EFFECT OF THE PARAMETERS OF A GAS-DISCHARGE PLASMA ON THE EQUILIBRIUM TEMPERATURE AND FLOATING POTENTIAL OF MACROPARTICLE

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The effect of discharge plasma density and energy of the electron beam on the potential of the solitary macroparticle (MP) has been investigated. It is shown that increasing of the plasma density as well as the electron beam energy lead to heating of the MP and to the appearance of the effect of thermionic emission, which leads to a decrease in the absolute value of its potential. The mutual influence on each other of the MP charging processes and its heating has been studied.

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INTRODUCTION

Previously [1] we investigated the behavior of floating MP potential in the beam-plasma system at different constant temperatures of the MP. We studied also [2] the energy balance of MP, assuming that the potential is determined by the plasma parameters at constant temperature. In this paper, we study the influence of the plasma parameters and the electron beam in plasma on floating potential of the particle and its equilibrium temperature, and the mutual influence on each other charging and heating of the MP.

1. CHARGING OF MP IN PLASMA-BEAM SYSTEM

We first consider the peculiarity of MP charging in an argon plasma with an electron beam taking into account the effects of secondary and thermionic emission from the MP surface.

As is well known the MP in plasma under the effects of various processes charged to a floating potential φ_a .The main charge processes are flows of ions and electrons from plasma, as well as particles fluxes of beam on the MP surface [3]. The fluxes in the approximation of the OML model are determined by:

$$I_e^{pl} = \sqrt{8\pi}a^2 n_0 e_e v_{Te}\exp\left(-e_e\varphi_a/T_e\right), \tag{1}$$

$$I_i^{pl} = \sqrt{8\pi}a^2 n_0 e_i v_{Ti}\left(1-e_i\varphi_a/T_i\right), \tag{2}$$

$$I_e^b = \pi a^2 e_e n_b v_e^b\left(1-e_e\varphi_a/\varepsilon_e^b\right), \tag{3}$$

where n_0 and n_b are the plasma and electron beam densities, respectively, $T_{e(i)}$ are the temperatures of electrons and ions, $v_{Te(i)} = \sqrt{T_{e(i)}/m_{e(i)}}$ are their thermal velocity, $v_e^b = \sqrt{2\varepsilon_e^b/m_e}$ is the electron beam velocity, ε_e^b is the electron beam energy. It is assumed that $T_e = 10\,eV$, $T_i = 1\,eV$. The collisions of the MP with high-energy electron beam leads to the secondary electron emission current from the surface of the MP I_s^{e-e} which given by $I_s^{e-e} = I_e^b\delta_s^{e-e}$ where δ_s^{e-e} is the secondary yield. Thus, an effective current of the beam electrons on the surface of MP is:

$$I_e^{b-eff} = I_e^b - I_s^{e-e} = I_e^b\left(1-\delta_s^{e-e}\right). \tag{4}$$

The effect of thermionic emission on the process of charging is significant at high temperatures of the MP. The density current of the thermal electrons with the Schottky effect is determined by [4]:

$$I_e^{sh} = \frac{T^2}{2\pi^2}\cdot\frac{E^{3/4}T^{-1}}{\sin\left(E^{3/4}T^{-1}\right)}\cdot\exp\left[-\frac{\phi-\sqrt{E}}{T}\right], \tag{5}$$

where E is the electric field on the surface of MP, T is the temperature of the MP, ϕ is the work function.

When the formation of the space charge near the MP surface occurs the current of thermal electrons is limited by the law "3/2" [5]:

$$I_e^{3/2} = \frac{4\sqrt{2}}{9}\sqrt{\frac{|e_e|}{m_e}}\frac{\varphi_a^{3/2}}{\alpha^2\left(\left(a+\lambda_D\right)/a\right)}, \tag{6}$$

where λ_D is the Debye length, α^2 is the transcendental function [5].

Thus, using (5) and (6), the current of thermal electrons from the MP surface is determined by condition:

$$I_e^{th} = \begin{cases} I_e^{3/2},\ I_e^{sh}\left(\varphi_a\right) > I_e^{3/2}\left(\varphi_a\right), \\ I_e^{sh},\ I_e^{sh}\left(\varphi_a\right) < I_e^{3/2}\left(\varphi_a\right). \end{cases} \tag{7}$$

The floating potential of MP is determined by equating of all currents (1), (2), (4), (7) at its surface:

$$I_e^{pl}\left(\varphi_a\right) + I_i^{pl}\left(\varphi_a\right) + I_e^{b-eff}\left(\varphi_a\right) + I_e^{th}\left(\varphi_a\right) = 0. \tag{8}$$

Figure 1 shows the numerical solution of equation (8) for different plasma densities in the absence of beam in the system. It can be seen that a significant influence of temperature on the MP potential due to the effect of thermionic emission occurs at temperatures $T_a \approx (1500\ldots2200)\,K$ depending on the plasma density. As the temperature of MP increases in the range $T_a \approx (2100\ldots2700)\,K$ the module of MP potential decreases to almost zero. For all values of plasma densities and temperatures T_a =2700 K the MP potential is independent on the temperature.

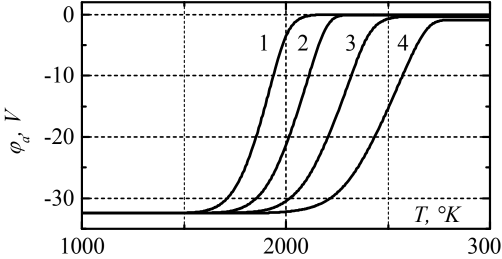

Fig. 1. The dependence of the potential of tungsten MP on its temperature at plasma densities:

$1 - n_0 = 10^9\ cm^{-3}$; $2 - n_0 = 10^{10}\ cm^{-3}$;

$3 - n_0 = 10^{11}\ cm^{-3}$; $4 - n_0 = 10^{12}\ cm^{-3}$

Figure 2 shows the potential of MP dependence on its temperature in the presence of an electron beam with energy $\varepsilon_e^b = 5keV$ for different plasma densities. Decreasing in absolute potential of MP occurs in the temperature range $T_a \approx (1700\ldots2300)\ K$. At temperatures T_a =2300 K the potential of MP is nearly zero, and independent on its temperature.

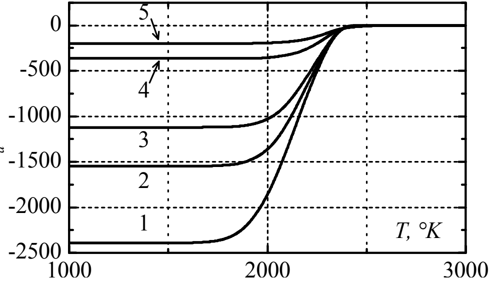

Fig. 2. The dependence of the potential of tungsten MP in a plasma with an electron beam ($n_b = 10^9\ cm^{-3}$, $\varepsilon_e^b = 5\,keV$) *on its temperature at plasma densities:* $1 - n_0 = 10^9\ cm^{-3}$;

$2 - n_0 = 5\cdot10^9\ cm^{-3}$; $3 - n_0 = 10^{10}\ cm^{-3}$;

$4 - n_0 = 5\cdot10^{10}\ cm^{-3}$; $5 - n_0 = 10^{11}\ cm^{-3}$

Thus, the effect of thermionic emission on the charging process of MP is important. The effect of thermionic emission in plasma without the beam MP occurs at temperatures $T_a > 1500°K$ for different plasma densities. In the presence of an electron beam thermionic emission appears at higher temperatures T_a =1700 K.

2. HEATING OF MP IN PLASMA-BEAM SYSTEM

Now we consider the basic mechanisms of energy exchange between the plasma with the electron beam and macroparticle. In the OML approximation the particle energy flux to the MP are determined by

$$P_e^{pl} = 8\sqrt{2\pi}a^2 n_0 v_{Te} \exp\left(-e_e\varphi_a/T_e\right)T_e , \quad (9)$$

$$P_i^{pl} = 4\sqrt{\pi}a^2 n_0 v_{Ti}\left(e_i\varphi_a/T_i\right)^2 T_i , \quad (10)$$

$$P_e^b = \pi a^2 n_b v_e^b\left(1 - e_e\varphi_a/\varepsilon_e^b\right)\varepsilon_e^b . \quad (11)$$

The energy which released due to the recombination of plasma ions at MP surface is:

$$P_i^{rec} = \varepsilon_i^{rec}\cdot I_i^{pl}/e_i , \quad (12)$$

where ε_i^{rec} is the recombination energy of an ion, for once ionized argon ion is.15.8 eV.

The energy flux of thermal radiation from MP surface is defined by the Stefan-Boltzmann low and is given by:

$$P_a^{rad} = 4\pi a^2\theta\sigma T_a^4 , \quad (13)$$

where θ is the emissivity of MP material, σ is the Stefan-Boltzmann constant, T_a is the MP temperature.

The MP temperature will change as long as the flows of heating and cooling are not equal, and the resulting equilibrium temperature T_a^{eq} is set. The value T_a^{eq} can be found from the condition:

$$P_a^{\Sigma}\left(T_a^{eq}\right) = 0 , \quad (14)$$

where $P_a^{\Sigma}(T) = P_e^{pl} + P_i^{pl} + P_e^b + P_i^{rec} - P_a^{rad}$ is the total energy flux, which includes the main energy processes (9)-(13). The MP temperature, as mentioned, affects on the potential of MP due to the effect of thermionic emission, and its potential, in turn, affects on to the flow of energy from the plasma to the MP surface. Therefore, one should take into account the mutual influence on each other so that the MP potential and its temperature, which requires the solving of the current balance equation (8) and the energy balance equation (14) as a set of equations:

$$\begin{cases} I_i^{pl} + I_e^{pl} + I_e^{b-eff} + I_e^{th} = 0, \\ P_a^{\Sigma}\left(T_a^{eq}\right) = 0. \end{cases} \quad (15)$$

Fig. 3 shows the numerical solution of Eqs. (15) for the tungsten MP in the absence of the electron beam. One can see that with increasing the plasma density the MP temperature increases (curve 1) whereas its potential (curve 2) at the density $n_0 \approx 10^{12}\ cm^{-3}$remains constant. In the range of densities, $n_0 \approx (2\ldots8)\cdot10^{12}\ cm^{-3}$the potential drop occurs as a result of thermionic emission, which corresponds to the range of temperatures $T_a \approx (2100\ldots3000)\ K$.

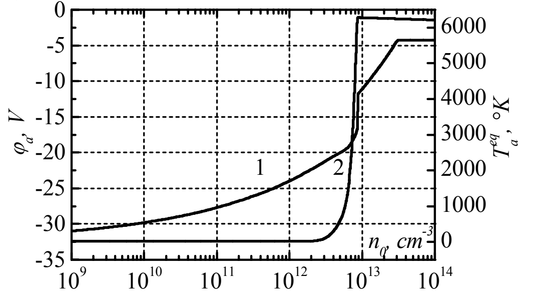

Fig. 3. Dependence of the equilibrium temperature (1) and the corresponding floating potential (2)of the tungsten MP on the plasma density

This is accompanied by an increasing in the equilibrium temperature as a result of increasing of the power transferred by the plasma electrons. A further increase in the plasma density leads to a slight increase in MP potential, due to the increased flow of electrons from the plasma.

Figure 4 shows the dependence of the equilibrium MP temperature (a) and the corresponding potential (b) versus the electron beam energy for different plasma densities. On can see from Fig. 4,a that collisions of electron beam with MP leads to its heating. The equilibrium temperature for the beam energy ε_e^b d $0.2keV$ is different for different plasma densities, due to predominance of the energy flow of plasma particles.

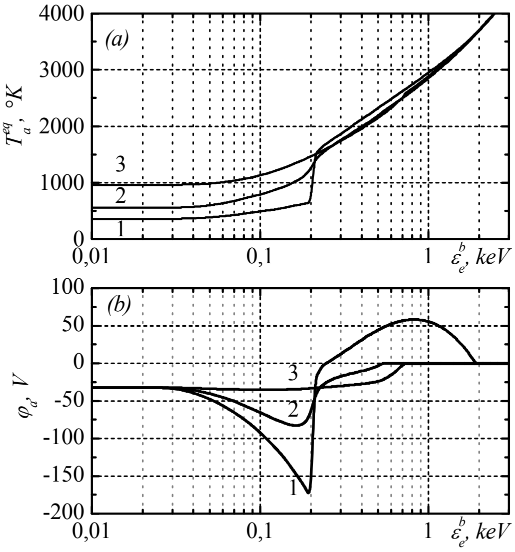

Fig.4. Dependence of the equilibrium temperature (a) and the corresponding floating potential (b)of the tungsten MP on the energy of the electron beam at plasma densities: 1 – $n_0 = 10^9 cm^{-3}$; *2 –* $n_0 = 10^{10} cm^{-3}$; *3 –* $n_0 = 10^{11} cm^{-3}$

Increase in the beam energy to the values $\varepsilon_e^b \approx 0.2 keV$ leads to a sharp increase in the equilibrium temperature (see curves 1 and 2 in Fig. 4,a) coinciding with a decreasing of absolute potential (see curves 1 and 2 in Fig. 4,b) due to effect of secondary electron emission. For curve 3 the sharp changes do not occur because dense plasma compensates charging MP by electron beam. For the beam energy $\varepsilon_e^b \approx (0.5 \div 0.7) keV$ potential decreases to zero (lines 2 and 3) due to thermionic emission. In a rare plasma for the energy interval $\varepsilon_e^b \approx (0.25...2) keV$ (curve 1) the potential takes the positive values as in the interval $\delta_s^{e-e}\left(\varepsilon_e^b\right) > 1$. For the beam energy ε_e^b t $2keV$ MP potential is reduced to zero for all curves and the differences in the values of the equilibrium temperatures are reduced.

CONCLUSIONS

The effect of the thermionic emission from MP in plasma appear at the temperature of MP T_a^{eq} t $2000°K$, which corresponds to the plasma density. $n_0=2 \cdot 10^{12}$ .For plasma density $n_0=8 \cdot 10^{12}$ the MP absolute potential is reduced to zero. In the presence of electron beam this effect occurs for beam energies $\varepsilon_e^b \approx (0.5...0.7) keV$ at higher temperatures $T_a^{eq}(2400...2500)°K$.

REFERENCES

1. A.A. Bizyukov, K.N. Sereda, A.D. Chibisov. Charging processes of metal macroparticles in the low-temperature plasma at presence of high-energy electron beam/ / *Problems of Atomic Science and Technology. Series "Plasma physics" (17).* 2011, №1, p. 107-109.

2. A.A. Bizyukov, E.V. Romashchenko, et. al. Heating and evaporation of metal macroparticles in beam-plasma system // *Problems of Atomic Science and Technology. Series "Plasma Electronics and New Methods of Acceleration" (7).* 2010, № 3, p. 189-192.

3. V.E. Fortov, A.G. Khrapak, et. al. Dusty plasmas // *Uspekhi Fizicheskikh Nauk.* 2004, v.174, p. 495-544.

4. E.L. Murphy, R.H. Good. Thermionic emission, field emission and the transition region // *Phys. Rev.* 1956, v. 102, p. 1464-1473.

5. I. Langmuir, K.B. Blodgett. Current limited by space charge between concentric spheres // *Phys. Rev.* 1924, v. 24, №1, p. 49-59.

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ВЛИЯНИЕ ПАРАМЕТРОВ ГАЗОРАЗРЯДНОЙ ПЛАЗМЫ НА РАВНОВЕСНУЮ ТЕМПЕРАТУРУ И ПЛАВАЮЩИЙ ПОТЕНЦИАЛ МАКРОЧАСТИЦЫ

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Исследовано влияние плотности газоразрядной плазмы и энергии электронного пучка на потенциал уединенной макрочастцы (МЧ). Показано, что увеличение плотности плазмы, а также энергии электронного пучка приводят к интенсивному разогреву МЧ и возникновению эффекта термоэлектронной эмиссии, который приводит к снижению по абсолютной величине ее потенциала. Изучено взаимное влияние процессов зарядки МЧ и ее разогрева.

ВПЛИВ ПАРАМЕТРІВ ГАЗОРОЗРЯДНОЇ ПЛАЗМИ НА РІВНОВАЖНУ ТЕМПЕРАТУРУ І ПЛАВАЮЧИЙ ПОТЕНЦІАЛ МАКРОЧАСТКИ

О.А. Бізюков, А.Д. Чібісов, О.В. Ромащенко

Досліджено вплив густини газорозрядної плазми і енергії електронного пучка на потенціал відокремленої макрочастки (МЧ). Показано, що збільшення густини плазми, а також енергії електронного пучка призводять до інтенсивного розігріву МЧ і виникнення ефекту термоелектронної емісії, що призводить до зниження за абсолютною величиною її потенціалу. Вивчено взаємний вплив процесів зарядки МЧ і її розігріву.