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Calculation of the composition of the equilibrium dusty plasma

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Abstract. We consider the equilibrium dusty plasma consisting of neutral atoms of the gas, the gas ions, free electrons and charged dust particles. We obtained the generalized Saha-equation for equilibrium dusty plasmas. In the approximation of a rectangular potential well at the surface of dust grains are calculated charge of the dust particles, the concentration of ions and electrons. It is shown that depending on the basic parameters of the plasma charged dust particles can be both positive and negative.

1. Introduction

Dust equilibrium plasma is formed in the process of combustion of various fuels, with functional coatings applied by thermal plasma flow and plasma chemical reactors of nano-and micro-sized particles [1-6]. Particles condensed substances called particulates or dust particles in the plasma at atmospheric pressure are in the statistical balance with their surrounding electrons, ions and neutral atoms. This mixture is generally electrically neutral system.

2. Theoretical background

We assume that the concentration of particulate matter is n_r, the average concentration of electrons in a gas or plasma is n_e, one has a particulate charge in units of electron charge is equal to N, the electron gas and particulates are in a state of statistical equilibrium. Also, we introduce the following notation: z_i and z_a - the partition on the electronic states of the ion and atom respectively, φ_u - single ionization potential of the gas atom, q - the absolute value of the electron charge, n_i - ion concentration, n_a - the concentration of atoms, h - Planck's constant, θ - statistical temperature is equal to kT, k - Boltzmann constant, T - absolute temperature, m_e - mass of the electron.

From the law of mass action:

$$\frac{n_i n_e}{n_a} = \frac{2z_i}{z_a}\left(\frac{2\pi m_e \theta}{h^2}\right)^{\frac{3}{2}} \cdot e^{-\frac{e_1\varphi_u}{\theta}}. \tag{1}$$

and balance of charged particles: $n_r N + n_i = n_e$ obtain

$$\frac{x_i(n_r N + x_i n)}{1 - x_i^2} = \frac{2z_i}{z_a}\left(\frac{2\pi m_e \theta}{h^2}\right)^{\frac{3}{2}} \cdot e^{-\frac{e_1\varphi_u}{\theta}}, \tag{2}$$

where $x_i = \dfrac{n_i}{n_a + n_i}$ - the degree of ionization, $n = n_e + n_i + n_a$ – the total electron density of the plasma ions and atoms.

Thus, (2) is a generalization of the Saha-equation, taking into account the impact of particulates on the degree of ionization.

The condition of statistical equilibrium [7] of the electron gas in a dusty plasma is expressed by the following equation

$$\mu_1 + e\varphi_1 = \mu + e\varphi,$$

where μ_1 - to the Fermi energy of the electronic gas inside in dust particle and μ - the Fermi energy of the electronic gas outside of dust particle, φ_1 and φ - the potentials of the electric field inside and outside the particulates, e - electron charge. We assume that $\varphi = 0$ and inside dust particle $\varphi_1 = const$, $|e| = q$. With this in mind, equation (1) can be written as

$$\mu_1 - \mu = q\varphi_1. \tag{3}$$

from (12) we obtain

The potential energy of an electron inside the dust particle, the charge is equal to Nq, is determined by the known equation

$$W_n = -q\varphi_1 = -\frac{q^2 N}{4\pi\varepsilon\varepsilon_0 R}. \tag{4}$$

where ε - relative dielectric permittivity, ε_0 - electric constant.

The concentration of free electrons in a gas or plasma is usually low, and therefore as μ it necessary to use the Fermi energy of a nondegenerate electronic gas

$$\mu = \theta \ln(a n_e), \; a = \frac{1}{2}\left(\frac{h^2}{2\pi m_e \theta}\right)^{\frac{3}{2}}. \tag{5}$$

Depending on temperature and concentration of electrons in dusty particles are two possibilities. For large n_{e0} and small T the electronic gas in a dusty particle is degenerate, while for small n_{e0} and large T it is nondegenerated. Lets consider second case in more detail. The Fermi energy of the electronic gas in a dusty particle is defined by

$$\mu_1 = \theta \ln(a n_{e1}), \tag{6}$$

where n_{e1} - concentration of the electrons in a dusty particle after emission.
Substituting the expressions (4), (5) and (6) into (3) gives

$$\theta \ln\frac{n_{e1}}{n_e} = bN, \; b = \frac{q^2}{4\pi\varepsilon\varepsilon_0 R}.$$

$$\frac{n_r N + n_i}{n_{e0} - \dfrac{N}{V}} = e^{-\frac{bN}{\theta}} \tag{7}$$

3. Results

Using equations (2) and (7) can perform calculations of electrons and ions in plasma dust depending on the radius of the dust particles, their concentration and the temperature of the plasma. The results are presented in Fig. 1-6. It is assumed here that the total volume fraction of all dust particles is constant and amounts to 4% of the entire plasma, n_{e0} = 10^{19} m^{-3}, the gas pressure is 10^5 Pa, φ_u = 4,3 eV, which corresponds to the argon.

As seen from these figures the electron density of the plasma at a temperature of 1000 K and 1500 K with increasing radius grains decreases. This phenomenon can be explained by the fact that the electron yield is strongly dependent on the radius of the dust particles, smaller particles efficiently emit and absorb electrons. Since the electrons emerging from the plasma with grains increasing *R* becomes smaller, as expected, an increase in ion concentration associated with a reduction of their recombination with electrons (Fig. 2 and 4).

Another character of the observed at 2000 K. This is due to the fact that at the higher temperature, the concentration of their own plasma electrons generated in the process of ionization of the gas is greater than the initial concentration of electrons in the dust particles . Dust particles are smaller with increasing radius capture electrons , so the concentration of ions in the plasma decreases (Fig. 5,6). At smaller values of the radius of dust more electrons from the plasma enters inside of the dust particles , thus the concentration of ions decreases.

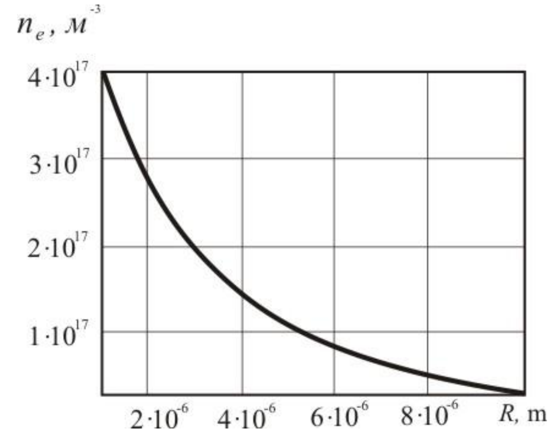

Fig. 1. The dependence of the electron density of the plasma radius of dust particle matter at T = 1000 K.

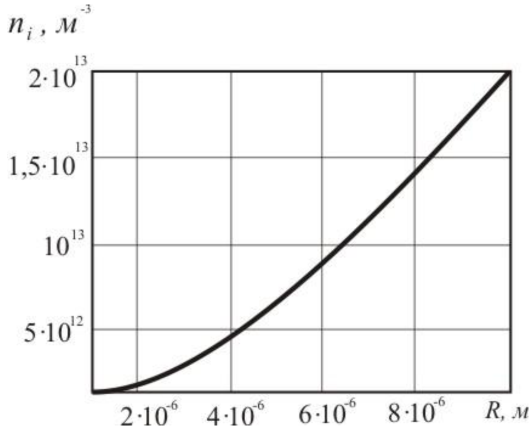

Fig.2. The dependence of the ion density of the plasma radius of dust particle matter at T = 2000 K.

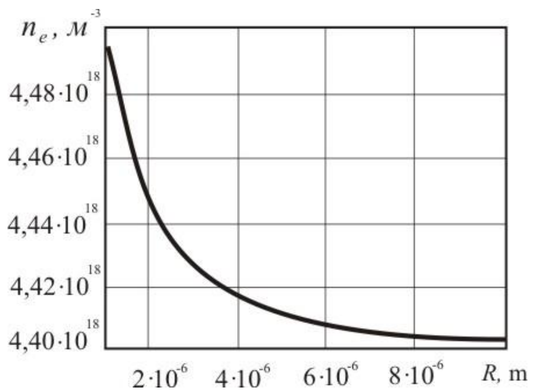

Fig. 3. The dependence of the electron density of the plasma radius of dust particle matter at T = 1500 K.

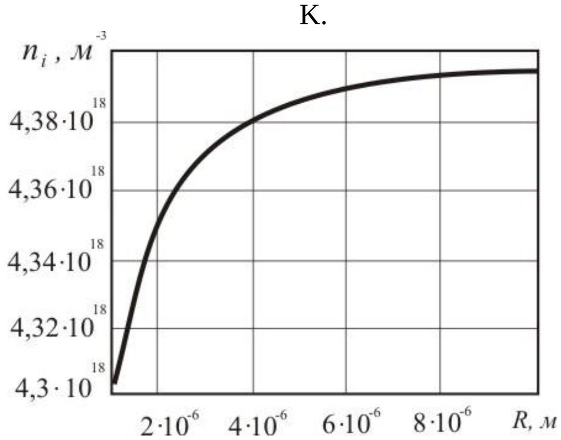

Fig. 4. The dependence of the ion density of the plasma radius of dust particle matter at T = 2000 K.

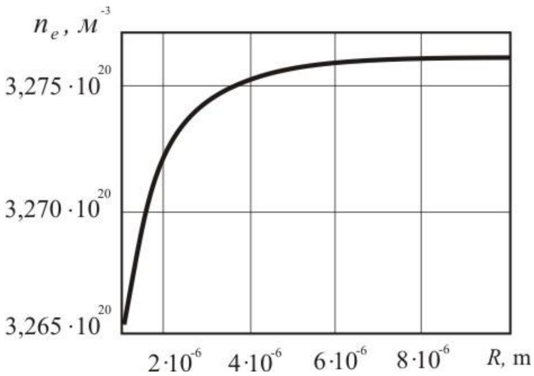

Fig. 5. The dependence of the electron density of the plasma radius of dust particle matter at T = 2000 K.

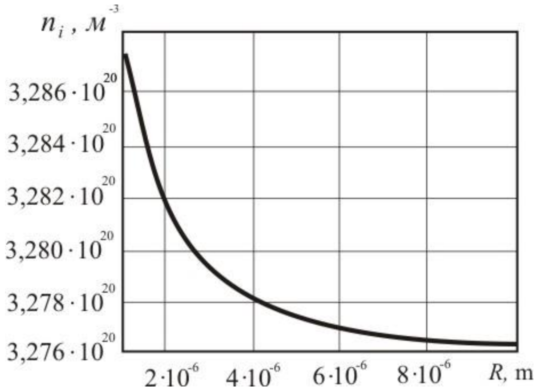

Fig. 6. The dependence of the ion density of the plasma radius of dust particle matter at T = 2000 K.

From Fig. 7 that the charge of the dust particles in absolute terms decreased linearly as a function of their radius.Thus, the specific charge of the particles with a decrease in R will increase, which confirms the above assumption about the growth of the efficiency of the emission or absorption of electrons with a decrease in the size of dust particles.

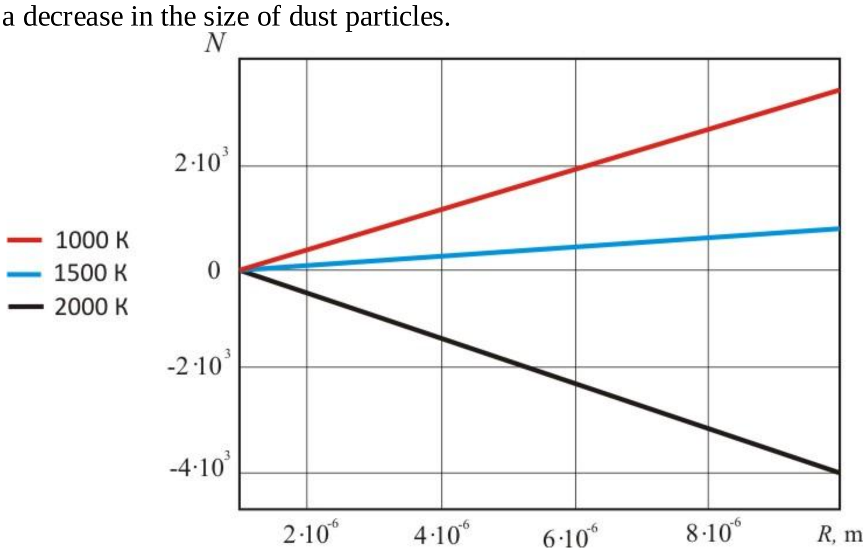

Fig. 7. The dependence of the particle charge on their radius in units of electron charge at different temperatures of the plasma, calculated using the formula (7).

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