Dust particles in a spherical glow discharge

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Abstract. The results of an experimental study of dusty plasma of a spherical gas discharge have been presented. It has been found out that the current density in the locations of dust particles remains unchanged in an unstratified glow discharge. The upper limit of the charge and size of particles have been evaluated.

1. Introduction

Synthesis of nanoparticles in low-temperature plasma plays an important role in fundamental research and in plasma technology [1,2]. Dust particles may be found in astrophysical experiments, in the ionosphere, and in fusion plasma. The possibility of formation of nanometer or micron size particles in laboratory plasma was described in [3-5]. The formation and growth of dust particles were observed in various types of gas discharges: RF discharges [3], DC discharges [4], and arc discharges [5].

In 2015, a new phenomenon was discovered [6]: in spherical strata, the clouds of dust particles are formed; they occasionally explode, split into two clouds and scatter in opposite directions. It turned out that the compact cloud entrained to the reactor wall decelerates many times slower than it could be expected from the evaluation on Epstein force of nanoparticles on a neutral background gas.

Spherical striations appear around a point anode (placed at the center of a grounded vacuum chamber, whose walls serve as cathode) at low pressures (10-50 Pa) of high-molecular gases (acetone, ethanol, methane, acetylene, etc.) and present a set of concentric luminous regions [7]. In discharge plasma in the high-molecular gas the complex plasma-chemical processes of dissociation, ionization and recombination result in the appearance of radicals, ions and small clusters. Their coagulation and recharge lead to the formation of negatively charged clusters and dust particles of nano or micro size. A special feature of the spherical gas discharge is absence of transverse and the presence of only radial flows of particles and energy, which allows concentrating high-density plasma in the central part of the discharge and enables considering discharge to be a one-dimensional problem.

2. Experimental setup

Experiments were carried out in a grounded steel cylindrical vacuum chamber (1) 60 cm in height and 50 cm in diameter (figure 1). An isolated electrode with a non-isolated tungsten end (2) 5mm in diameter was placed at the center of the vacuum chamber. The discharge occurred between the central electrode and grounded steel chamber wall. The gas discharge was supported by a high-voltage current source (3). Experiments were carried out under continuous pumping by a mechanical pump. Pressure was controlled by the pumping speed and by the inflow of ethanol vapor into the vacuum chamber. At positive potential of the central electrode, several spherical striations (4) around the central electrode were formed. The photo and video visualization was carried out through the glass windows. For
observation, a quartz window (5) was placed perpendicular to the basic windows at half-height of the chamber, and a solid-state laser (6) with 35mW power and 532 nm wavelength was installed. Between the laser and the window a cylindrical lens (7) was placed. The vertical laser sheet formed by the laser beam and lens illuminated and highlighted the strata and space in the chamber between the anode and the window.

![Figure 4. Spherical glow discharge experimental setup.](image)

1 - vacuum chamber (cathode);
2 - central electrode (anode);
3 - high-voltage current source;
4 - striations;
5 - quartz window;
6 - laser;
7 - cylindrical lens;
8 - clouds of dust particles;
9 - hollow cathode.

3. Results and discussions

Below is a description of the condition of forming and the dynamics of dust particles depending on the conditions of a spherical gas discharge glow.

3.1. Glow discharge in ethyl alcohol.

Complex plasma-chemical processes in a spherical glow discharge in high-molecular gases result in formation a variety of molecules, active radicals and ions. It was discovered that the differential conductivity in the formed gas can be non-monotonic, which probably leads to the formation of spherical stratification [8]. At coagulation of these active particles the molecular clusters are formed; with discharge increase they grow to nano or micro size, acquiring a large negative charge $Q_d = -e Z_d$ in plasma. Charge number $Z_d$ of the dust particles in the plasma, as a rule, is directly proportional to the radius $R_d$ of particles, and is determined by the equality of flows of plasma electrons and ions on the surface of dust particles.

In about a minute of glowing of a spherical stratified gas discharge particles are formed with sizes and in numbers that are sufficient to make scattering of laser radiation visible to the naked eye (figure 1(8)). In figure 2 it can be seen that the dust particles are concentrated at the boundaries of the strata towards the hollow cathode. The potential of the plasma discharge is shown in figure 3, where solid lines mark the location of dust particles. It is worth noting that since the Langmuir probe, having both a negative and a zero potential relative to the plasma, repels negatively charged dust particles [9], the measured potential is not affected by the cloud particles. Particles in the case of a stratified discharge are located in the region of the potential well, as it was previously proposed by the authors in [6]. However, in contrast to previous work, the cloud of particles did not leak in the direction of the cathode that is apparently related to the high electric field in the strata.
Figure 2. Photograph of the spherical striations and the clouds of dust particles. The pressure in the gas-discharge chamber is 0.1 Torr, the voltage and the discharge current are 538V and 15.3 mA, respectively.

Figure 3. The radial distribution of the plasma potential in the discharge shown in Figure 2. The solid lines show location of dust particles.

3.2. Glow discharge in nitrogen

It was discovered that some of the particles formed in spherical stratified discharge have magnetic properties. This is due to the fact that the appearance of dust particles in gas discharge is not only caused by coagulation of chemically active molecules, but by sputtering of the electrodes as well. As a result, in a glow discharge in atomic and simple molecular gases there are formed particles consist of a substance of the electrodes, mainly the cathode. This is confirmed by the fact that dust particles are formed even in a glow discharge in simple molecular and atomic gases, for example nitrogen.

Photograph showing the discharge in nitrogen and scattering of laser radiation on dust particles is presented in figure 4. The appearance of particles occurs sooner with increasing discharge current (figure 5). Probe measurements show that the plasma potential outside of the anode and cathode regions is monotonous, and the electric field is almost constant and is approximately 2.5 V/cm. It has been found out that under rapid increase in the total current of the discharge the cloud of dust particles, whose boundaries are shown in figure 6 in solid lines, is moved from the anode so that the current density at the location of particle remains constant. The dependence of the current density $j$ in the locations of the particles under various conditions is shown in figure 7.
Figure 4. Photograph of the dust particles in the spherical gas discharge in nitrogen. The pressure in the gas-discharge chamber is 0.268 Torr, the voltage and the discharge current are 421V and 2 mA, respectively.

Figure 5. The dependence of time of appearance of dust particles on the discharge time.

Figure 6. The radial distribution of the plasma potential in nitrogen. The solid lines show the location of dust particles. 1, 2, 3 are discharge currents of 20, 10, 6 mA, respectively.

Figure 7. The dependence of the current density at the location $r^*$ of the dust particles on the total discharge current. 1, 2, 3, 4 are nitrogen chamber pressures of 0.237, 0.268, 0.272, 0.421 Torr, respectively.
The location of the cloud of particles is determined by the forces acting on dust particles: gravity $F_g$, thermophoretic force $F_{th}$, the electrostatic force $F_{el}$, the drag force on the neutral gas $F_{nd}$, and the ion drag force $F_{id}$ [6]. The force of neutral drag $F_{nd}$ can be neglected because the gas at the center of the chamber is stationary. Evaluation of gravity $F_g = M_d \cdot g$ for particles with a $R_d = 1$ micron and $g = 9.8$ m/s$^2$ is approximately $F_g \approx 5 \cdot 10^{-15}$ N, i.e. by an order of magnitude smaller than typical values of other forces. Thermophoretic force $F_{th} \sim R_d^2 \cdot \nabla T_n$ is proportional to the square of particle radius and temperature gradient $\nabla T_n$. The temperature gradient decreases rapidly with increasing distance from the anode due to spherical geometry, and for particles with radius $R_d = 1$ µm the thermophoretic force is small [6].

Thus, the particles are affected by two differently directed forces: the electric force $F_{el}$ and the ion drag force $F_{id}$. The electric force in the field $E$ of the discharge plasma acts on particle with a negative charge $-eZ_d$ in the direction of the anode:

$$F_{el} = -eZ_d E.$$  \hspace{1cm} (1)

The ions in the field of the discharge move toward the cathode, dragging the particles with a force [6]:

$$F_{id} = \frac{4}{3} \left( \frac{2}{\pi} \right)^{1/2} \pi R_d^2 n_i \nu_i \left( \frac{e^2 Z_d}{R_i T_i} \right)^2 m_i \mu_i \Lambda(\beta_i),$$  \hspace{1cm} (2)

where $\Lambda(\beta_i)$ is the Coulomb logarithm, and $n_i$, $\nu_i$, $u_i$, $T_i$, $m_i$ are concentration, thermal and drift velocity, temperature and mass of ions, respectively.

Let’s evaluate the charge of the particle in the dust cloud in the experiment whose data are shown in figure 7 (1). Given the stationary nature of the gas discharge, forces (1) and (2) must be equal therefore:

$$Z_d = \frac{T_i^{3/2}}{4 \left( \frac{2}{\pi} \right) m_i \pi n_i \mu_i e^3 \Lambda(\beta_i)}$$  \hspace{1cm} (3)

where $\mu_i$ is the ion mobility, which at pressure $p = 0.237$ Torr is equal to $\mu_i = 6 \cdot 10^3$ cm$^2$/(V·s). In the experiment, the current density of electrons $j_e = 0.861$ mA/cm$^2$, the drift velocity of the electrons $u_i(E/N) \approx 10^6$ cm/s at $E/N \approx 3$ Td. Given quasineutrality of plasma, we find the concentration of ions in the localization of dust particles $n_i \approx n_e = j_e/u_e = \approx 5 \cdot 10^9$ cm$^{-3}$. Taking $\Lambda(\beta_i) = 1$ and $T_i = 0.03$ eV (3), we find the charge number of an individual dust particle $Z_d \approx 4 \cdot 10^3$.

In the experiment ($n_i \approx n_e$ and $u_i/\nu_i < 1$) the absolute value of the dimensionless charge of the particle $z$, equal to the ratio of the potential energy of the particle to the energy of the electrons is approximately equal to 1[2]:

$$z = \frac{|Z_d| e^2}{R_i T_i} \approx 1.$$  \hspace{1cm} (4)

Given (3) and (4), and taking the electron temperature $T_e = 2$ eV [10], the radius of dust particles can be calculated to be about 3 microns.

It should be noted that the estimates given above did not take into account the thermophoretic force $F_{th}$ which is directed towards the cathode and due to high heating of the anode may have a large value. Accounting for $F_{th}$ can lead to a significant decrease in the value $Z_d$ and $R_d$, so these are upper limits for the charge and size of the dust particles.
4. Conclusion

This paper presents the results of experimental studies of dusty plasma of spherical gas discharge, using optical and Langmuir probe methods. It is shown that dust particles are formed in a glow discharge in ethanol and nitrogen. In the case of the stratified discharge, the particles are concentrated at the border of strata. In unstratified discharge in nitrogen the dust particles gather in the cloud, which moves away from the anode along with the increase in the discharge current so that the current density in the cloud remains unchanged. The evaluation has showed that the particle size in the dust cloud in the glow discharge of nitrogen is about 5 microns under assumption that the thermophoretic force acting on the particles is small.

Acknowledgments

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