Journal of Experimental and Theoretical Physics, Vol. 92, No. 1, 2001, pp. 86–92.
Translated from Zhurnal Éksperimental'noĭ i Teoreticheskoĭ Fiziki, Vol. 119, No. 1, 2001, pp. 99–106.
Original Russian Text Copyright © 2001 by Balabanov, Vasilyak, Vetchinin, Nefedov, Polyakov, Fortov.

PLASMA, GASES

The Effect of the Gas Temperature Gradient on Dust Structures in a Glow-Discharge Plasma

V. V. Balabanov, L. M. Vasilyak*, S. P. Vetchinin, A. P. Nefedov, D. N. Polyakov, and V. E. Fortov

Institute of High Energy Density, IVTAN (Institute of High Temperatures) Scientific Association,
Russian Academy of Sciences, Moscow, 127412 Russia

**e-mail: lab852@hedric.msk.su*

Received June 30, 2000

Abstract—An experimental investigation is performed of the effect of the neutral gas temperature gradient on plasma-dust formations in the positive column of a glow discharge. It is demonstrated that the thermophoretic forces arising due to the temperature gradient are comparable with radial electric fields and define the condition of formation and different shapes of plasma-dust structures, in particular, the formation of rings in the vicinity of tube walls. A model description of this effect is given. *© 2001 MAIK "Nauka/Interperiodica".*

1. INTRODUCTION

The formation of ordered structures of micron-sized dust particles was observed under different conditions in a low-pressure plasma and in radio-frequency and glow discharges [1, 4–6], as well as in thermal and nuclear-excited plasmas [1–3]. In so doing, microparticles acquire a high negative charge $q = (10^4–10^5)e$ (where e is the electron charge), corresponding to the floating plasma potential, and the structures proper resemble Coulomb crystals [1–4]. The possibility of formation and the stability of ordered dust structures in a plasma depend on temperature. The nonideality parameter γ is proportional to the square of charge on particles,

$$\gamma = q^2 n_d^{1/3}/kT,$$

where n_d is the concentration of dust particles, and defines the temperatures at which a stable crystal structure of charged dust particles will be formed, the temperature at which structures of the liquid type will be formed, and the temperature at which no structures will be formed [1]. In addition to the value of the temperature proper, the formation of ordered dust structures must be further affected by forces associated with the temperature gradient. These forces are also capable of having decisive effect both on the conditions of emergence of ordered structures and on their geometric shape and arrangement in space. A plasma system is always characterized by the presence of sources of energy release and by the presence of boundaries; therefore, there always exist both the temperature gradient and the forces it causes. Up to now, the forces associated with fluxes and with interaction of charged components of plasma were largely included in the analyses and investigations of ordered dust formations [2, 3, 7, 8], while the forces due to the temperature gradient were disregarded.

Ordered plasma-dust formations in a dc glow discharge are formed in strata in which a fairly strong longitudinal electric field exists, which that makes it possible to contain particles in the field of gravity [1, 4–6]. Experimental results demonstrate [6] that plasma-dust structures of different shapes may form in a glow discharge. The shape and structure of dust formations depend on the conditions of equilibrium in the radial direction [6]. In the radial direction, the particles of a plasma-dust formation are acted upon by various forces directed towards the axis and the wall of the discharge tube. The force directed toward the axis is defined by the radial electric field and by the dust-particle charge. The forces urging the dust particles towards the walls may be caused by the motion of ions to the wall under conditions of ambipolar diffusion and by the neutral gas temperature gradient. The effect of temperature gradients due to Joule heating on ordered plasma structures has not been taken into account up to date. It is the objective of this study to investigate the effect of the temperature gradient on the formation of dust structures in the positive column of a glow discharge.

2. EXPERIMENT

Ordered dust structures were developed in the positive column of a glow discharge in discharge tubes 1 and 2 cm in diameter and 30 cm long. The experimental scheme is given in Fig. 1. Two metal rings *1* were glued into the tube walls at distances of 10 and 15 cm from the cathode for measuring the voltage drop in the positive column and for stabilizing the strata. Air at a pressure from 0.2 to 0.8 torr served as the working gas. The positive column was stratified, and the first stratum emerged in the vicinity of the first ring. Introduced from above into the discharge were particles of alumina 3 to 10 μm in diameter and particles in the form of hollow glass spheres 20 to 60 μm in diameter. The discharge current varied from 0.1 to 3 mA.

The current-voltage characteristic of the positive column of a discharge in air is given in Fig. 2; also shown in this figure are the shapes assumed by dust structures at different values of current. At a low current of 0.1 to 0.3 mA, ordered filaments of particles approximately 1 cm long were observed, concentrated in the vicinity of the tube center. When the discharge current increased to 0.6–1 mA, we observed the formation of an ordered structure in the form of a cylinder with the diameter of approximately one-third or one-fourth of the tube diameter. The diameter of the ordered structure increased with current and reached two-thirds of the tube diameter at a current of 1–2 mA. The structure thickness decreased as the current increased, and, at a current from 1.5 to 2 mA, plane structures were observed consisting of several (five to ten) layers of particles. A further increase of current resulted in the formation of a ring structure whose diameter increased and the width decreased with increasing current. No particles were present in the axial region. The values of the current at which transitions occurred between different shapes of ordered structures decreased with increasing size of dust particles.

The following experiments were performed to check the effect of the temperature gradient on the structures.

1. After an ordered structure was formed, a rod *3* heated to 100°C (Fig. 1) was brought close to the side wall of the tube (opposite the ordered structure). After a period of 2–3 s, particles started to leave the structure and move away from the rod, and, after a short time, all particles from the structure moved over to the wall (Fig. 3). Approximately 10–20 s after this, if the rod was removed, the structure started to be built up gradually from the particles that came from the walls. In so doing, the center of localization of particles was first biased toward the cold wall and then shifted slowly toward the center.

2. If the wall was touched by the cooled (to –10°C) rod, the structure was set up in the form of a cone with the vertex at the point of contact between the cold rod and the wall and flowed down slowly (15 s) onto the wall (Fig. 4). After the rod was removed, the structure was built up in the same manner as that described for the case of heating.

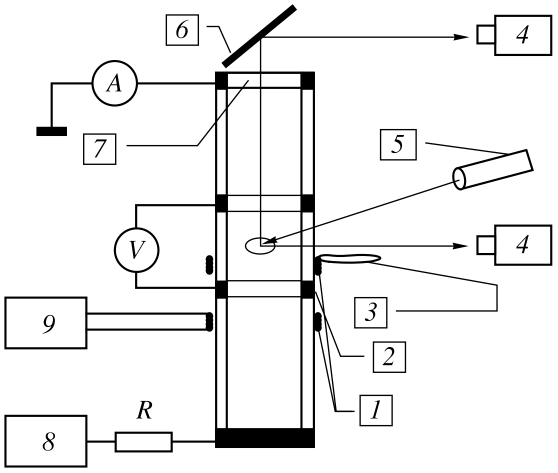

Fig. 1. Experimental scheme: (*1*) metal rings, (*2*) heater, (*3*) heated or cooled rod, (*4*) video camera, (*5*) laser, (*6*) mirror, (*7*) glass window, (*8*) discharge supply source, (*9*) heater supply source; *R*, ballast resistor.

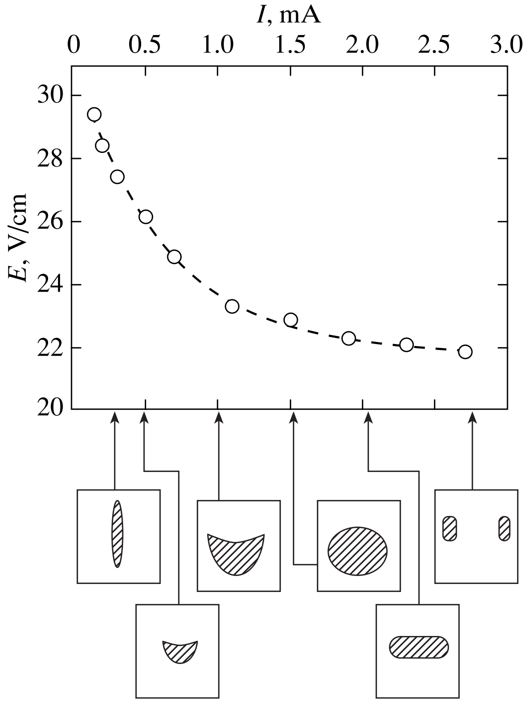

Fig. 2. The mean intensity of longitudinal electric field between rings as a function of the discharge current. Shown schematically at the bottom are the configurations of plasma-dust structures in the longitudinal cross section, corresponding to the above-identified values of current.

3. In the third experiment, a heating coil *2* (Fig. 1) 0.5 cm wide was wound at a distance of 1 cm above the bottom metal ring. Under the experimental conditions, the heating largely affected the region between the metal rings. Because the heater width was small, it generated both the longitudinal and radial components of the temperature gradient. The discharge was ignited such that two strata were located between the metal rings above the heater. After switching on the heater at a power of 0.5 W (in so doing, the mean heat release in the discharge per unit length was 0.01–0.02 W/cm), the dust structure diameter in the stratum nearest to the heater decreased, and it was observed that particles

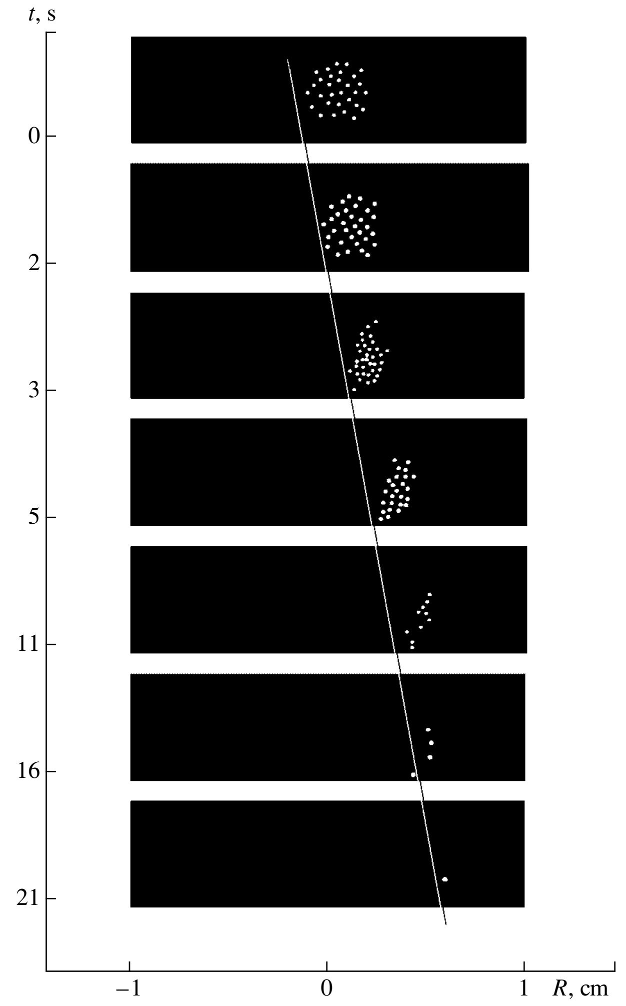

Fig. 3. Photographs of variation of the cross section of a dust structure upon contact of a heated rod with the discharge tube wall (on the left); *O*, tube center; *R*, tube radius; *T*, time of stimulation in seconds.

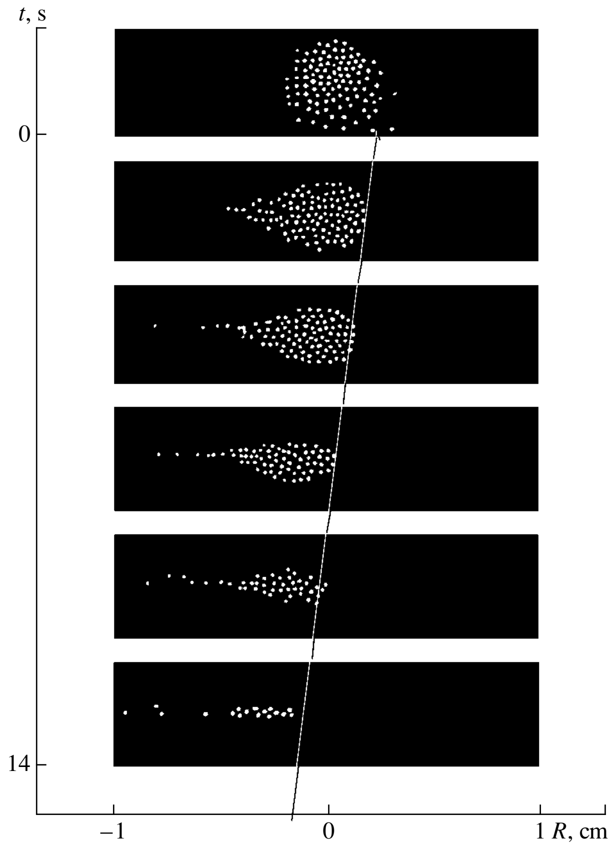

Fig. 4. Photographs of variation of the cross section of a dust structure upon contact of a cooled rod with the discharge tube wall (on the left); *O*, tube center; *R*, tube radius; *T*, time of stimulation in seconds.

occasionally flew from this stratum to the top one and back. When the heater power was increased to 1 W, particles from the bottom stratum were scattered into the region between the strata and occupied almost the entire volume. In so doing, the particles in the axial region were motionless and the distance between them increased; closer to the wall, the particles moved chaotically. Between these two regions, chaotically moving particles were observed among the motionless ones. This effect is possibly associated with the presence of particles of different sizes. In the vicinity of the wall closer to the heater, the particles performed circular motion. In the vicinity of the walls, they descended to the heater and then departed to the center, after which they ascended and moved towards the wall. This motion may be attributed to the presence of strong temperature gradients in the vicinity of the heater. When the power of heating increased to 2 W, the particles moved away from the heater and took up the top part of the region between the heater and the top ring. With a further increase of the heater power, the particles left the discharge. The effect of the rotation of particles was also observed in the case of contact between the wall tube and the cooled rod below the stratum with ordered structure. In so doing, the particles shifted towards the cooled spot (sideways and down), and the direction of particle rotation was opposite to that observed during heating.

Therefore, the presence of even insignificant temperature gradients may define the geometric shape of a dust structure, as well as fully distort or destroy the latter. The observed transition of an ordered dust structure from a disk or cylindrical shape to a ring shape with increasing discharge current may also be caused by a radial temperature gradient when the gas in the tube is heated by the flowing current.

3. CALCULATION MODEL

We will treat the steady state of a ring-shaped dust structure. The shape of the structure in the radial direction depends on the equilibrium position of dust particles, which is defined by the balance of radial forces.

The attracting force of the radial electric field of ambipolar diffusion is directed toward the center of the discharge tube, while the forces of entrainment by ambipolar ion and electron fluxes and the force caused by the temperature gradient are directed from the center to the wall of the tube. In calculating these forces, use was made of the model of the positive column of the plasma of a low-pressure glow discharge undisturbed by dust particles. The forces were calculated per single particle. Included in the calculations were the dependences of the reduced electric field intensity E/P (the values were borrowed from experiment, Fig. 2) and of the coefficients of diffusion and mobility of electrons and ions on the pressure and the tube radius [9]. In strata in the air, the longitudinal field intensity is high and the electron attachment is almost fully compensated by detachment; therefore, the concentration of negative ions in the strata is low compared with that of electrons. The electron temperature was taken to be 3 eV [10], because its variation has little effect on the calculation results. As was demonstrated by Nedospasov [11], a stratified column of a glow discharge is described by the ionization-diffusion model, and the radial distribution of the electron concentration in a stratum is the same as in a homogeneous column and is close to the Bessel function $J_0(r/\Lambda)$ with the boundary condition

$$n_e(R) = 0,$$

where $\Lambda = R/2.4$ and R is the tube radius. The loss of charged particles at the values of pressure $P = 0.2$–0.4 torr employed by us is largely defined by ambipolar diffusion, as a result of which a radial electric field arises. Because the drift velocity of electrons in the radial direction is low compared with their thermal velocity, the electron distribution over the discharge tube cross section satisfies the Boltzmann equation [12]:

$$e\varphi(r) = kT_e \ln(n_e(r)/n_e(0)), \qquad (1)$$

where $\varphi(r)$ is the field potential at the space point being treated and, on the tube axis, $\varphi(0) = 0$. In view of the fact that in the diffusion approximation the radial distribution of electrons is described by the Bessel function, one can determine the potential at the preassigned space point,

$$e\varphi(r) = kT_e \ln(J_0(r/\Lambda)), \qquad (2)$$

and then find the radial electric field $E_r = -d\varphi/dr$ and calculate the force acting on charged microparticles. This approach enables one to simplify the computation of radial electric field and avoid significant errors occurring when the field is found directly from an ambipolar flux of ions and electrons. Expression (2) is valid if the distance from the point being treated to the wall tube considerably exceeds the electron free path λ_e.

We expand the Bessel function in the vicinity of the wall at $R \gg \lambda_e$ into a Taylor series to derive from (2) the potential difference between the axis and the wall of the discharge tube,

$$e\varphi_W = kT_e \ln(R/\lambda_e). \qquad (3)$$

Formula (3) is valid within a numerical factor on the order of unity under the logarithm sign.

Such distributions of the electron and ion concentration and of the radial electric field are distorted in the vicinity of the discharge tube walls where the value of excess space charge becomes comparable with that of ion concentration, as a result of which the quasi-neutrality of plasma is disturbed. Therefore, in calculations, we restricted the field in the vicinity of the tube walls where the quasi-neutrality was disturbed and allowed for the fact that the dust particles lost their charge in the vicinity of the tube walls and left the discharge.

In order to find the radial distribution of the gas temperature, we solved the heat-conduction problem for a plasma column with known sources of heat release that, in our case, were proportional to the concentration of electrons and to the longitudinal intensity of electric field.

Given below are predicted correlations for the main radial forces acting on dust particles, namely, the force of radial electric field, the force due to the temperature gradient, and the force of entrainment arising as a result of the ionic drift to the tube walls.

3.1. Force of Radial Electric Field

This force is equal to the product of particle charge by radial electric field,

$$F_E = -qE_r = qkT_e\frac{\nabla n_e}{n_e}, \qquad (4)$$

where

$$q = aT_e \ln(0.4\sqrt{m_i/m_e})$$

is the equilibrium charge of a microparticle, and a is its radius. The dust particle charge is equal to $1.2 \times 10^4 e$. Figure 5 gives the radial electric force F_E as a function of distance.

3.2. Force of Temperature Gradient

If a temperature gradient is present in a gas, the body placed in this gas is acted upon by the force F_T which is proportional to the temperature gradient and caused by the sum of momenta imparted to a particle by bombarding molecules of gas. A microparticle moves along the line of temperature field toward a decrease in temperature. When the molecular free path of gas is

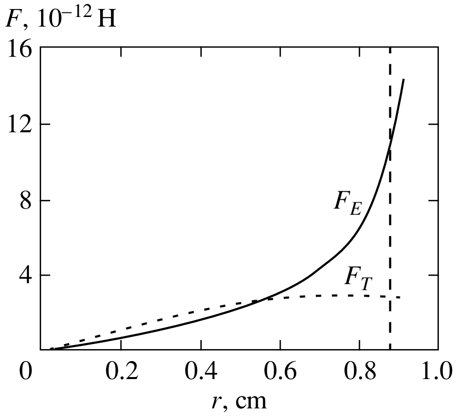

Fig. 5. The force of radial electric field and the thermophoretic force as functions of distance to the tube center at $P = 0.5$ torr and $I = 1$ mA; particle diameter, 10 μm.

much longer than the dust particle size, this thermophoretic force is defined by the formula [13]

$$F_T = -\frac{4PL}{T}a^2\frac{dT}{dr}, \tag{5}$$

where P is the gas pressure and L is the molecular free path. Given the current density and the longitudinal electric field, one can find the correlation for local heat release and then the temperature distribution and the thermophoretic force.

Because the longitudinal intensity of electric field is independent of radius, the radial heating of neutral gas is defined by the heat equation

$$\lambda\Delta T = -Q_0 J_0(r/\Lambda) \tag{6}$$

with nonuniform heat release, where the heat release on the discharge axis is $Q_0 = j(0)E$, $j(0)$ is the density of electric current on the axis, and λ is the thermal conductivity coefficient of gas. Convective heat transfer is negligibly small, because the Rayleigh criterion is invalid due to the low density of gas and insignificant temperature gradients. The solution of Eq. (6) may be written as

$$T(r) \approx \frac{1}{8}\frac{iE}{\lambda}J_0(r/\Lambda) + T_w, \tag{7}$$

where i is the total current of the discharge and T_w is the wall temperature. For the conditions of our experiment, the temperature on the axis exceeds the wall temperature by 5 to 15 K.

The $T(r)$ profile in this case coincides with the profile of heat release and defines the radial thermophoretic force acting on a microparticle (Fig. 5). In treating thermophoresis, we did not include the heat release associated with charged particle fluxes attracted by the dust cloud, because, in our case, these fluxes are much lower than both the radial ambipolar flux to the wall and the conduction current. One can see in Fig. 5 that the forces F_E and F_T are comparable in magnitude, act in different directions, and exhibit different dependences on the radius.

3.3. Ionic Drift and Its Effect on Particles

An ambipolar diffusion of electrons and ions occurs in a diffusion-controlled glow discharge. In so doing, the fluxes of ions and electrons and, consequently, their drift velocities coincide in the radial direction. Ion and electron fluxes affect a dust particle. The main contribution to this force is made by the ion momentum. The momentum transfer from ions to dust particles is defined by the velocity of ions in the vicinity of the surface of a charged particle, and the difference between ion fluxes affecting the particle is defined by the drift velocity of ions in a radial ambipolar field; therefore, the force with which a particle affected is

$$F_i = n_i m_i v_r v_i \sigma, \tag{8}$$

where n_i is the concentration of ions in a stratum, m_i is the mass of ions, v_r is the radial drift velocity, v_i is the ion velocity in the vicinity of a particle, and σ is the effective cross section of capture of ions by a charged microparticle [7].

The force of ionic entrainment (8) is an order of magnitude less than the force of radial electric field (4) and the thermophoretic force (5). Because the thermophoretic and ionic entrainment forces exhibit the same dependences on the particle size and on the discharge tube radius, one can assume that a dust structure is largely affected by the temperature gradient force. The thermophoretic force attempts to pull the particles held at the stratum center to the tube walls; however, it is inhibited by the force of radial ambipolar electric field.

3.4. Particle Energy

The motion of a dust particle in the radial direction is defined by its potential energy. Because the radial forces are proportional to the respective gradients, one can introduce the concept of potential energy for each one of these forces,

$$F(r) = -\frac{dU}{dr}. \tag{9}$$

Then, the total potential energy is

$$\begin{aligned} U(r) &= -\int_0^r [F_T(r) + F_E(r)]dr \\ &= -4PLa^2\ln\frac{T(0)}{T(r)} - qe\varphi(r). \end{aligned} \tag{10}$$

In our experiments, Joule loss is small, and the temperature on the tube axis $T(0)$ only slightly exceeds the wall temperature, $T(0) - T_w \ll T_w$; therefore,

$$U(r) = -\alpha(1 - J_0(r/\Lambda)) - \beta\ln(J_0(r/\Lambda)), \tag{11}$$

where

$$\alpha = \frac{1}{2}\frac{PLa^2iE}{\lambda T_W}, \quad \beta = qkT_e. \tag{12}$$

In the vicinity of the axis, where $r/\Lambda \ll 1$,

$$U(r) \sim (\beta - \alpha)r^2/\Lambda^2.$$

If $\alpha/\beta \geq 1$, the root of $J_0(r_m/\Lambda) = \beta/\alpha$ defines the minimum of the function $U(r)$ (11),

$$U(r_m) = \beta(1 - \ln(\beta/\alpha)) - \alpha. \tag{13}$$

At the minimum, the value of $U(r_m)$ is always negative, $U(r_m) < 0$. In the vicinity of the axis, the potential energy is $U(r) < 0$, and then passes through the minimum. The value of potential energy (11) in the vicinity of the wall in view of φ_W is

$$U_W = -\alpha + \beta\ln(R/\lambda_e). \tag{14}$$

In the case when the electric forces prevail over the thermophoretic forces, $\beta > \alpha$, the potential energy $U(r) > 0$ has no local minimum, and the particles assemble in the vicinity of the axis. The behavior of the function $U(r)$ depending on r defines the region of finite motion of dust particles or departure to the wall. There are two characteristic regions, namely, $U(r) > 0$ and $U(r) < 0$. The particles go to the wall if their total energy is

$$\varepsilon = \sum_i \frac{m_i v_i^2}{2} + U(r) > U_W. \tag{15}$$

The summation is made over all particles in the layer in the entire region of motion. For finite motion, the total energy (15) is negative, and $U(r_m) < \varepsilon < U_W$. The particles “slide down” to the potential minimum.

Hence, it follows that two options are possible of radial structures of dust clouds in a glow discharge, namely,

(1) the particles take up either the central region or the entire cross section of the discharge tube, except for a small region of $\sim\lambda_e$ in the vicinity of the tube walls, and

(2) the particles are located at the potential minimum and form a space structure in the form of a ring in the neighborhood of the wall.

4. ANALYSIS AND COMPARISON WITH EXPERIMENT

We will determine the dependence of the forces of radial electric field and temperature gradient on the conditions of discharge, gas pressure, tube radius, current, and particle size. The force of radial electric field depends on the particle charge (proportionally), electron temperature, and radial electric field which increases with radius. The temperature gradient force is proportional to the cross-sectional area of particles and increases with current and pressure, because the longitudinal electric field and heat release increase with pressure and decrease as the tube radius increases.

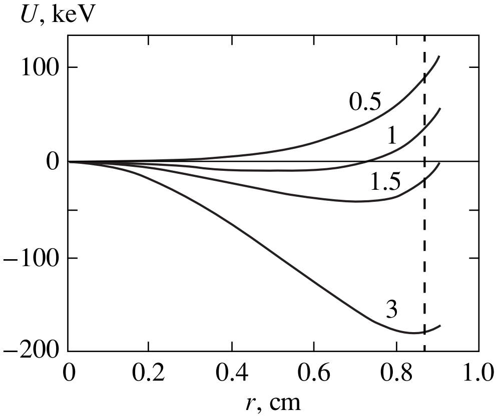

Fig. 6. The potential energy of charged dust particles 10 μm in diameter as a function of the distance from the tube center for different values of discharge current (0.5, 1, 1.5, and 3 mA).

We will treat an ordered dust structure under conditions of variation of the discharge conditions. Figure 6 shows the variation of the potential energy of particles 10 μm in diameter as a function of discharge current. In the case of currents of up to 1 mA, it is advantageous for the particles to be in the central region of the tube, because a potential well is present at the tube center, as is observed in the experiment: the particles take up mainly the central part of the tube and form well-ordered structures. When the current increases (1–2 mA), the minimum of potential well shifts toward the walls; however, the potential energy of particles in the vicinity of the tube walls is higher than that at the center. In so doing, the particles may both form ring structures and take up almost the entire cross section of the tube except for the region in the vicinity of the tube walls. In this case, the size of the region taken up by the particles depends on the number of horizontal layers of dust particles that may be contained by the longitudinal electric field in a stratum. In order to calculate the space dimension of a dust structure, one must take into account the number of layers that may be contained in a stratum and, accordingly, solve a two-dimensional problem. The characteristic depth of potential well in the axial direction is defined by the potential drop on the stratum and, in our case, amounts to 20–40 V, and the radial potential drop $e\varphi_W$ does not exceed several values of T_e. Therefore, the depth of potential well in the longitudinal direction is much greater than that in the radial direction. In the case of weak fields in a stratum, the number of layers is small, and particles are absent from the central region; i.e., a wide ring structure is formed with the particles absent from a very narrow central part of the tube. In the case of fairly strong longitudinal fields in a stratum, when the number of layers is large, the particles take up almost the entire cross section of the tube. In so doing, excess particles from the structure spill down. As the current continues to rise, the thermophoretic forces start playing the decisive part, the potential energy of particles at the tube center starts exceeding the energy in the vicinity of the tube walls, and the particles form only ring structures. The departure of excess particles also depends on the longitudinal electric field, and the particles either spill down or depart to the walls. The higher the current, the narrower the ring formed and the greater its inside diameter. At some value of the current, the potential barrier in the vicinity of the tube wall disappears and all particles in the stratum depart to the wall. The disintegration of a structure in the vicinity of the wall may occur because of a different reason. In the vicinity of the tube wall, the concentration of ions exceeds considerably that of electrons; this leads to a reduction of the particle charge, and the particles are not contained by the longitudinal field.

When the particle size changes, the values of critical current at which the structure disintegrates vary approximately inversely proportionally to the particle size. One can say that the less the particle size, the less the effect of the thermophoretic forces on the particles in the structure. The structure becomes more stable, the number of particles in the structure increases, and the range of currents at which the structure exists becomes wider. The effect of the gas pressure on the structure is defined by the variation of longitudinal field in the stratum and by heat release. The higher the pressure, the stronger the longitudinal electric field and, accordingly, the narrower the range of current values at which the structure may exist. At values of the gas pressure that are too low, the structure may not exist either, because a decrease in pressure leads to a reduction of the longitudinal field necessary to contain particles and to a reduction of the electron concentration in the discharge. Therefore, an optimal range of pressure exists for a “good” ordered structure, which depends on the tube radius and on the particle size.

The suggested model describes qualitatively all of the experimentally observed transitions between different forms of plasma-dust formations for dust particles of different sizes. A numerical comparison of predicted and experimentally obtained values of current, at which the observed transitions occur, has revealed a good agreement at a pressure of 0.8 to 1 torr. At a pressure from 0.3 to 0.5 torr, the qualitative pattern is maintained; however, a numerical discrepancy is observed. The numerical difference between experiment and theory is associated with other effects observed in the strata of a glow discharge, such as an inhomogeneity of electric and thermal fields along the tube axis, end effects, and the effect made on the plasma by the structure of dust particles proper. We are inclined to attribute the discrepancy between the prediction and experimental data to the effect of the cuplike shape of the stratum and, accordingly, to the presence of stronger radial fields than those in our calculations. In this case, the problem is two-dimensional. This assumption is favored by the fact that a transition to a ring structure was observed for particles 5 μm in size with a close-to-predicted value of current only at a pressure on the order of 1 torr when the shape of stratum became flatter.

5. CONCLUSION

In a bounded plasma with current, the thermophoretic forces associated with heat release may be of the same order of magnitude as the electric forces and, together with the electric forces, play the main part in the construction, stability, and disintegration of plasma-dust structures; in numerous cases, they define the structure and shape of dust formations and the conditions of their existence. The effect of thermophoresis may be used for removal and deposition (for example, onto a substrate) of charged particles and ordered structures, for separation of particles, in microelectronics, and for other applications. The forces of temperature gradient may be used in developing traps for containment of charged microparticles, for example, under conditions of microgravitation.

REFERENCES

1. A. P. Nefedov, O. F. Petrov, and V. E. Fortov, Usp. Fiz. Nauk **167**, 1215 (1997) [Phys. Usp. **40**, 1163 (1997)].
2. V. I. Molotkov, A. P. Nefedov, V. M. Torchinskiĭ, *et al.*, Zh. Éksp. Teor. Fiz. **115**, 837 (1999) [JETP **88**, 460 (1999)].
3. V. E. Fortov, A. P. Nefedov, V. I. Vladimirov, *et al.*, Phys. Lett. A **258**, 305 (1999).
4. V. E. Fortov, V. I. Molotkov, A. P. Nefedov, and O. F. Petrov, Phys. Plasmas **6**, 1759 (1999).
5. N. Sato, G. Uchida, R. Ozaki, *et al.*, in *Frontiers in Dusty Plasmas*, Ed. by Y. Nakamura, T. Yokota, and P. K. Shukla (Elsevier, Amsterdam, 2000).
6. A. P. Nefedov, L. M. Vasilyak, S. P. Vetchinin, and D. N. Polyakov, in *Proceedings of the Second International Conference on the Physics of Dusty Plasma*, Hakone, Japan, 1999, p. 104.
7. V. N. Tsytovich, Usp. Fiz. Nauk **167**, 57 (1997) [Phys. Usp. **40**, 53 (1997)].
8. A. M. Ignatov, Fiz. Plazmy **24**, 731 (1998) [Plasma Phys. Rep. **24**, 677 (1998)].
9. *Tables of Physical Quantities. Handbook*, Ed. by I. K. Kikoin (Atomizdat, Moscow, 1976).
10. Yu. P. Raĭzer, *The Physics of Gas Discharge* (Nauka, Moscow, 1992).
11. A. V. Nedospasov, Usp. Fiz. Nauk **94**, 439 (1968) [Sov. Phys. Usp. **11**, 174 (1968)].
12. B. M. Smirnov, *Physics of Weakly Ionized Gases* (Nauka, Moscow, 1972; Mir, Moscow, 1981).
13. H. L. Green and W. R. Lane, *Particulate Clouds: Dusts, Smokes and Mists* (Spon, London, 1964; Mir, Moscow, 1969).

Translated by H. Bronstein