Ordered spatial structures of dust grains in the thermal plasma

V. I. Vishnyakov and G. S. Dragan
Mechnikov Odessa National University, Odessa 65026, Ukraine
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The thermal complex plasma of atmospheric pressure, containing the grains of condensed phase, has been studied. It has been demonstrated that the existence of the space charge areas around the dust grains leads to the inhomogeneous ionization of the plasma and the occurrence of the fluxes of nonequilibrium charge carriers. These fluxes change the pressure of the gas on the grain surfaces and define the forces that force the grains to move towards the zone of maximum ionization perturbation of the plasma. It has been shown that the combined operation of the electrical forces and the forces of the interface pressure leads to the formation of the ordered structures, corresponding to the balance of forces. The results of computer simulation, corresponding to the experimental data, are given.

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I. INTRODUCTION

The low-temperature thermal plasma is a gas at atmospheric or higher pressure and at temperatures of 1000–3000 K. Ionization in the thermal plasma occurs due to the collisions between gas particles, therefore, such plasma is strongly collisional, unlike the low-pressure gas-discharge plasma. It usually contains easily ionizable atoms of alkali metals, as a natural impurity or in the form of special additional agents, which are the basic suppliers of free electrons and singly charged positive ions.

Combustion plasma is a thermal collisional plasma, containing solid or liquid grains that appear as a result of volume condensation or represent not-burnt-down particles of fuel. The values of components' temperatures are close to each other, and the whole system can be considered as isothermal. The interaction between phases leads to the charging of the grains and change of the ionization degree of the plasma.

The study of similar two-phase systems in collisionless gas-discharge plasma has allowed finding out that the dust grains tend to form ordered structures, which are called "plasma crystals," the low-pressure two-phase gas-discharge plasma is called "dusty plasma" [1,2]. The study of the interface interaction in dusty plasmas has led to the development of the two basic theoretical models of ordering of the dust grains: shadow forces, the essence of which consists in the fact that the stream of plasma on the surface of the dust grain carries away other grains [3–5], and the ion drag forces entrainment, which arises if the average velocity of ions relative to the dust grain is not equal to zero [6–9].

The experimental researches of the plasma of metallized fuel combustion, headed by M. N. Chesnokov, Odessa University, 1982, have revealed the formation of the ordered structures in thermal collisional plasma [10], which, unlike the collisionless dusty plasma, is called "smoky plasma" [11]. Figure 1 shows a typical spatial distribution of the grains in the sample, selected in the smoky plasma.

A previous paper [12] considered the thermodynamic reasons for the agglomeration of dust grains in thermal plasma. The present paper is dedicated to the detailed study of the mechanisms of the dust grains' interaction in smoky plasma, which causes the formation of equilibrium structures.

II. THE STATE OF THE PROBLEM

The equilibrium ionization in thermal plasma, which does not contain a dust component, is described by the Saha equation

$$\frac{\bar{n}_e \bar{n}_i}{\bar{n}_a} = \frac{g_i}{g_a} \nu_e \exp\frac{-I}{T} \equiv K_S, \tag{1}$$

where $\nu_e = 2(m_e T/2\pi\hbar^2)^{3/2}$ is the effective density of the electron states, g_i and g_a are the statistical weights of ions and atoms, respectively I is the ionization potential of the alkali-metal atoms, T is the equilibrium temperature of the plasma, which in this case is an isothermal system, m_e is the electronic mass, $\hbar$ is the Planck constant, and K_S is the Saha constant.

It is true provided the charge and mass are preserved, i.e.,

$$n_e = n_i = n_0, \quad n_i + n_a = n_A, \tag{2}$$

where n_0 is the unperturbed number density, n_A is the number density of easily ionizable additional agents, and in the low-temperature plasma the ionization degree is so low that $n_i \ll n_a \sim n_A$.

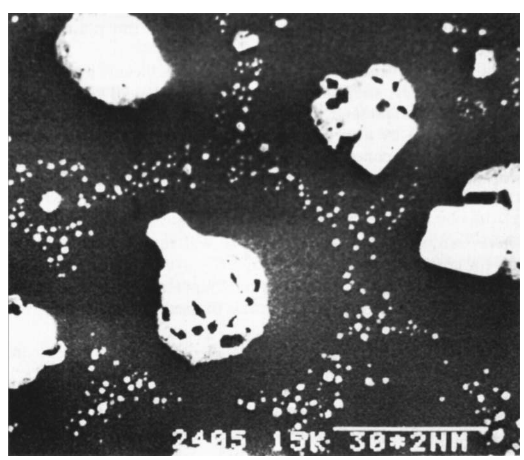

FIG. 1. Photomicrography of the sample, selected in the plasma of combustion of the metallized fuel [10].

The presence of any external perturbation in the plasma causes the increase or decrease of the ionization degree, i.e., displaces the ionization equilibrium. It was suggested to describe such displacement of ionization equilibrium by the thermodynamic parameter of nonequilibrium ψ [13], which can be presented as some additive to the potential of ionization $I_{eff}=I-\psi$. Thus, in the Saha equation there is an additional factor:

$$\frac{n_e n_i}{n_a} = K_S \exp \frac{\psi}{T}. \qquad (3)$$

The presence of the charged dust grains of condensed phase in the plasma also is the source of perturbation in relation to the equilibrium gas phase, which leads to the displacement of ionization equilibrium and the existence of a nonzero value of the parameter ψ, depending on the charges of the grains.

The necessity of use of the concept of bulk plasma potential for the description of the electrostatic potential distribution in the systems of dust grains in the plasma was proved and experimentally confirmed [14,15]. The bulk plasma potential is linearly related to the thermodynamic parameter of nonequilibrium $\psi=-e\varphi_{pl}$, i.e., if the displacement of the plasma ionization equilibrium occurs only due to the action of the charged grains, the effective potential of ionization is equal to $I_{eff}=I+e\varphi_{pl}$, and the Saha Eqs. (3) should look as follows:

$$\frac{n_e n_i}{n_a} = K_S \exp \frac{-e\varphi_{pl}}{T}. \qquad (4)$$

The intensity of collision ionization in the any microvolume of the thermal plasma at the atmospheric pressure (the smoky plasma) is much more than the diffusion or drift velocities of the charge carriers through this volume. This means that the number densities of the charge carriers can be described by the Boltzmann distribution law

$$n_e = n_q \exp \frac{e\phi}{T}, \quad n_i = n_q \exp \frac{-e\phi}{T}, \qquad (5)$$

where n_q is the quasiunperturbed number density: $n_q = n_0 \exp(-e\varphi_{pl}/2T)$.

The value of the bulk plasma potential is determined by the height of the potential barrier at the phase boundary. For example, for a plane with the surface potential ϕ_s [15],

$$\varphi_{pl} = -2\frac{T}{e} \tanh\left(\frac{e\phi_s}{4T}\right). \qquad (6)$$

Accordingly, the quasiunperturbed number density is equal to

$$n_q = n_0 \exp\left[\tanh\left(\frac{e\phi_s}{4T}\right)\right]. \qquad (7)$$

The quasiunperturbed number density characterizes the degree of ionization of the plasma in the space charge layer near the grain surface. The perturbation, caused by the grain in the plasma, should damp as it is removed from its surface. This means that values n_q, ψ, and φ_{pl} should have a spatial distribution. In [14] it was shown that the distribution of the bulk plasma potential $\varphi_{pl} \sim 1/r$ around the grain completely satisfies the equilibrium theory. For a spherical grain with radius a, it should be $\varphi_{pl}(r)=\varphi_{pl}^s(a/r)$; i.e., the bulk plasma potential decreases with the increase of the distance from the grain. In order to define the relative potential ϕ, it is still possible to use the Poisson-Boltzmann equation, and in order to describe, the electron and ion number densities, the Eqs. (5) are valid.

Thus, the thermodynamic parameter $\psi \sim 1/r$ behaves in the same way as the electrical potential in vacuum. The electrical forces could compensate the forces caused by thermodynamic parameter ψ, if there was no screening. However, the screening effect in the plasma leads to diminution of the effective length of the grains' electrical interactions, restricting it to the characteristic Debye gauge length r_D. Therefore, the long-range interaction of the dust grains is determined only by the nonuniform ionization, caused by one grain near the surface of the other grain:

$$\frac{n_q^2(r)}{n_A} = K_S \exp\left(\frac{-e\varphi_{pl}^s}{T}\frac{a}{r}\right). \qquad (8)$$

Thus, the change of the ionization state of the plasma as a result of interface interaction near the surface of one grain is spread in the volume of plasma with damping, inversely proportional to the distance from the grain.

III. ION INTERFACE PRESSURE

The existence of the space charge layer at the dust grain surface leads to the change of the spatial distribution of electrons and ions as a result of electrostatic interaction. Hence, there is the imbalance between the ionization rate of atoms of the additional agent $G_I=\beta_V n_e n_a$ and the intensity of the volumetric recombination $G_R=\gamma_V n_e n_i$, where β_V is the coefficient of volumetric ionization, and γ_V is the coefficient of volumetric recombination. Therefore, if far from the space charge layer the continuity equation looks like

$$\frac{\partial n_{e(i)}}{\partial t} + \mathrm{div}(j_{e(i)}) = G_I - G_R = 0, \qquad (9)$$

inside the space charge layer the right part is not equal to zero.

The nonequilibrium charge carriers, which are not described any more by the Eqs. (5), are formed as a result of this process. It leads to the infringement of the balance between the diffusion and drift streams:

$$j_e = \mu_e n_e^* \nabla \phi - D_e \nabla n_e^* \neq 0,$$

$$j_i = -\mu_i n_i^* \nabla \phi - D_i \nabla n_i^* \neq 0, \qquad (10)$$

where $\mu_{e(i)}$ is the electron (ion) mobility, $D_{e(i)}$ is the electron (ion) diffusivity, and "*" means nonequilibrium character of the charge carriers number density.

However, it is possible to consider the nonequilibrium values as a deviations from the equilibrium number densities of electrons and ions:

$$n_e^* = n_e + \delta n, \quad n_i^* = n_i + \delta n. \tag{11}$$

The electron and ion number density deviations are equal, as ions of alkaline metals are singly charged, and for each ion, formed as a result of collision ionization, there appears one electron.

As a result, the continuity equation can apply only for the nonequilibrium additives:

$$\frac{\partial \delta n}{\partial t} - D\Delta \delta n = G_I - G_R \neq 0. \tag{12}$$

In a stationary case the Eq. (12) is reduced to the following form [16]:

$$\lambda_R^2 \Delta\left(\frac{\delta n}{n_q}\right) = \left[\frac{1}{1+\left(\frac{er_D}{T}E\right)^2}\left(\frac{\delta n}{n_q}\right)^2 + \frac{\delta n}{n_q} - \frac{\exp(e\phi/T)-1}{1+\left(\frac{er_D}{T}E\right)^2}\right] \times\left[1+\left(\frac{er_D}{T}E\right)^2\right], \tag{13}$$

where $\lambda_R = \sqrt{D\tau_R}$ is the recombination length, $D = 2D_eD_i/(D_e+D_i)$ is the ambipolar diffusion coefficient, and $\tau_R = (\beta_V n_A)^{-1}$ is the lifetime of nonequilibrium charge carriers.

Equation (13) can be reduced, taking into account the following:

(i) At small values of the potential $e\phi \ll T$ the ratio $\delta n/n_q \ll 1$; therefore, in Eq. (13) it is possible to neglect the quadratic term. However, it can also be made at more potentials, as in this case $\delta n/n_q \sim 1$, but $er_D E/T \gg 1$.

(ii) In the smoky plasma the divergence of electron and ion fluxes is much less than the ionization and recombination rates, and the Maxwell relaxation time $\tau_M \gg \tau_R$; accordingly, the ratio of the recombination length λ_R to the screening length $\lambda_R/r_D = \sqrt{\tau_R/\tau_M} \ll 1$. Therefore, it is possible to consider the potential and the field as constant values on the recombination length.

Basing on such assumptions, the solution of Eq. (13) is the function

$$\delta n = n_q \frac{\exp(e\phi/T)-1}{1+\left(\frac{er_D}{T}E\right)^2}\left[1+\frac{\lambda_R}{r_D}\exp\left(\frac{-r}{\lambda_R}\sqrt{1+\left(\frac{er_D}{T}E\right)^2}\right)\right]. \tag{14}$$

Accordingly, the flux of the nonequilibrium charge carriers, providing the transfer of momentum to the dust grain surface, is equal to

$$j^* = \frac{Dn_q}{r_D}\frac{\exp(e\phi/T)-1}{\sqrt{1+\left(\frac{er_D}{T}E\right)^2}}\exp\left(\frac{-r}{\lambda_R}\sqrt{1+\left(\frac{er_D}{T}E\right)^2}\right). \tag{15}$$

The gas phase of smoky plasmas puts pressure upon the grain surface, which is radially symmetrical, if there are no other grains. The presence of other grains causes additional nonequilibrium ionization of the plasma near the surface of the grain, which can be asymmetrical. Therefore, the change of pressure on the grain surface can be related only to the surface inhomogeneity of the flux of nonequilibrium ions Eq. (15) as the flux of electrons can be neglected in the isothermal system. If such inhomogeneity exists, there appears the force of the ion interface pressure [16]

$$\mathbf{F} = -\lambda_R m_i \int_S j^* d\mathbf{s} = -\frac{m_i\lambda_R D}{r_D\tau_R}\frac{\exp(e\phi_s/T)-1}{\sqrt{1+\left(\frac{er_D}{T}E_s\right)^2}}\int_S n_q d\mathbf{s}, \tag{16}$$

which depends only on inhomogeneity of the quasiunperturbed number density, characterizing the nonequilibrium ionization, when the distance between the grains exceeds the size of the space charge layer.

IV. EQUILIBRIUM SPATIAL DISTRIBUTION OF THE DUST GRAINS

The force equation (16) provides for the movement of the dust grain towards the greater ionization perturbation of the plasma. The flux of nonequilibrium ions [Eq. (15)] is directed so that the ion interface pressure would be directed toward the greater change of the ionization degree in both cases: as the ionization degree increases and as it decreases. It provides for the force, which attracts the likely charged dust grains. The attraction continues until the space charge layers overlap and the forces of the electrical repulsion start being effective. When there is balance of forces, there is also some equilibrium spatial distribution of the grains.

The force equation (16), in view of $n_q = n_0 \times \exp(-e\varphi_{pl}/2T)$, can be represented in the following form:

$$\mathbf{F} = -\frac{m_i n_0 \lambda_R D}{r_D\tau_R}\frac{\exp(e\phi_s/T)-1}{\sqrt{1+\left(\frac{er_D}{T}E_s\right)^2}}\int_S \exp\left(-\frac{e\varphi_{pl}}{2T}\right)d\mathbf{s}, \tag{17}$$

and taking into account the discrete arrangement of the neighboring grains, forming the anisotropic value φ_{pl}, this force can be represented as

$$\mathbf{F} = \frac{4\pi a^2 m_i n_0 \lambda_R D}{r_D\tau_R}\frac{\exp(e\phi_s/T)-1}{\sqrt{1+\left(\frac{er_D}{T}E_s\right)^2}}\sum_k \exp\left(\frac{-e\varphi_{pls}^k}{2T}\frac{a_k}{r_k}\right)\mathbf{e}_k, \tag{18}$$

where φ_{pls}^k is the bulk plasma potential at the surface, a_k is the radius of the kth neighboring grain, r_k is the distance from the surface of the chosen grain to the surface of the kth neighboring grain, and $\mathbf{e}_k$ is the unit vector, directed from chosen grain to neighboring one.

In the weakly coupled plasma, the exponents in Eq. (18) can be linearized, and the force of the ion interface pressure can be represented as the interaction of effective charges

$$\mathbf{F} = Q_{eff} \sum_k \frac{q_k}{4\pi\varepsilon_0 r_D r_k} \mathbf{e}_k, \tag{19}$$

where

$$Q_{eff} = \frac{\varepsilon_0 \pi a^2 m_i \lambda_R D \phi_s}{2 r_D^2 \tau_R T}$$

is the effective charge of the chosen grain and $q_k = -4\pi\varepsilon_0 a_k \varphi_{pls}^k$ are the effective charges of the neighboring grains. The interaction Eq. (19) is not Coulomb-type as it is proportional to $1/r$, instead of $1/r^2$ and, accordingly, more long range.

In the strongly coupled plasma, the force of the ion interface pressure depends nonlinearly on the potential of the grain surface, which is connected not only with the presence of the exponential curve in Eq. (18), but also with the nonlinear dependence of the bulk plasma potential on the potential of the grain surface. For example, if the size of the grain allows applying the "flat" approach of the Poisson equation, the bulk plasma potential for a single grain is described by Eq. (6). Accordingly, the force equation (18) depends on the potential of the grain surface as follows:

$$\mathbf{F} = C \frac{\exp(e\phi_s/T) - 1}{\sqrt{2\cosh(e\phi_s/T) - 1}} \sum_k \exp\left[\frac{a_k}{r_k} \tanh\left(\frac{e\phi_{sk}}{4T}\right)\right] \mathbf{e}_k, \tag{20}$$

where $C = (4\pi a^2 m_i n_0 \lambda_R D)/(r_D \tau_R)$, and ϕ_{sk} is the surface potential of the kth neighboring grain.

Let us consider the two identical dust grains on which the attraction force of the ion interface pressure and the repulsion electrical force act. When the grains are located far apart, the force of the ion interface pressure [Eq. (20)], which causes the grains to attract, is defining. When the space charge layers of the grains overlap, the repulsion electrical force become effective. When the distance between the surfaces of the grains becomes equal to some value d_0, the balance of the forces is reached. The dependence of the equilibrium distance between the surfaces of the two grains on their potential is represented in Fig. 2. In this case the parameters of plasma that correspond to the experiment [10] are used: the number density of atoms of additional agent of cesium (the ionization potential is $I = 3.89$ eV) $n_A = 2 \times 10^{15}$ cm^{-3}, the temperature $T = 0.2$ eV (2300 K), and the radius of the grains $a = 2\mu$. The equilibrium value of the unperturbed number density in this case is $n_0 \sim 4 \times 10^{13}$ cm^{-3}, and the screening length is $r_D \sim 0.4\mu$.

The equilibrium distance between the positively charged grains depends weakly on the value of the surface potential and, accordingly, on the value of the grain charge, if $e\phi_s > T$. However, at highly negative surface potential $-e\phi_s > T$, the equilibrium distance grows as the dust grain charge increases. This is explained by that the fact that the low-temperature (1000–3000 K) plasma is weakly ionized. Therefore, the limits of variation of the nonequilibrium carriers' number is wider at the increased ionization degree than at the decreased ionization degree. The increase of the ionization degree at the positive charge of dust grains leads to

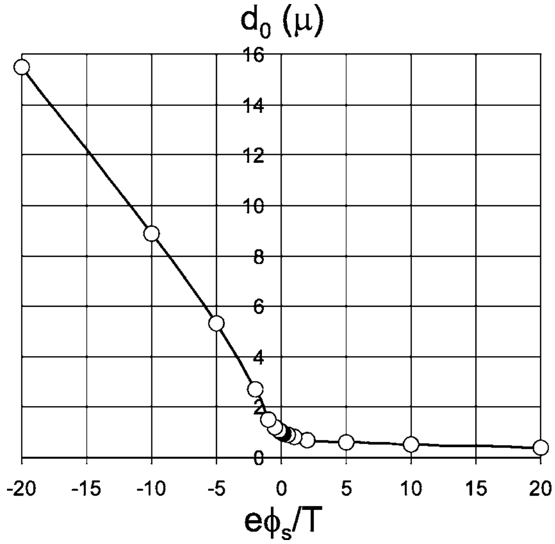

FIG. 2. Dependence of the equilibrium distance between the two identical grains on the surface potential.

an increase of the repulsion electrical force and simultaneous increase of the ion interface pressure, providing for the attraction of the dust grains. As a result, the distance corresponding to the equilibrium state remains constant. At the negative charge of the dust grains the plasma ionization degree in the space charge layer decreases to the near-zero value already at $-e\phi_s \sim T$. The further increase of the negative surface potential does not lead to the increase of the ion interface pressure; however, the repulsion electrical force increases. That is why the equilibrium distance between grains increases.

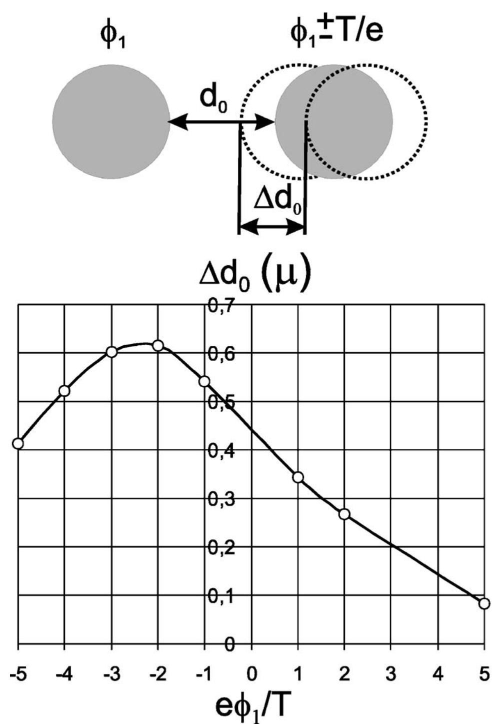

FIG. 3. Dependence of the variation of equilibrium distance, caused the deviation $e\phi_2 = e\phi_1 \pm 1T$ on the potential ϕ_1.

The difference in the interaction between the positively and negatively charged dust grains leads to different patterns of influence of the fluctuations of the positive and negative charges on the rate of this interaction.

The deviation of the equilibrium distance between the dust grains, corresponding to the deviation of the surface potential of the second grain by $\pm 1T/e$, on the value of the surface potential of the first grain is presented in Fig. 3. Here it is clearly seen that at identical variations of the potential of the second grain, the oscillations of the grains in relation to the equilibrium state $\phi_2=\phi_1$ decrease as the positive grains' charges increase, and increase up to a certain value as the negative grains' charges increase. The peak dependence of the grains' oscillations on the change of potential is observed, at the given parameters of the plasma, at $-e\phi_1 \sim 2T$. The further increase of the potential $-\phi_1$ leads to impairment of this dependence.

Thus, it is possible to conclude that the impairment of the influence of variation of the charge of one grain on the equilibrium spatial distribution of the dust grains in the plasma corresponds to greater charges of dust grains both positive and negative. Such impairment is connected to the nonlinear dependence of the bulk plasma potential φ_{pl} on the surface potential of the grains. This means that the ordered structures of the dust grains in the smoky plasma, formed by the grains with greater charges, are more inconvertible than the structures formed by grains with small charges, or, in other words, the dusty structures are more inconvertible in the strongly coupled plasma.

V. COMPUTER SIMULATION

Equation (20), used jointly with the well-known equations of electrical interaction, allows calculating the equilibrium distribution of a system of grains in the plasma.

For each grain, the resultant force as the difference between the force of the ion interface pressure [Eq. (18)] and the force of electrical interaction of the chosen grain j and each of other grains k $(k\neq j)$ has been calculated:

$$F_{j,k}=eZ_iE_k-Ca_j^2\frac{\exp(e\phi_j/T)-1}{\sqrt{2\cosh(e\phi_j/T)-1}}\exp\left[\frac{a_k}{R_k}\tanh\left(\frac{e\phi_k}{4T}\right)\right], \tag{21}$$

where $C=4\pi m_i n_0 \lambda_R D/r_D\tau_R=32\ \mathrm{N/m^2}$, ϕ_j is the potential of the surface of the chosen grain, ϕ_k is the potential of the surface of the kth grain, and Z_j is the charging number of the chosen grain [17]:

$$Z_j=\frac{8\pi\varepsilon_0 a_j(a_j+r_D)T}{e^2 r_D}\sinh\left(\frac{e\phi_j}{2T}\right),$$

where E_k is the field created by the kth grain at the surface of the chosen jth grain.

For the potential of the surface where $e\phi_s<T$, the following expression for the electric field can be used:

$$E_k(R_{j,k})=\phi_k\frac{a_k}{R_{j,k}}\left(\frac{1}{r_D}+\frac{1}{R_{j,k}}\right)\exp\left(\frac{a_k-R_{j,k}}{r_D}\right), \tag{22}$$

where $R_{j,k}$ is the distance between the grains j and k.

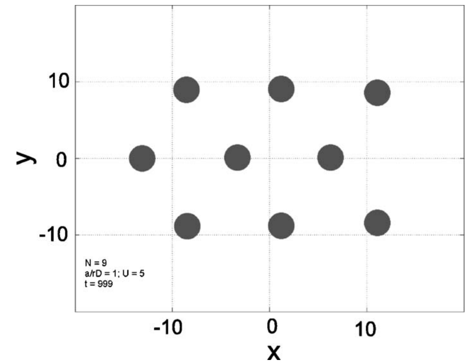

FIG. 4. Result of the 2D computer simulations of the interaction of nine identical grains.

For grains with radius $a\gg r_D$, the following expression can be used:

$$E_k(R_{j,k})=2\frac{T}{er_D}\sinh\left\{\ln\left[\frac{1+\tanh\left(\frac{e\phi_k}{4T}\right)\exp\left(\frac{a_k-R_{j,k}}{r_D}\right)}{1-\tanh\left(\frac{e\phi_k}{4T}\right)\exp\left(\frac{a_k-R_{j,k}}{r_D}\right)}\right]\right\}$$

$$=\frac{-2T}{er_D\sinh\left\{\ln\left[\tanh\left(\frac{e\phi_k}{4T}\right)\right]+\frac{a_k-R_{j,k}}{r_D}\right\}}. \tag{23}$$

However, the computer research of Eqs. (22) and (23) demonstrate the possibility to use the following expression:

$$E_k(R_{j,k})=\frac{-2T\frac{a_k}{R_{j,k}}\left(\frac{1}{r_D}+\frac{1}{R_{j,k}}\right)}{e\sinh\left\{\ln\left[\tanh\left(\frac{e\phi_k}{4T}\right)\right]+\frac{a_k-R_{j,k}}{r_D}\right\}}, \tag{24}$$

which describes the electrical field generated by small and large grains with any values of the surface potential.

Having calculated the resultant force of interaction of each jth grain with all other grains, we obtain N values of coordinate components of the force, where N is the total number of grains. For the two-dimensional (2D) simulation it is a $2\times N$ matrix, containing Fx and Fy components of the forces, acting on each of the grains

$$Fx_j=\sum_{k=1,k\neq j}^{N}F_{j,k}\frac{x_j-x_k}{R_{j,k}},\quad Fy_j=\sum_{k=1,k\neq j}^{N}F_{j,k}\frac{y_j-y_k}{R_{j,k}},$$

where x and y are the coordinates of grains, and

$$R_{j,k}=\sqrt{(x_j-x_k)^2+(y_j-y_k)^2}.$$

If the time step is Δt, then over this time the grains will travel

$$\Delta x_j=\frac{Fx_j\Delta t^2}{2m_j},\quad \Delta y_j=\frac{Fy_j\Delta t^2}{2m_j},$$

where m_j is the mass of the grain.

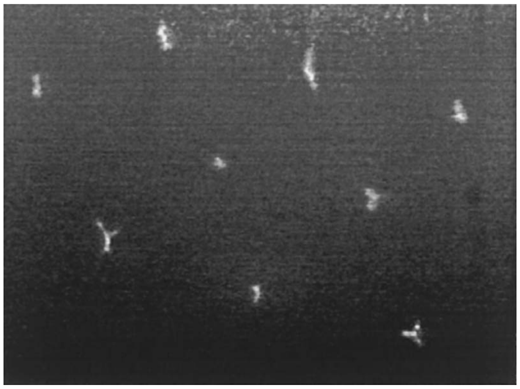

FIG. 5. Photo of the spatial distribution of nine grains according to [18].

The calculation is finished when grains reach the equilibrium state; i.e., there are no further changes of the average relative position in time.

Figure 4 shows the results of 2D computer simulation of the motion dynamics of nine identical grains in the plasma with the parameters specified above. At the initial moment the grains are located far apart. As a result of activity of the force of the ion interface pressure and the electrical forces of repulsion the grains form a hexagonal structure.

The continuation of simulation demonstrates further movement of grains, but only as a whole structure, which rotates and moves incidentally. The spatial distribution of grains in relation to each other is preserved. This result well correspond to the experimental data [18], given in Fig. 5.

The following simulation was made for the plasma with the same parameters, but containing three fractions of grains, corresponding to the three fractions, obtained experimentally [10] and presented in Fig. 1. The calculation is based on the use of six grains with radius $a_1=2r_D\sim 1\mu$, 13 grains with radius $a_2=0.2r_D\sim 0.1\mu$ and 270 grains with radius $a_3=0.02r_D\sim 0.01\mu$, which corresponds to the quantity of similar grains in the photomicrography Fig. 1.

When the potentials of the grain surfaces were equal $\phi_1=5T/e=1$ V for the first fraction, $\phi_1=2T/e=0.4$ V for the second fraction, and $\phi_1=1T/e=0.2$ V for the thirds fraction, the grains formed the structure, presented in Fig. 6.

The structure, formed by the grains of three fractions as a result of computer simulation, corresponds well to the structure obtained experimentally and presented in Fig. 1.

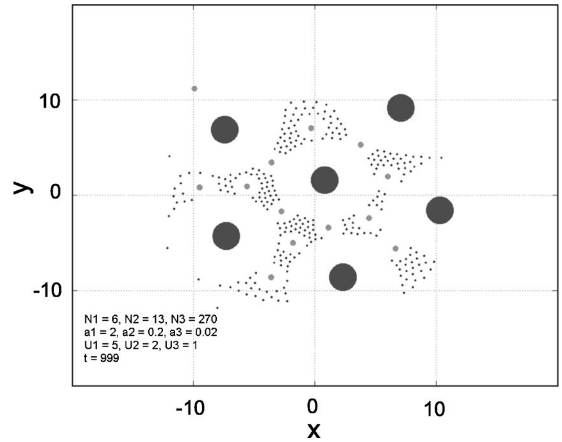

FIG. 6. Result of the 2D computer simulations for the plasma containing three fractions of the condensed grains.

VI. CONCLUSION

The proposed model of long-range interaction of the dust grains in the plasma, based on the concept of the bulk plasma potential as the method of the description of the inhomogeneous ionization of plasma, corresponds well to the experimental data and is suitable for description of the collective interaction of the condensed grains and formation of ordered structures in thermal collision (smoky) plasma.

According to this model, the emergence of ordered spatial structures of dust grains in smoky plasma is caused by inhomogeneous ionization, resulting from interface interaction. The displacement of the ionization equilibrium in the space charge layer around the dust grain occurs as a result of local infringement of electroneutrality of the gas phase of plasma. A flux of nonequilibrium ions appears here, which changes the pressure of the gas phase on the surface of the grain. The ionization perturbation caused by one grain is transferred to other grains, damping according to the hyperbolic law. When the grains are located nonuniformly at the surface of a separate grain, radial asymmetry of the ionization perturbation and, accordingly, asymmetry of the flux of nonequilibrium ions appear, which cause the ion interface pressure directed towards the zone of greater ionization perturbation of the plasma irrespective of the fact whether this perturbation consists in the increase or decrease of the ionization degree. Thus a force appears that attracts the likely charged grains.

As a result, the electrical forces and forces of the ion interface pressure act on the charged dust grains. Under the influence of these forces, the grains tend to form structures corresponding to the balance of forces. It should be noted that the impairment of the influence of variation of the charge of one grain on the equilibrium spatial distribution of the dust grains in the plasma corresponds to greater charges of dust grains both positive and negative. This means that the ordered structures of dust grains in the smoky plasma, formed by the grains with greater charges, are more inconvertible than the structures formed by the grains with small charges.

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