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Grain surface heating in cryogenic environment

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The surface temperature of the dust particle in cryogenic complex plasmas at gas pressure 0.6–10 Pa is considered. It is shown that at low pressure the dust particle surface temperature is significantly higher than that of the background gas, as a result of which the atom drag force is comparable with the screened Coulomb interaction and even exceeds it for the large-size dust particles. As the gas temperature near the grain surface is a slowly decreasing function of distance with asymptotic $\sim 1/r$ behavior, for correct description of the cryogenic complex plasma at low gas pressure, it is important to include effects related to the dust particle surface temperature. *Published by AIP Publishing.* [http://dx.doi.org/10.1063/1.4982606]

Dusty plasma has been the subject of intensive research since the beginning of the nineties. There is a large scope of experimental data on static and dynamic properties of dusty plasmas, which were successfully explained in the framework of theoretical models and computer simulation.[1,2] Most of the dust plasma experiments were carried out under the conditions of terrestrial laboratories at room temperature (300 K), where plasmas are characterized by electrons with a temperature of a few eV and ions with a temperature of about 0.03 eV. In such plasmas, micron-sized dust particles have large negative charges as a result of interaction with ambient plasma. One of the main problems of such experiments is difficulty in realizing an extended three-dimensional isotropic structure of dust particles. To avoid this problem, some experiments were performed under microgravity conditions.[3] On the other hand, the study of complex plasma in cryogenic environments has only started.[4] Earlier experimental studies suggested production of cryogenic plasma by pulse discharge in liquid helium[5,6] and ultracold plasma by laser cooling.[7] Rosenberg and Kalman suggested a unique nature of the two-dimensional dust structure on the surface of liquid helium.[8]

Cryogenic plasma with clusters of the dust particles was experimentally realized by Antipov *et al.*[9] at $p = 100$–700 Pa. They found out that in the case of spherical dust particles with a radius $\sim 2.7\,\mu$m, the mean interparticle distance does not exceed 30 μm and the dust cloud density is $\sim 10^9\,\text{cm}^{-3}$ (which is extremely high for the dust structure). The authors explained this result by smaller value of the dust particle charge and shorter screening length in comparison with the room temperature case,[10] which means a weaker repulsion between dust particles.

In the later experiments by Ishihara and his coworkers at lower pressures $p = 0.6$–10 Pa (Ref. 11) with 0.4 μm dust particles, the mean distance between dust grains was ~ 0.5 mm, which is thousand times greater than the grain size. This finding is rather unexpected as much shorter interparticle distances in the cryogenic environment were reported in other works.[9,12] Therefore, it is necessary to find an explanation to the larger interparticle distance at low pressures. The dust particle charging at the conditions of experiments at low pressures was considered in Refs. 13 and 14.

In this work, we consider the dust particle surface temperature in the low pressure plasma $p = 0.6$–10 Pa in cryogenic conditions. Below, we will show that the dust particle surface temperature can be significantly higher than that of the background gas.

To calculate the electron flux to the grain surface, the collisionless orbit motion limited (OML) expression can be used

$$J_e = \sqrt{8\pi} a^2 n_e v_{T_e} \exp(-z), \tag{1}$$

where a is the grain radius, n_e is the electron density, $v_{T_e} = \sqrt{k_B T_e/m_e}$ is the electron thermal velocity, $z = e|Q_d|/(a k_B T_e)$ is the normalized charge of the dust particle and k_B is the Boltzmann constant.

Khrapak *et al.* discussed the effect of ion-neutral collisions on the steady-state dust charge in plasma.[15] An approximate expression for the ion flux in a weakly collisional regime has the following form:

$$J_i \simeq \sqrt{8\pi} a^2 n_i v_{T_i} \left(1 + z\tau + 0.1(z\tau)^2 \frac{\lambda}{l_i}\right). \tag{2}$$

Here, $\tau = T_e/T_n$ is the ratio of the electron temperature to the neutral atom temperature, λ is the screening length, and $l_i \sim 1/n_n\sigma_{in}$ with the cross section $\sigma_{in} \sim 10^{-15}\,\text{cm}^{-2}$ of the resonant charge exchange of the helium ion with a stationary atom. In our model, $\lambda \simeq \lambda_i = (k_B T_i/4\pi n_i e^2)^{1/2}$ and $T_i \simeq T_n$.

The electron temperature and density, $k_B T_e \simeq 3$ eV and $n_e \simeq 10^9\,\text{cm}^{-3}$, are considered. The background neutral atom temperature ranges from 300 K to 4.2 K. Equating the electron and ion fluxes, Eqs. (1) and (2), we calculated z. The value of z as a function of τ for the pressures 2 Pa and 10 Pa is shown in Fig. 1. A drastic decrease in the dust charge due to increase in the number of trapped ions with an increase in τ is observed. Fig. 1 shows a comparison of the experimental

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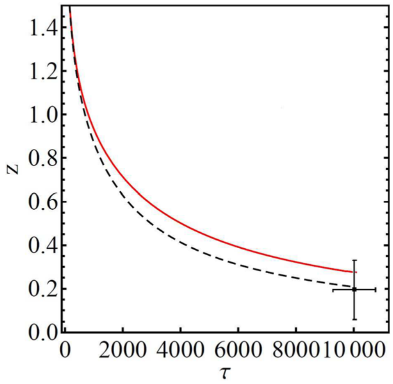

FIG. 1. Normalized charge z vs. temperature ratio $\tau = T_e/T_n$ at $T_e \simeq 3\,\text{eV}$ for neutral gas pressures 10 Pa (dashed line) and 2 Pa (solid line). The experimental result is shown with error bars.[11,16]

result for the cryogenic dusty plasma[11,16] with the results of our calculations. It is seen that the result of the experimental measurement of the dust particle charge can be described by collisional charging theory. The calculated value of z at 300 K is also in agreement with the results of the previous studies.[11,13,16]

The relative temperature difference between the dust particle surface and the surrounding gas in the low-pressure weakly ionized complex plasmas is calculated using the formula derived by Khrapak and Morfill[17]

$$\Delta T/T_n = (1/2\alpha)(n_e/n_n)(T_e/T_n)\left(v_{T_e}/v_{T_n}\right) \times \left(2 + z + \frac{I}{k_B T_e}\right)(1+R)^{-1}\exp(-z), \quad (3)$$

where $\Delta T = T_S - T_n$, T_S is the dust grain surface temperature, $R(T_s) = \Gamma_R/\Gamma_N$ is the ratio of the energy fluxes due to radiation $\Gamma_R \approx 4\pi a^2 \sigma_0 (T_s^4 - T_n^4)$ and neutral gas $\Gamma_N = \alpha 2\sqrt{8\pi} a^2 n_n v_{T_n} k_B (T_s - T_n)$, σ_0 is the Stefan-Boltzmann constant, $\alpha \sim 1$ is the accommodation coefficient, p is the neutral gas pressure, and I is the ionization potential. In Ref. 17, the ratio Γ_R/Γ_N is approximately taken in the form $R \approx \sqrt{8\pi}(\sigma_0/\alpha p v_{T_n})(T_n)^4$, as in the case of neutrals at room temperature in a gas discharge $\Delta T/T_n \ll 1$. At 300 K and 20 Pa in gas discharge, it was obtained that $\Delta T/T_n \simeq 0.2$.[17,18] At the given pressure, the number density of neutral atoms increases with a decrease in gas temperature as $\sim 1/T_n$. Therefore, we have $\Delta T/T_n \sim \sqrt{T_e/T_n}$ dependence of the relative temperature difference between the dust particle surface and the surrounding gas on the parameter $\tau = T_e/T_n$. The temperature at normal conditions 300 K and temperatures at the cryogenic conditions 30 K and 4.2 K correspond to $\tau \sim 100$ and $\tau \sim 1000$, $\tau \sim 8000$–$10\,000$, respectively. In Fig. 2(a), the values of the relative temperature of the dust particle surface T_S/T_n at different values of pressure τ for $p = 10$ Pa, $p = 2$ Pa, and $p = 0.6$ Pa are shown. One can see that in a low pressure cryogenic dusty plasma, the grain surface temperature is more than two times higher at $T_n = 30$ K and ten times higher at $T_n = 4.2$ K than the surrounding gas temperature. Apparently, the increase in the grain surface temperature is caused by the increase in the ion-electron recombination rate on the surface of the dust particle with decreasing gas temperature.

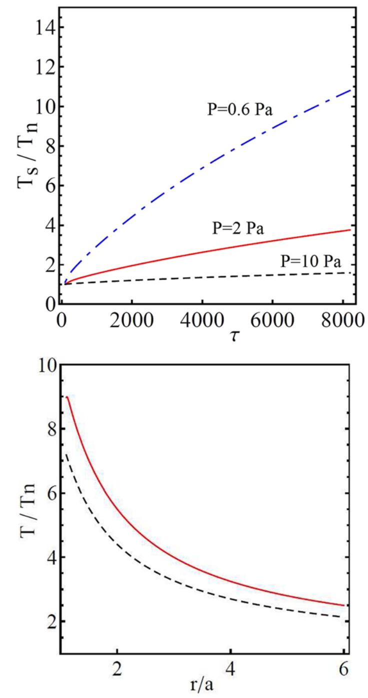

FIG. 2. Top: Relative temperature of the dust particle surface T_S/T_n vs. temperature ratio $\tau = T_e/T_n$ at $T_e \simeq 3\,\text{eV}$ for neutral gas pressures 10 Pa (dashed line), 2 Pa (solid line), and 0.6 Pa (dashed-dotted line). Bottom: Gas temperature as a function of the distance from the grain surface for $T_S/T_n = 9$: solid line was obtained using Eq. (4) and dashed line was obtained taking into account the slip coefficient.[21]

Recently, using the drift-diffusion equations, Totsuji[19] proposed the model for evaluation of the dust particles' cloud size, i.e., the mean interparticle distance, which depends on the value of parameter τ inside the dust cluster. One can assume that the mean temperature of ions (atoms) in the cryogenic environment is higher in the space inside the dust cluster than outside the dust structure due to dust surface heating. Therefore, it is interesting to evaluate the gas temperature distribution near the dust particle surface. In general, as it is well-known, dust particle charge fluctuates with time, as a result of which the temperature difference between the dust particle surface and the surrounding gas is a function of time $\Delta T = \Delta T(t)$. If the dust particle is supposed to be immersed into the plasma at time $t = -\infty$, the value of the gas temperature at the distance r from the dust grain surface at time t can be obtained from[20]

$$T^*(r,t) = \frac{a(r-a)}{2r\sqrt{\pi\chi}} \int_{-\infty}^{t} \frac{T_S^*(t')}{(t-t')^{3/2}} \exp\left(-\frac{(r-a)^2}{4\chi(t-t')}\right) dt', \quad (4)$$

where χ is the gas thermal diffusivity (here by the asterisk symbol, we indicate that the temperature is measured starting from the value of the gas temperature at $r \gg a$).

As in our model we do not consider the dust charge fluctuations, in Fig. 2(b), the gas temperature is shown as a function of the distance from the grain surface at $t = \infty$. Eq. (4) was derived for the case $l/a \ll 1$. However, the comparison with the result derived by Liu *et al.*[21] for any value of the ratio l/a shows that Eq. (4) gives good qualitative description of the temperature distribution at large times. According to Liu *et al.*, the static distribution of temperature around the grain is $T - T_s = (T_s - T_n)(1 - c/r)$, where $c \simeq 0.86$ is the constant determined by the so-called slip coefficient and describes the temperature jump at the particle surface.[21] It should be noted that this result was obtained under the condition of a small temperature difference or constant thermal conductivity and is valid at large distances from the particle. However, it is useful for a qualitative description of the temperature distribution as nonmonotonic behavior of the temperature distribution in considering case is not expected.

In Fig. 2(b), the distance is given in the units of the dust radius and the gas temperature in the units of its value T_n at $r \gg a$. The gas temperature near the grain surface is a slowly decreasing function of distance with asymptotic $\sim 1/r$ behavior. It is clearly seen that the dust surface heating does not strongly affect the gas (ion) temperature at the length scale comparable with the average interparticle distance. Therefore, this mechanism cannot explain the observed large mean interparticle distance. However, the dust surface heating is important for space around the dust particle with a radius $\sim 2 \times a$. As in the cryogenic conditions the screening length is of the order of the dust particle size,[10,13,14] the dust surface heating can be important in more precise calculations of the dust particle charging[22] and can have a strong impact on the wake effect.[23–26]

The other factor that may cause the large mean interparticle distance is the so-called neutral shadowing interaction, which appears due to the temperature difference between the dust surface and the surrounding gas. This interaction is the result of the net momentum flux carried by neutrals to (from) the grain and has the following form:[27]

$$U_n(r) = (3\pi/8)(a^4 p/r)(\Delta T/T_n), \tag{5}$$

where the interaction is repulsive as $\Delta T > 0$ and a slowly decreasing function of distance $\sim 1/r$.

The ion shadowing interaction $U_{\rm sh}$ is attractive; thus, it cannot be responsible for the large interparticle distance. The relative magnitude of the neutral and ion shadowing interactions can be derived by the following expression: $|U_n/U_{\rm sh}| \approx 0.6/(z\tau)^2(a/\lambda)(n_n/n_i)|\Delta T/T_n|$.[17] Taking $z\tau \approx 10^3$, $\Delta T/T_n \approx 10$, and assuming that the ionization fraction $n_n/n_i \approx 10^6$ is the same as in experiments at room temperature, as the ionization is caused by electrons and its temperature is nearly independent of the gas temperature, we obtain the following expression for $p = 0.6$ Pa:

$$|U_n/U_{\rm sh}| \approx 6 \times (a/\lambda), \tag{6}$$

where it should be noted that the ionization fraction n_n/n_i can have lower value due to electrons release during binary collisions between metastable helium atoms in cryogenic environment.[12]

For the relative magnitude of the neutral and bare Coulomb interactions $|U_n/U_C| \approx 0.1/(z\tau)^2(a/\lambda)^2(n_n/n_i)|\Delta T/T_n|$,[17] for $p = 0.6$ Pa, we obtain the following relation:

$$|U_n/U_C| \approx (a/\lambda)^2, \tag{7}$$

where it is worth noting here that this ratio increases if one considers more realistic screened Coulomb interaction.

For the dust particle with the radius 0.4 μm taking $T_i \approx T_n$, one can obtain $a/\lambda \sim 0.1$–1. It means that, in contrast to the experiments at room temperature, the atom shadowing interaction is comparable with the screened Coulomb interaction and even exceeds it for the dust particles with larger size, as in dusty plasma experiments the grain size is up to 10 μm. For comparison in the experiments at room temperature, $|U_n/U_C| \approx 2 \times 10^{-3}$–$2 \times 10^{-2}$. The atom drag interaction is not screened by plasma ions and electrons, in contrast to Coulomb interaction, and affects all dust particles around the considered one (but not to all dust particles in the system). Therefore, we conclude that in the experiments by Kubota *et al.*[11] on the cryogenic dusty plasma, the neutral shadowing interaction is crucial and can be responsible for the large interparticle distance at low pressure $p = 0.6$ Pa.

At 10 Pa, for the surface temperature of the dust particle, we have $\Delta T/T_n = 0.5$, which is still more than two times higher than that at room temperature. The importance of the atom drag interaction for the considered system of the dust particles is determined by the ratio of the atom drag interaction to the characteristic kinetic energy of the dust particle's chaotic motion. Unfortunately, Kubota *et al.* did not present the characteristic kinetic energy of the dust particle in their experiment. It is worth noting that at the given pressure, the friction due to neutral particles approximately 8–9 times higher in the cryogenic environment than in the case of room temperature atoms. Furthermore, in the cryogenic environment, the parameter which stands for the ratio of the energy fluxes due to radiation and neutral gas is $R \sim 10^{-5}$–$10^{-2} \ll 1$ and, therefore, as $R \sim n$ a slight change in the pressure (number density) does not affect the value of the factor $(1 + R)^{-1}$ in Eq. (3), which is in contrast to the room temperature case where $R \sim 1$. Taking into account this fact, from Eqs. (3) and (5), one can find that in the cryogenic environment the neutral shadowing interaction is $\sim a^4$ and independent of pressure. However, the change in the pressure affects the mean free path l of the neutrals. In the free molecular regime $l/a \gg 1$, this parameter is in fact the length scale of the neutral shadowing interaction due to grain surface heating. It is physically unreasonable to consider this kind of interactions at larger distances. At $p = 0.6$ Pa, one can find that $l \sim 2$ mm, which is larger than the mean interparticle distance. At $p = 10$ Pa, the mean free path of the neutrals is $l \sim 0.1$ mm, which is still comparable with the mean distance between dust grains. Therefore, the neutral shadowing interaction is important at considered parameters of the cryogenic dusty plasma and has to be taken into account in the future works in this field. For the parameters of the experiments by Antipov *et al.*,[9] which was carried out at $p = 100$–700 Pa, one can find that $l \simeq 10^{-2}$–10^{-3} mm. Therefore, in the experiments by Antipov *et al.*,[9] the characteristic scale of the neutral shadowing interaction is at least hundreds times smaller than that in the experiments by Ishihara and coworkers.[11]

In general, the mean inter-dust particle distance is determined not only by the interaction forces between dust grains but also by the collective effects and, in particular, by the external electric field that captures the negatively charged particles into the cloud in the central part of the discharge. In the cryogenic regime, the screening length is of the order of the dust particle size and, in the absence of other mechanisms which can cause strong inter-grain correlations, weak confinement by external fields leads to the so called gaseous state of the system of dust particles (i.e., disordered chaotic motion of dust particles). Such a gaseous state was noticed in the experiments by Antipov *et al.*,[9] whereas Kubota *et al.*[11] observed the ordered structure of dust particles. On the other hand, strong confinement by external fields, in the absence of strong dust particle-dust particle repulsion, constricts structure. Therefore, the inter-dust particle distance becomes comparable with the screening length as in the experiments by Antipov *et al.*[9]

Cryogenic complex plasma is an emerging field for studying dust-plasma interaction in extreme conditions. The main goal of the experiments on dusty plasma in the cryogenic environment is to create strongly coupled two dimensional systems with unique features[8] and with possible quantum effect on a pair of dust particles.[28] The grain surface heating has not been considered in the previous works. The result presented in this work is rather unexpected as the surface heating effect in the experiments at room temperature is negligible and important only in hot plasma of tokamak.[29] Finding of the strong atom drag interaction between the dust particles in the cryogenic environment at low pressure is of high importance, as, in general, understanding of interparticle interactions is a fundamental problem.[30–32]

To summarize, we have shown that at cryogenic conditions the dust particle surface temperature is significantly higher than that of the background gas. This can affect ion temperature and energy distribution function, dust particle charge screening, the neutral shadowing force, and characteristic temperature of the dust particle motion as a whole. Using the Boltzmann equation, the authors[33–35] showed that the impact of dust particles on the surrounding plasma can be significant. This implies that self-consistent consideration of the cryogenic complex plasma must include the effect of the dust particle surface temperature. In general, the cryogenic gas discharge is poorly investigated and accurate simulation of the dusty plasma in the cryogenic environment is a subject of the future work.

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