Influence of emitting nanoparticles concentration to the density of free electron in the thermal dusty plasma

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Abstract. On the basis of a statistical model describing the emission of electrons from the surface of dust particles in thermal plasma, a nonmonotonic character of the dependence of the concentration of emitted electrons on the concentration of grains has been established. The nature of the influence of the equilibrium temperature of the system and the size of dust particles on this effect is studied.

1. Introduction

Thermal plasma containing particles of condensed matter in the form of nanoparticles is widely distributed in nature, is used in many technological processes and is one of the varieties of complex plasma [1–2]. The presence of particles in thermal plasma leads to their charging. One of the key mechanisms of charge acquisition by nano and microparticles in a high temperature gas is thermionic emission [3–12]. The acquisition of an electric charge by nanoparticles due to the emission of electrons strongly affects the electrophysical properties of the system as a whole and the electrical conductivity in particular.

The most common approach to describing the process of charging dust particles as a result of thermionic emission is the Richardson model [3–5]. This model is based on the Poisson-Boltzmann equation and the Richardson formula for the electron concentration near the surface of a solid [3]. An alternative approach is the description method based on the "jelly" model for condensed particles. For micron particles in plasma, this model was first applied in [6–9]. The advantage of this model is that it can take into account the features of the internal structure of particles. Thus, hollow particles were considered in [9].

2. Theoretical background

The buffer gas surrounding the particles is assumed to be neutral at all considered temperatures of the system. As a dust subsystem, we consider nanoparticles, which are balls of an n-type semiconductor [6, 7], with particle radius $R$. Let us take the value of the charge inside a sphere with radius $R$ as the charge of a dust particle. Then, under the condition that the buffer gas is not ionized for concentration of free electrons in the space between particles $n_{ed}$ we get:

$$n_{ed} = \frac{3\bar{V}_d}{a^3}(n_i - n_{e0})(a \chi - \sigma a).$$

(1)
Here $\bar{V}_d$ is the volume fraction of dust particles in the plasma, $n_i$ is the concentration of ions of the positive background of dust particles, $n_{e0}$ is the concentration of free electrons in the geometric center of the dust particle, the dimensionless parameter $a$ is given as follows

$$ a = \sqrt{\frac{q^2 R^2 n_{e0}}{\varepsilon_0 k T}}, \quad (2) $$

where $R$ – is the dust particle radius, $T$ – is the absolute temperature of the system, $\varepsilon_0$ – electric constant, $k$ – is the Boltzmann constant. The value $n_{e0}$ is calculated using the following relationship:

$$ n_{e0} = n_i \left[ 1 - a(\lambda - 1) \text{ch}(a(\lambda - 1)) - (1 - a^2 \lambda) \text{sh}(a(\lambda - 1)) \right] \frac{a\lambda (a\lambda - \text{sh}(a\lambda))}{a\lambda (a\lambda - \text{sh}(a\lambda))}, \quad (3) $$

where $\lambda = \frac{l}{R}$, $l$ – half the distance between the centers of two neighboring particles.

Thus, using relations (1) - (3), one can calculate the dependence of the concentration of free electrons in thermal dusty plasma on various system parameters, in particular, on the concentration (or volume fraction) of the dust particles themselves. Next, the values of $n_{e0}$ will be calculated for various system parameters. The value of the parameter $\lambda$ is directly related to the volume fraction of dust particles in the entire system $\bar{V}_d = \pi / (6 \lambda^3)$. The value of $n_i$ is taken based on the condition of nondegeneracy of the electronic subsystem. The work takes $n_i = 5 \cdot 10^{21} \text{m}^{-3}$. Here we note that real substances with such a concentration of free charge carriers at the considered temperatures do not exist in nature. However, this model can describe a number of effects at a qualitative level, which can manifest themselves, for example, in thermal plasma with nanoparticles of various substances.

3. Results

Calculations showed that the dependence of the concentration of free electrons in the space between dust particles on the volume fraction of dust particles has a maximum at a certain value (Fig. 1).

![Fig. 1. Dependence of the concentration of free electrons in thermal dusty plasma on the volume fraction of dusty nanoparticles at different particle radii and system temperature.](image)
The concentration of free electrons in the space between particles increases with an increase in the concentration of nanoparticles. However, if the concentration of particles becomes sufficiently high, then a further increase in the concentration of nanoparticles leads to a decrease in the concentration of free electrons in the plasma. This is explained by the fact that when the particles are close to each other, the emission of electrons from one particle is significantly affected by electrons from another particle. There is some dependence on the particle size of the value of the parameter $\tilde{V}_d$, at which the maximum average concentration of free electrons in the space between the particles is realized. For example, for $R = 50$ nm and $T = 2000$ K, the maximum $n_{de}$ is observed at $\tilde{V}_d=0.265$, and at $R = 100$ nm and $T = 2000$ K, the same maximum falls on $\tilde{V}_d=0.28$. Consequently, with a smaller particle size, their concentration at which the maximum electron yield is carried out is less than with larger particles. This effect is explained by a higher concentration gradient of free electrons near the surface of smaller particles.

4. Conclusion

Based on the previously developed analytical model, the concentration of free electrons in thermal dusty plasma is calculated depending on the volume fraction of dusty nanoparticles. It is established that this dependence has a nonmonotonic character.

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