrical capacity (size and shape). To study the characteristics of particle selection in traps, as well as for the practical use of dust plasma filters, an experimental study of the parameters of polydisperse dust particles with variations in the main plasma parameters, primarily — temperature (energy) of electrons, is of interest. Such a study is possible with the use of polydisperse particles of the same density in the discharge of different inert gases.

Dust structures formed in a glow discharge can contain up to 8000 particles. The method of capturing particles directly from the discharge was developed in [6]. The particles extracted from the discharge are observed in an optical microscope, and an electron microscope is used to study the shape of the surface [7,8]. The projected two-dimensional particle size is determined statistically from the collected samples [9]. Further, the mass, electrical capacity are determined by the characteristic particle size and the forces involved in the balance of forces during the levitation of particles in a dust trap are estimated.

A specific feature of the presented study is the study of the characteristics of the particles selected in the dust trap, depending on the discharge parameters. When the working gas varies from helium to xenon, the ionization potential changes by half. Accordingly, the electrical characteristics change: the energy of electrons (the charge of dust particles), the retaining electric field. The mass of ions, due to the ionic entrainment of [1–3], increases by 33 times. On the one hand, this created difficulties in the formation of dusty plasma under very different conditions, as it manifested itself in a special selection of conditions in neon and krypton [10,11] and when using a mixture of helium and xenon gases in limited proportions [12]. On the other hand, having overcome this difficulty, we were able to consistently trace the change in the size of levitating particles during the transition from a gas with a maximum ionization potential (helium, 24,eV) to a gas with a minimum potential (xenon, 12,eV). This change showed that under experimental conditions (the same pressure and discharge current), the forces involved in the balance change. The absolute values of the forces are falling, but their ratio is changing. The balance is determined by the weight of the particle and the electrostatic force in light inert gases, the weight turns out to be insignificant in gases heavier than argon and the balance is determined by the electrostatic force and the ionic entrainment force.

1. Experiment

Polydisperse quartz with a density of $2.5\,\mathrm{g/cm^3}$, sifted through a vibrating screen system, the size range of the initial powder up to $25\,\mu$m was used for the study. The characteristic size d was determined by projection measurements of the maximum particle size x and the perpendicular size y as $d = (x + y)/2$ [9,13]. The imperfect (non-spherical) shape of the particle surface was estimated

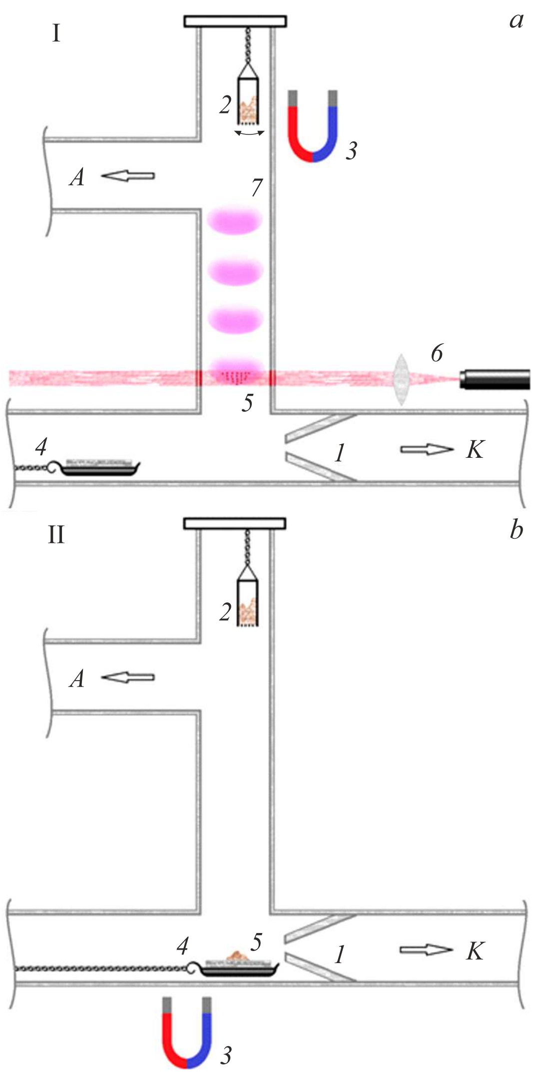

Figure 1. Diagram of the experimental setup showing two stages of the experiment: *a* — Stage I — selection of dust particles by stratified discharge; *b* — Stage II — capture and extraction of levitated particles from the discharge chamber. *1* — dielectric insert used to form standing strata; *2* — container filled with backfill polydisperse powder; *3* — magnet moving metal movable elements inside the discharge chamber; *4* — collecting device; *5* — particles selected by the discharge for levitation; *6* — laser illumination system; *7* — standing strata.

by the shape factor $f = x/y$ [9]. The shape factor f did not depend on the particle size d in the initial powder, its average value $\langle f \rangle$ was close to 1.5.

Dust traps were formed in standing strata in a glow discharge in different inert gases at the same discharge parameters: pressure $P = 0.33$ Torr, discharge current $i = 1.5$ mA. The use of a discharge diaphragm forcibly formed a positive column in a stratified mode. Particles were injected into the vertical section of the discharge chamber (a tube with a length of 10 cm and a radius of 1 cm) with a formed stratum system from above from a container with a mesh bottom, they levitated in the head part of the stratum — areas with a strong electric field. The particles are under a floating potential U_{fl} in the plasma and accumulate a negative electric charge on the surface, in our conditions of the order of 10^4 elementary. If the vertical and radial balance of forces are carried out, then a dust structure is formed in the dust trap. Strict conditions for levitation of calibrated particles of a given size were not selected in our experiments. On the contrary, particles capable of levitation were selected in the experiment from polydisperse particles in the discharge, particles of specific size in different inert gases.

The lower part of the discharge chamber had a horizontal section along which the collecting device could move to capture and collect particles. It consisted of a metal carriage controlled from the outside by a permanent magnet, and a strip of cover glass or a silicon plate placed on it, depending on the type of microscope used. After the formation of dust plasma in the vertical section of the chamber, a collecting device was brought under it, and the discharge was extinguished. The process of formation and capture of the dust structure was controlled by illumination and recording on a video camera located on the side. A schematic representation of the discharge tube is shown in Fig. 1. Electrodes for creating a field of the desired polarity to hold negatively charged particles were located in the lateral processes (cathode from below, anode from above).

The collecting device with trapped particles was placed under a microscope after extraction from the discharge chamber. Axio Lab A1 optical microscope was used. The collected objects were photographed with the required magnification and their size and shape were monitored. Distributions were constructed like in [12] using the obtained data and these distributions were used to determine average characteristic size d, the shape factor f and the dispersion of the size distribution in different gases σ. These values should characterize the parameters of dust particles and plasma traps. Probably, d and f should characterize the depth of the pit, and σ can be related to the width, since the stratum is a volumetric trap, and in its different phases the plasma parameters (field, concentration of charged particles, electron energy) are different [14–16]. Experimental data did not reveal a significant difference for f and σ in different gases, but demonstrated a significant change for d. For example, the ratio d is 2.1 in helium and xenon, i.e. the particle masses differ by almost an order of magnitude. The dependence of the characteristic particle size d on the gas grade is shown in Fig. 2. Next, we will analyze this result from the point of view of the acting forces and the conditions of particle levitation.

2. Analysis of the levitation conditions of dust particles in different gases

The detected changes in the average particle size from 6.3 to 3.0 μm show a very large change in gravity, from

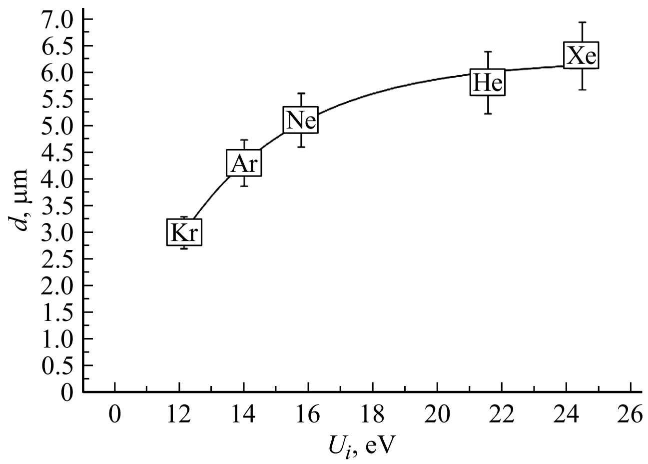

Figure 2. The dependence of the average particle size on the ionization energy of the atom of the plasma-forming gas in which the levitating particles were collected. For all gases, pressure — 0.33 Torr, discharge current — 1.5 mA.

3.27 pN in helium to 0.34 pN in xenon. This should greatly affect the vertical balance of the forces holding the particles, which must be quantified. It follows from Fig. 2 that the nature of the change in particle size between helium and neon and between krypton and xenon is different. The curve of the dependence of the size d on the ionization potential U_i is generally smooth, but its derivatives on the left and right differ. In discharges of weak current and low pressure, the main characteristics depend significantly on the ionization potential of the gas, first of all, the electron energy and the magnitude of the field [16]. The curve in Fig. 2 indicates a change in the nature of the dependence for light and heavy inert gases. We get a smooth change with a constant value of the derivative $\Delta d/\Delta m_i$ for both the region of light and heavy gases if we imagine the dependence of the change d on the mass of the ion (Fig. 3). The change in particle size is more sensitive to the replacement of the ionization potential of the gas than to the replacement of the ion mass. The change in the ionization potential affects the discharge field, the average electron energy and, as a consequence, the charge of the dust particle [1–3]. The experimental dependence shown in Fig. 2, as well as its representation as a derivative of $\Delta d/\Delta m_i$ depending on U_i or on m_i indicate that the change in discharge characteristics manifests itself significantly in heavy gases when the mass of trapped dust particles the smallest. In this range of discharge parameters, the forces associated with the particle charge should vary significantly. This is due to a change in the field E, the particle charge q in the holding force q_E, as well as an additional change in the ion concentration n_i and the electron temperature T_e in the power of ionic infatuation. Let us estimate the changes in these forces quantitatively in accordance with the dynamics of solitary dust particles [1–3].

The electric field to compensate for the weight of particles is directed against gravity in typical experiments with dust plasma [17]. This geometry causes the movement of ions, creating an ionic entrainment force F_{id} directed downward. Then the force balance equation for a levitating particle is written as

$$qE = mg + F_{id}. \quad (1)$$

In electric force

$$F_E = qE \quad (2)$$

the electric field E is determined by the conditions in the plasma, and the charge of the particle q depends on its electrical capacity and floating potential U_{fl}. The expression for the ion entrainment force has the form

$$F_{id} = \frac{8\sqrt{2\pi}}{3} a^2 n_i m_i V_{T_i} V \left\{ 1 + \frac{z\tau}{2} + \frac{z^2\tau^2}{4} \Pi \right\}, \quad (3)$$

where V_{T_i} and V — thermal and directional velocity of ions; $z = |Z_d|e^2/aT_e$ — dimensionless particle charge; Z_d — charge number; a — particle radius; electron-ion temperature ratio $\tau = T_e/T_i$; Π — Coulomb logarithm integrated by ion distribution function [1–3], $\Pi \sim 1$. It is necessary to perform force estimates in (1) for all inert gases to interpret the obtained particle sizes. Simulation results based on the OML [1–3] model are used in (2) to estimate the charge depending on the gas grade and particle size, the field E was determined by experimental measurements. The plasma concentration n_i in (3) was determined by the discharge current. The temperature values T_e in different gases were taken according to calculations [18–20]. The numerical estimates made are summarized in a table. The bottom row of the table shows the change in the ratio of the ionic entrainment force to gravity (both forces are directed downward). It can be seen that when the force of ion entrainment exceeds the force of gravity, the size change occurs faster (the curve in Fig. 2, starting with argon).

The following should be noted regarding the strengthening of the action of the force of ion entrainment. Two factors can be distinguished in expression (3): an increase of the

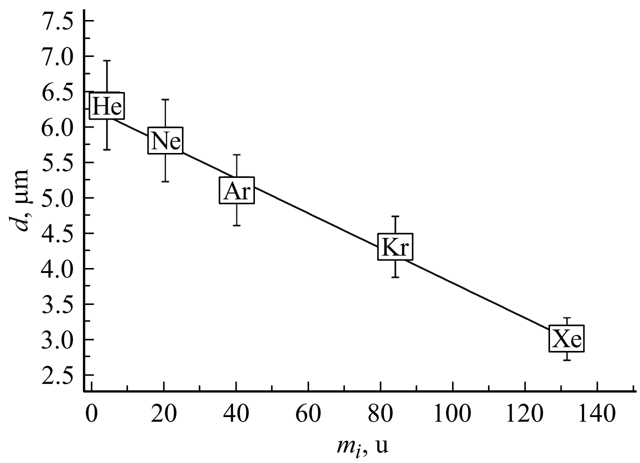

Figure 3. The dependence of the average particle size on the mass of the atom of the plasma-forming gas in which it levitates. For all gases, pressure — 0.33 Torr, discharge current — 1.5 mA.

Forces acting on a particle in different gases

Forces	He	Ne	Ar	Kr	Xe
qE, pN	5.40	4.80	3.20	2.15	1.35
mg, pN	3.27	2.44	1.56	0.90	0.34
F_{id}, pN	2.13	2.36	1.64	1.25	1.01
F_{id}/qE	0.40	0.49	0.51	0.58	0.75

mass of an ion and a change in the charge of a dust particle, which contribute to the force when the gas grade changes. A relative increase of force occurs in the experiments presented as the transition to a gas with a lower ionization potential. m_i changed immediately with minimal addition, and plasma parameters (E, T_e, n_e) changed gradually as the addition increased in a recent series of works [12,21], where the problem of levitation of dust particles in gas mixtures was considered when easily ionized xenon was added to basic helium. F_i/qE ratio was in the order of 0.2 in pure helium, and the ratio was equal to about one with the addition of xenon in 10%. The ion entrainment exceeded gravity already at about 5% additive (in [12] the pressure P was 1.0 Torr), although the replacement of the helium ion with the xenon ion in (3) at the degree of plasma ionization 10^{-7} occurs with extremely small additives [22]. The analysis allows for a separate evaluation of two factors of the relative increase of the force of ion entrainment and detect its replacement of gravity occurring in heavy plasma-forming gases.

According to the available literature data, F_i exceeded m_g only in case of particles smaller than $1\,\mu$m and at high directional ion flow rates (at low pressure) [23,24]. The effect found in this study in heavy gases allows for the creation of dust plasma traps with the direction of the electric field reversed.

It can be noted that mechanical trapping can be applied in a wide range of dust particle masses, gas types and plasma parameters since it is used in the applied technique. In particular, the method used can operate in the pressure range from close to atmospheric [25] to the case of highly rarefied gas, or in atmospheric-free conditions [26,27].

Conclusion

Such conditions of a glow discharge are experimentally selected in this paper under which it is possible to create dust traps in strata in different inert gases with the same discharge parameters (current, pressure, tube radius). The sizes of dust particles selected by discharge in different inert gases are determined. It was found that the particle sizes in helium and xenon differ by half.

It is shown that when replacing the working gas with a gas with a lower ionization potential, large particles are ejected from the trap due to an increase of the strength of the ion entrainment relative to the weight of the particle.

The conducted studies allowed for the creation of dust traps with an inverted electric field, when the dust plasma can be held due to the force of ion entrainment acting against gravity.

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Conflict of interest

The authors declare that they have no conflict of interest.

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