Charging of dust in thermal collisional plasmas

Vladimir I. Vishnyakov
Physical-Chemical Institute for Environmental and Human Protection, UA-Odessa 65082, Ukraine
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Thermal strongly collisional dusty plasma is studied. The electrical neutrality of the plasma suggests that the gas phase has some electrostatic energy when the plasma contains charged dust grains. The value of this energy determines the interphase interaction and ionization balance in the plasma. Proceeding from this, a new method of calculation of the dust grains' charges in plasmas with any number of ions (down to zero) has been proposed. The correspondence between the theory and the experimental data is demonstrated.

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I. INTRODUCTION

One of the problems of dusty plasma theory is the determination of the dust charge as the charge determines the interaction of the dust grains with the gas component and among themselves. This problem emerged when Sugden and Trush [1] determined the increase of the electron number density in the hydrocarbon combustion flames, which was explained by the thermionic emission from the soot particles [2,3]. This phenomenon has been extensively studied [4–12], and even technical applications for it have been found. For example, some authors proposed the seeding of working fluids of magnetohydrodynamics (MHD) generators with refractory grains of a low work function in order to increase their electrical conductivity [13]. Nevertheless the problem of calculation of the dust charge in the plasma has not been solved completely.

I have considered a thermal plasma at atmospheric pressure, i.e., a strongly collisional plasma, for which the time of ionization relaxation is much less than the time of diffusion-drift relaxation. Such plasmas are formed as a result of the combustion of various fuels, in the channels of MHD generators, and in welding fumes. They are charged solid or liquid particles (dust grains) suspended in a partially ionized gas at atmospheric or higher pressures. The system is considered isothermal with the average temperature around $T \sim 0.1$–0.3 eV ($T/k_B \sim 1200$–3500 K). At such temperatures, the ionization of the air, which is the gas component of the plasma, is low. Therefore, the additional agents of alkali metals are introduced into the fuel or another plasma source. The alkali metal atoms have a low ionization potential, and in this case, the gas phase of the plasma is the neutral buffer gas containing the singly charged positive ions, emerging as a result of the collision ionization of the additional agent atoms, and the electrons, resulting from both processes—the collision ionization and the emission from the dust grains' surfaces.

When plasma does not contain the dust component, the ionization balance is described by the Saha equation [14]

$$\frac{n_e n_i}{n_a} = \frac{g_i}{g_a} \nu_e \exp\left(\frac{-I}{T}\right) \equiv K_S, \qquad (1)$$

where n_e is the average electron number density; n_i is the average ion number density (in a low-temperature plasma, the singly charged positive ions only are considered); n_a is the average number density of atoms; $\nu_e = 2(m_e T/2\pi\hbar^2)^{3/2}$ is the effective density of the electron states; g_i and g_a are the statistical weights of the 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. Also, the neutrality equation and the conditions of the mass conservation should be considered:

$$n_e = n_i, \quad n_i + n_a = n_A, \qquad (2)$$

where n_A is the number density of the additional agent.

When the plasma contains dust grains, the number density of electrons is changed by the interphase interaction. The neutrality of plasma with polydisperse (in a general case) dust component is described by the following equation:

$$\sum_j Z_j n_j = n_e - n_i, \qquad (3)$$

where Z_j is the charge number of the dust grains of kind j (the charge is expressed in the elemental charges) with the number density n_j.

It should be noted that the charge exchange between the dust and gas phases and the collision ionization are not additive processes. The detailed analysis of the ionization and recombination in the space charge layer near the dust grain surface in plasma [15,16] demonstrated that the interphase interaction results in the ionization balance displacement and the emergence of nonequilibrium charge carriers. The local increase or decrease of the plasma ionization degree, which occurs as a result of interphase interaction, entails changes of the electron and ion number densities, i.e., the ionization balance in the space charge layer is not described by the Saha Eq. (1). Therefore, the modernization of the Saha equation, taking into account the interphase interaction, was proposed in Refs. [17,18] as

$$\frac{n_e n_i}{n_a} = K_S \exp\frac{e\varphi_0}{T}, \qquad (4)$$

where φ_0 is the bulk plasma potential, the value of which is defined by the total charge of the plasma gas phase.

The bulk plasma potential is the reference level for the electrostatic potential in the system of charged particles. It is well-known that the potential is defined by a constant. This problem is easily solved when the charged particles are in vacuum, i.e., the Coulomb interactions are considered. In this case, the value of the potential at infinity is assumed equal to zero, providing a reference point. In the plasma, such an approach can be implemented only for a single grain in the perpetual system. The restriction of the plasma volume results in a potential barrier on the boundary due to different mobilities of electrons and ions. In this case, it is impossible to define the point at infinity or to equate arbitrarily the value of potential to zero because the whole plasma volume is charged (though the charge is small). The system of polydisperse dust grains in the plasma is even more complex. Using the Poisson equation, it is possible to calculate the potential distribution around a separate grain but up to a constant. Thus, inevitably there is a problem concerning the correlation of the calculations done for different dust grains among themselves.

The concept of the bulk plasma potential allows for the solving of this problem: the existence of plasma based on electrical interaction of its components. The whole plasma volume is neutral, but the presence of the charged dust grains entails a volumetric charge in the gas phase. The bulk plasma potential characterizes the size of the operation that is necessary for the plasma to gain some volumetric charge. Thus, the gas phase of plasma contains some electrical energy, which determines the energy level $e\varphi_0$. The potential barrier near the dust grain surface is determined by the difference of the energies of the electron on the grain surface and on the level $e\varphi_0$.

This question in Ref. [19] for interacting planes has been considered in detail; it has been demonstrated that the value of the bulk plasma potential defines whether the planes are repulsive or attractive. This problem in spherical symmetry was considered in Ref. [20]. Besides, the possibility of describing the dust grains' long-range interaction and their ordered structure formation in the thermal plasma (to which the orbit-limited (OML) theory [21] is not applicable) by the concept of bulk plasma potential was demonstrated in Ref. [18]. Thus, the definition of the bulk plasma potential is directly linked with the determination of the dust grain charges.

By now, I have considered the complex plasma containing ions with a high number density. However, there is another kind of thermal plasma. It is the dust-electron plasma, which does not contain ions. Such plasma exists, for example, in the welding fumes in which all ions are nucleation centers. Thus, in this system, there are hot dust grains in the neutral buffer gas. The system is saturated with electrons as a result of thermionic emission from the grains surfaces, and the dust-electron plasma emerges, so the neutrality equation acquires the following form:

$$\sum_j Z_j n_j = n_e. \tag{5}$$

Such a system was considered in Refs. [22,23] in which the theory of neutralized charges, allowing to calculate the dust grain charges in a polydisperse system, was proposed. This theory also uses the concept of bulk plasma potential; however, here it is defined in a way different from that of the complex plasma (containing ions).

The plasma containing a small number of additional alkaline agents, for example, in the form of natural impurities, is absolutely beyond the scope. This transition stage is not described at all, and it is not clear how the grain charges are calculated in this case. The present paper is dedicated to the development of a general procedure for defining the dust grains' charges in a thermal strongly collisional plasma with any number of ions.

In order to solve this problem, a general concept of bulk plasma potential applicable to both dust-electron plasma and complex plasma needs to be defined, and the theory should correspond to the known experimental data of, for example, Refs. [24–26].

Consideration will be concentrated on the plasma with a dust component that acquires charge due to thermionic emission, i.e., it is charged positively. The following notations will be used further: the total potential with respect to any reference system φ, the bulk plasma potential in the same reference system φ_0, the relative potential $\phi = \varphi - \varphi_0$, and the dimensionless relative potential $\Phi \equiv e\phi/T$.

II. THERMAL DUST-ELECTRON PLASMA

The subject of interest is thermal plasma; therefore, the formation of dust-electron plasma as a result of thermionic emission is considered. The photoemission and the field emission that may take place in some cases are neglected. Thermal dust-electron plasma is formed in the combustion products' condensation zone of various fuels without additional alkali metal agents. The high-temperature vapor of the combustion products condenses and forms the nano-sized particles that grow into larger conglomerates. These particles are in a state close to thermodynamic equilibrium with the environmental gas. The Kelvin temperature of the gas is about 1200–3500 K; accordingly, the condensed dust has the same temperature. At such a temperature, thermionic emission from the dust grain surfaces is essential, and the equilibrium electron number density near the grain surface is described by the Richardson equation

$$n_{es} = \nu_e \exp\frac{-W}{T}, \tag{6}$$

where W is the electronic work function from the grain surface. For the nano-sized grains, the correction factor to the work function given in the reference books for the flat surface is required. Such a correction factor can be found in the papers by B. Smirnov [27,28].

The dust grains are charged positively, and the emitted electrons saturate the environment. The theory of neutralized charges [22] suggests that most of the electrons in the plasma volume are distributed uniformly with some uniform (or unperturbed) number density of n_0 with the increase of the electron number density only in the thin layer near the dust grain surface. Therefore, the description of the system uses relative values in this theory. The electron number density is measured based on the uniform number density n_0, and the potential is measured based on the bulk plasma potential, which is the potential of the neutralized background φ_0 here. The neutralization consists of the fact that the electrons with number density n_0 and some part of the dust grains' charges $Z_0 < Z$ (Z is the average charge number) neutralize each other. As a result, the grain interaction depends only on the visible part of the charge $\tilde{Z}_j = Z_j - Z_0$. The neutralized charge Z_0 is linked with the uniform number density by the following equation:

$$Z_0 n_d = n_0. \tag{7}$$

The total dust grain charge is described by the following equation [22]:

$$Z_j = Z_0 + \frac{\sqrt{2}(r_D + a_j)a_j T}{\mathrm{sgn}(\Phi_{sj})e^2 r_D}\sqrt{\exp(\Phi_{sj}) - \Phi_{sj} - 1}, \tag{8}$$

where a_j is the grain radius, $r_D = \sqrt{T/4\pi e^2 n_0}$ is the screening length, and Φ_{sj} is the potential barrier with respect to φ_0,

$$\Phi_{sj} = \ln\frac{n_{ej}}{n_0} = \ln\frac{\nu_e}{n_0} - \frac{W_j}{T}. \tag{9}$$

The potential of the neutralized background can be defined as follows. If the total charge of the dust grains is equal to zero $Z_k = 0$, the total potential of this grain surface is equal to zero too. Thus, the relative charge of this grain $\tilde{Z}_k = -Z_0$, and the relative surface potential $\phi_{sk} = -\varphi_0$. Then, from Eq. (8) it follows that

$$\frac{e^2 Z_0}{\sqrt{2}aT} = \sqrt{\exp\frac{-e\varphi_0}{T} + \frac{e\varphi_0}{T} - 1}, \tag{10}$$

where a is the average dust grain radius. Here, it is considered that the inequality $a \ll r_D$ is valid for most dust grains in the combustion plasma and that $\mathrm{sgn}(-\varphi_0) = -1$ for $\varphi_0 > 0$. When the potential of the neutralized background $\varphi_0 \ll T/e$, Eq. (10) reduces to the Coulomb potential $\varphi_0 = eZ_0/a$.

As the potential of the neutralized background is defined, it is possible to use it to define the average electron number density, and $e\varphi_0$ is considered as the correction factor for the electron chemical potential,

$$n_e = n_0 \exp\frac{e\varphi_0}{T}. \tag{11}$$

Now, it is possible to calculate the dust grain charges and the average electron number density in thermal dust-electron plasma, i.e., those parameters that can be measured. It allows one to compare the theoretical model with the experimental data. For example, in Ref. [24], the experimental data, obtained by the study of thermal plasma formed in the flame of burning aluminum dust, was cited: the alumina grain radius $a = 0.05\ \mu$, the plasma temperature is 3150 ± 70 K ($T = 0.27$ eV), the dust number density $n_d = 10^{10}$ cm^{-3}, and the electron number density $n_e^{\mathrm{expt}} = 1.5 \times 10^{12}$ cm^{-3}.

The electronic work function for aluminum oxide is 4.7 eV, and with the correction to the work function for the curvature [29],

$$W = 4.7\ \mathrm{eV} + \frac{0.39e^2}{a} = 4.71\ \mathrm{eV}.$$

The values of the temperature and work function allow one to calculate the surface electron number density Eq. (6), $n_{es} = 2.5 \times 10^{13}$ cm^{-3}. Taking into account Eq. (9), the total charge is defined as a function of Z_0:

$$Z(Z_0) = Z_0 + \frac{\sqrt{2}aT}{e^2}\sqrt{\frac{n_{es}}{Z_0 n_d} - \ln\frac{n_{es}}{Z_0 n_d} - 1},$$

and the potential of the neutralized background is defined as a function of Z_0: $e\varphi_0/T = \ln(n_e/n_0) = \ln(Z/Z_0)$.

Thus, the equation for Z_0 is defined from Eq. (10) in the following form:

$$\frac{e^2 Z_0}{\sqrt{2}aT} - \sqrt{\frac{Z_0}{Z(Z_0)} + \ln\frac{Z(Z_0)}{Z_0} - 1} = 0.$$

Then, calculation produces the neutralized charge $Z_0 = 25$, the average dust grains' charge $Z = 154$, and the electron number density $n_e^{\mathrm{theor}} = 1.54 \times 10^{12}$ cm^{-3}, which well agrees with the experimental data.

III. COMPLEX THERMAL PLASMA

Complex thermal plasma consists of a dust component and additional alkali metal agents in the buffer gas. The average number densities of the electrons, ions, and atoms are linked by Eq. (4) for which the bulk plasma potential φ_0 describes the average displacement of the ionization balance. The mechanism of this displacement as a result of interphase interaction was described in Ref. [15]. The cause of the excess ionization near the surface of a positively charged dust grain is that the intensity of the collision ionization is proportional to the product $n_e n_a$ whereas the intensity of recombination is proportional to $n_e n_i$. If the Boltzmann distribution is assumed valid for the electrons and ions, then the recombination intensity is a constant $n_e n_i = n_0^2$, but the ionization intensity depends on the potential $n_e n_a = n_0 n_A \exp(\Phi) - n_0^2$, i.e., the ionization intensity increases near the positively charged dust grains. The tendency is opposite for the negatively charged grains.

If the Boltzmann distribution is considered equilibrium, then the local displacement of the ionization balance can be described as an additional correction factor $\delta n(\Phi)$ to the Boltzmann distribution,

$$n_{er} = n_0 \exp(\Phi) + \delta n, \quad n_{ir} = n_0 \exp(-\Phi) + \delta n,$$

where n_{er} and n_{ir} are the local number densities in contrast to the averages n_e and n_i, respectively. Here, it is taken into account that nonequilibrium additions for electron and ion number densities are equal between themselves in the case of single ionization. This addition is defined in Ref. [15] as

$$\delta n = n_0 \frac{\exp(\Phi) - 1}{2\cosh(\Phi) - 1}. \tag{12}$$

As a result, the additional ionization arising near the positively charged grains causes an almost uniform spatial distribution of ions [16], i.e., $n_{ir} \cong n_0$ when $\Phi > 0$.

The thermionic emission is not a unique perturbation of the complex plasma by the dust grains. The ionization of atoms and the recombination of ions on the grain surfaces also take place, i.e., there are fluxes of electrons, ions, and atoms near the grains. Therefore, the displacement of the ionization balance is determined by the diffusion processes considered in Refs. [15,16]. It should be taken into account that Eq. (12) is applicable to the strongly collisional plasma for which the extent of the diffusion flux perturbations is much less than that of the electrical perturbations (i.e., the recombination length is much less than the screening length).

Besides, this theory is applicable to plasma with a great amount of additional agent when the initial ionization degree is low and additional ionization in the field of positive grains is possible. This situation remains as the number density of the additional agent n_A decreases down to the limiting value when the full ionization of atoms provides for the necessary displacement of the ionization balance.

The concept of the unperturbed number density n_0 is used to describe the complex plasma. It is the electron and ion number densities in the unperturbed plasma area, i.e., outside the space charge layers near the dust grains. This area is neutral for high number densities of the additional agent. The decrease of the amount of additional agent results in the necessity of separation of the total unperturbed number density on the electron unperturbed number density n_{e0} and the ion unperturbed number density n_{i0}, and the nonequilibrium addition δn is determined by the ion unperturbed density $n_{i0} = n_i$ because it describes the additional ionization. The low number density of additional agent suggests that the displacement of ionization balance should be considered with the neutralization of the spatial electron charge by the part of the dust component charge Z_0. The neutralization is described by Eq. (7) for dust-electron plasma. The ions in the complex plasma neutralize the part of the spatial electron charge, and the equation $n_{e0} = Z_0 n_d + n_{i0}$ should be used instead of Eq. (7). As the ions are allocated uniformly by additional ionization, the following equation should be used:

$$n_{e0} = Z_0 n_d + n_i. \tag{13}$$

The bulk plasma potential in the complex plasma can be described by the same equation as the potential of the neutralized background in the dust-electron plasma Eq. (10) if the neutralized charge is described by Eq. (13).

The dust grain charge in the complex plasma at a high number density of ions and under the condition $a \ll r_D$ is described by the following equation [18]:

$$\tilde{Z} = 2\frac{aT}{e^2}\sinh\frac{\Phi_s}{2}, \tag{14}$$

which coincides with Eq. (8) up to a factor of $\sqrt{2}$ for positive values of Φ_s. Therefore, instead of Eq. (10), the following equation may be used for a neutral grain:

$$\frac{e^2 Z_0}{\sqrt{2}aT} = 2\sinh\frac{e\varphi_0}{2T},$$

and, accordingly,

$$\varphi_0 = 2\frac{T}{e}\text{arsinh}\frac{e^2 Z_0}{2\sqrt{2}aT}. \tag{15}$$

The increase of the amount of additional agent can result in the negative potential barrier that causes a local decrease of the ionization degree. However, as it follows from Ref. [16], the uniform space distribution of ions remains valid for negative dust grains if $\Phi_s \geqslant -0.7$, corresponding to the visible charge number $\tilde{Z} \geqslant -500a(\mu)T(\text{eV})$. Accordingly, Eq. (15) remains valid in this range.

Therefore, it is possible to calculate the parameters of the complex thermal plasma. The following combined equations should be used:

$$\begin{aligned}
\varphi_0 &= 2\frac{T}{e}\text{arsinh}\frac{e^2(n_{e0}-n_i)}{2\sqrt{2}an_dT},\\
\tilde{Z} &= \frac{2\sqrt{2}aT}{e^2}\sinh\left[\frac{1}{2}\ln\left(\frac{\nu_e}{n_{e0}}\right)-\frac{W}{2T}\right],\\
\tilde{Z}n_d &= \left(\exp\frac{e\varphi_0}{T}-1\right)n_{e0}.
\end{aligned} \tag{16}$$

Here, we assume that the ion number density is known as it takes place in the experimental data considered below. If the number density of the additional agent is given, the modernized Saha Eq. (4) must be used too.

The combined Eq. (16) is reduced to one equation based on Z_0. The potential barrier of Eq. (9) is defined as a function of Z_0, and accordingly, the relative grain charge is defined in the following form:

$$\tilde{Z}(Z_0) = \frac{2\sqrt{2}aT}{e^2}\sinh\left(\ln\sqrt{\frac{n_{es}}{Z_0 n_d + n_i}}\right).$$

The bulk plasma potential is defined as a function of Z_0 by Eq. (15). Thus, the equation for Z_0 is defined from Eq. (16) in the following form:

$$\tilde{Z}(Z_0) - \left[\exp\left(2\text{arsinh}\frac{e^2 Z_0}{2\sqrt{2}aT}\right)-1\right]\left(\frac{Z_0 n_d + n_i}{n_d}\right) = 0.$$

The results of measurement of the thermal complex plasma containing grains of cerium oxide ($W = 2.75$ eV) with radii of $a = 0.4\ \mu$ and a number density $n_d = 6.8 \times 10^7$ cm^{-3} and sodium ions with a number density $n_i = 4.2 \times 10^9$ cm^{-3} in Ref. [25] are presented. The Kelvin temperature of the system is 1700 K, the measured electron number density is $n_e = 7.2 \times 10^{10}$ cm^{-3}, and $Z \sim 1000$. The calculation using Eq. (16) produces the following results: $n_e = 7.27 \times 10^{10}$ cm^{-3} and $Z = 1007$.

In the same reference, the following data are presented. The thermal complex plasma contains grains of aluminum oxide ($W = 4.7$ eV) with radii of $a = 0.8\ \mu$ and a number density $n_d = 1 \times 10^6$ cm^{-3} and sodium ions with a number density $n_i = 8.6 \times 10^{10}$ cm^{-3}, and the Kelvin temperature is 2035 K. The measured electron number density is 1.3×10^{11} cm^{-3} in this case; the calculated electron number density is 0.9×10^{11} cm^{-3}.

The results of measurement of the thermal complex plasma containing grains of cerium oxide with radii of $a = 0.4\ \mu$ and a number density $n_d = 5 \times 10^7$ cm^{-3} and sodium ions with a number density $n_i = 4 \times 10^{10}$ cm^{-3} at Kelvin temperature 1700 K in Ref. [26] are presented. The measured electron number density is 7×10^{10} cm^{-3}, and the charge number is $\sim$500. The calculation produces the following results: $n_e = 6.2 \times 10^{10}$ cm^{-3}, $Z = 433$, and $n_{e0} = 4.08 \times 10^{10}$ cm^{-3}. It should be noted that $n_{e0} \sim n_i$ in this case, i.e., the plasma is neutral outside the space charge layers.

Thus, the proposed theory and the experimental data agree well. The dependence of the electron number density on the ion number density should be considered in the example of the last system (Fig. 1).

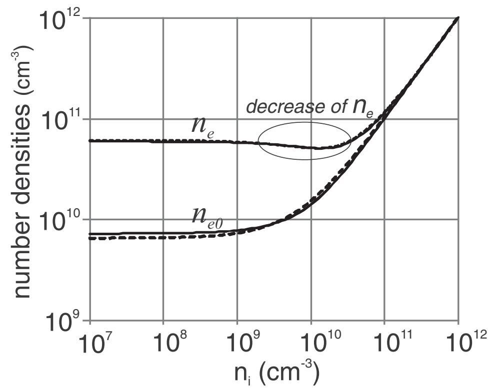

FIG. 1. Dependences of the average electron number density n_e and the unperturbed electron number density n_{e0} on the ion number density. The dotted curves illustrate the use of Eq. (17).

The injection of ions into the plasma does not influence the electron number density in such a system if the ion number density $n_i < 10^8$ cm^{-3}, i.e., the plasma can be considered dust-electron where $n_{e0} \cong Z_0 n_d$. On the other hand, the thermionic emission does not influence the collision ionization of the complex plasma if the ion number density $n_i > 10^{11}$ cm^{-3}, and $n_{e0} \cong n_e \cong n_i$ in this case. The transition range in which the thermionic emission and collision ionization are the competitive processes takes place between the values of ion number density 10^8 cm^{-3} $< n_i <$ 10^{11} cm^{-3}.

The bulk plasma potential is determined as a potential barrier near the surface of a neutral dust grain. Meanwhile, the bulk plasma potential characterizes the electrical energy contained in the plasma gas phase. In this case, it is background energy that consists of the electron energy, the ion energy, and the energy of the neutralized part of the grain charges. The bulk plasma potential was defined based on the total electric energy of the plasma in Refs. [17,18]. In dust-electron plasma, the visible part of the grain charge $\tilde{Z}$ is screened by the electrons of the space charge layer; the other part of the grain charge Z_0 is screened by the uniformly allocated electrons that define the neutralized background, i.e., a part of the grain electric energy compensates for the total energy of the background electrons. This part of the grain energy is described by the potential of the neutralized background or the bulk plasma potential. When the ions are injected into the plasma, the background energy decreases because a portion of the background electrons is neutralized by the ions, and the neutralized charge Z_0 decreases too.

The Coulomb energy per electron can be defined [30] as e^2/R_e, where $R_e = (3/4\pi n_e)^{1/3}$ is half of the average distance between the electrons. Accordingly, the Coulomb energy per ion is e^2/R_i, where $R_i = (3/4\pi n_i)^{1/3}$, and the Coulomb energy of the neutralized charge per dust grain is $(eZ_0)^2/R_W$. Then, taking into account that n_e/n_d electrons and n_i/n_d ions are required per dust grain, it is possible to define the bulk plasma potential [31]

$$\varphi_0 = \frac{3}{2}\frac{e}{n_d}\left(Z_0^2 n_d^{4/3} - n_e^{4/3} + n_i^{4/3}\right), \tag{17}$$

taking into account that $\sqrt[3]{4\pi/3} \cong 3/2$.

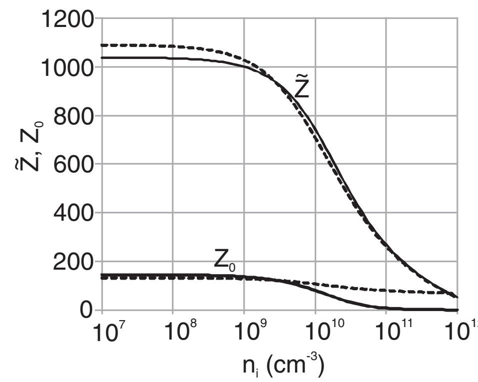

FIG. 2. Dependences of the visible charge and the neutralized charge on the ion number density. The dotted curves illustrate the use of Eq. (17).

In this case, the combined Eq. (16) should be used to calculate the dust grain charges, but the equation for the bulk potential needs to be replaced by Eq. (17). The results of such calculations in Figs. 1–3 are represented by dotted curves. Only the values of the neutralized charge Z_0 in the range of high ion number density differ much. However, it is not significant as $n_e \sim n_i \gg Z n_d$ in this case.

Thus, both methods produce similar results. It means that both the theory of neutralized charges describing dust-electron plasma and the theory of complex plasma with a high content of ions well coexist in the transition range where $n_i \sim Z n_d$.

It should be noted that in the range of densities equal to $n_{e0} \cong n_i$, there is a decrease of the average electron number density (Fig. 1). The visible charge falloff takes place in this range (Fig. 2). The average electron number density is defined by the number of electrons in the unperturbed plasma area and, additionally, in the space charge layer $n_e = n_{e0} + \tilde{Z} n_d$. When the increase of n_{e0} is less intensive than the decrease of $\tilde{Z}$, the average electron number density decreases. The physics of this process is as follows. The potential barrier on the plasma-grain boundary $e\phi_s$ decreases when the visible charge $\tilde{Z}$ decreases. The thermionic emission flux does not change though. Therefore, the electron backflow from the gas phase on the grain surfaces increases, caused by the increase of the unperturbed electron number density as a result of the collision ionization. At the same time, the bulk plasma

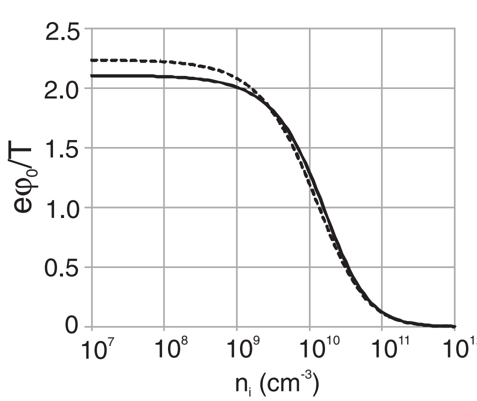

FIG. 3. Dependence of the bulk plasma potential on the ion number density. The dotted curves illustrate the use of Eq. (17).

potential decreases (Fig. 3), and accordingly, the additional ionization, caused by the interphase interaction, decreases also [see Eq. (4)]. As a result, the number of electrons in the space charge layer $n_{er} - n_{e0}$ decreases simultaneously with the increase of the unperturbed number density n_{e0}. Thus, the average electron number density tends to n_{e0}, i.e., it decreases in the transition range.

IV. CONCLUSION

A general theory for the dust-electron and complex plasmas can be constructed if different values of unperturbed number densities for electrons and ions are used. The concept of the bulk plasma potential as a common reference level for the electrostatic potential in the whole system is a basic concept of this theory. The bulk plasma potential can be determined as the potential barrier on the boundary plasma-neutral grain or as the Coulomb energy of the plasma components. Both methods produce similar results.

The injection of the additional alkali metal agents into thermal dust plasma (the flame or MHD generator channel) does not always result in an increase of the electron number density. From the spent analysis, it follows that there can be a range of ion number densities in which the increase of the additional agent number density causes the decrease of the electron number density.

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