CHARGING PROCESSES OF METAL MACROPARTICLES IN THE LOW-TEMPERATURE PLASMA AT PRESENCE OF HIGH-ENERGY ELECTRON BEAM

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The dependences of potential of macroparticle from the parameters and characteristics of plasma-beam system are studied. The modeling of charging processes of the macroparticles in approach of ions and electrons orbit motion limited theory made. The effect of electron emission from macroparticle has been investigated taking into account the space charge on potential of macroparticle.

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1. INTRODUCTION

"Dusty plasma" is one of most intensively developing branches in plasma physics. In particular, it is widely used in technology of hardening of tools and in mechanical engineering the coating got by condensation of substance from a plasma stream, generated by low pressure arc, in a conditions of ionic bombardment of a condensate. The presence on a cathode surface of quickly moving cathodes spots is the typical feature of the arc discharge in vacuum. Erosion of cathode surface by vacuum arc caused by a cathode spot generates particle, which neutral atoms, ions and macroparticles, for example the drops and hard fragments of a cathode material. The contribution of a drop phase into the total mass flux of a cathode material may be as high as 90 %. Typical size of the macroparticles is in the range of 1…100 microns; however larger and smaller particles may be observed. The velocity of drop flux is in the range of $10^2…10^4$ cm/s [1]. The concentration of the macroparticles depends on a material of the cathode, as well as the arc discharge current and thermal mode and geometry of the cathode [2]. The presence of the macroparticle phase in plasma of the vacuum arc discharge limits applicability of this method in many areas including optics, micro-electronics, the precise mechanics, medicine. Presence of macroparticles in the coating has a harmful impact on its most important characteristics such as adhesion to the surface, porosity, surface roughness; they become unsatisfactory for the application in wide spectrum of technological problems. Most popular solution, which helps to reduce drops concentration in plasma flow of the vacuum arc, is based on magnetic separation of trajectories of drops and ions. A considerable quantity of various filters and the separators effectively deleting a drop phase from a plasma flow have been developed [3]. However, the removal of the drops decreases the deposition rate and with separation applied the efficiency of this method is comparable with others such as magnetron and ion beam sputtering methods.

2. STEADY-STATE POTENTIAL OF THE MACROPARTICLE IN PLASMA-BEAM SYSTEM

The macroparticles in plasma are charged to some potential φ_s, which is determined by plasma parameters as well as the size and properties of macroparticles. It can be calculated similarly to Ref. [4] by using the orbital model.

Injection of the high-energy electron beam in the macroparticle-plasma system increases the electron current on the macroparticle surface and leads to substantial growth of its potential as well as temperature of the macroparticles. The increase of the macroparticle temperature can lead to thermionic emission from its surface. In addition, there is an essential contribution of the secondary electron emission induced by high-energy beam electrons.

The equation describing the balance of charge currents on a macroparticle surface should take into account the secondary electron and thermionic emissions in plasma-beam system :

$$I_i + I_e + I_b\left(1-\delta_e\left(\varepsilon_b - e\varphi_s\right)\right) + I_{em} = 0 , \qquad (1)$$

where δ_e is the coefficient of the secondary electron emission for the macroparticle material, $I_b = \pi a^2 n_b v_{eb}\left(1-e\varphi_s/\varepsilon_b\right)$ is the electron beam current on a surface of a macroparticle, n_b is the density of the electron beam, $v_{eb} = \sqrt{k\varepsilon_b/m_e}$ is the electron beam velocity, e is the elementary electronic charge, ε_b is the electron beam energy, a is the radius of macroparticle.

The expressions for ion and electron currents is similar to that, which may be found in the theory of probes:

$$I_i = \sqrt{8\pi}a^2 n_0 v_{Ti}\left(1-\frac{e\varphi_s}{T_i}\right),$$

$$I_e = \sqrt{8\pi}a^2 n_0 v_{Te}\exp\left(\frac{e\varphi_s}{T_e}\right),$$

where n_0 is the plasma density, T_e and T_i are the electron and ion temperatures respectively, v_{Te} and v_{Ti} are the thermal velocities of electrons and ions. The contribution of the secondary electron emission caused by plasma electrons in cold plasma is negligible, because the energy of plasma electrons bombarding the surface of macroparticle, is close to zero. Therefore, the secondary electron emission from the macroparticle surface is the only term, which is considered in the equation of balance of charge currents.

The electron beam current on a surface of macroparticle is determined by the following expression:

$$I_b = \pi a^2 n_b v_{eb}\left(1-\frac{e\varphi_s}{\varepsilon_b}\right),$$

The secondary electron current can be calculated using the formula:

$$I_{es} = I_b \delta_e\left(\varepsilon_b - e\varphi_s\right),$$

In the present work we assume that the particles are heated to high temperature so that the effect of thermionic emission has an essential influence on the potential of a macroparticle. The maximum emission from the surface of the macroparticle due to the thermionic emission can be calculated using the formula taking into account the effect of Shottki j_{th} [5]:

$$j_{th} = \frac{2a^2(\mathrm{T})^2}{\pi}\frac{F^{3/4}\mathrm{T}^{-1}}{\sin(F^{3/4}\mathrm{T}^{-1})}e^{\left[-(W-\sqrt{E})/\mathrm{T}\right]}.$$

Here the current density is in units $m_e^3 e^9 \hbar^{-7} = 2{,}37\cdot 10^{14}\ A/cm^2$, electric field E is in units $m^2 e^5 \hbar^{-4} = 5{,}15\cdot 10^9\ V/cm$, the macroparticle temperature T and work function W in units $me^4\hbar^{-2} = 27{,}1\ eV$.

At high temperatures of macroparticles character the high emission ability of metals that can lead to restriction of an emission current by own bulk charge. In this case the current density of thermionic electrons is described by the law «3/2» which in spherical coordinate system can be expressed as:

$$j_{3/2} = \frac{4\sqrt{2}}{9}\sqrt{\frac{e}{m}}\cdot\frac{\varphi_s^{3/2}}{\alpha^2},$$

where α^2 is the tabulated function [6].

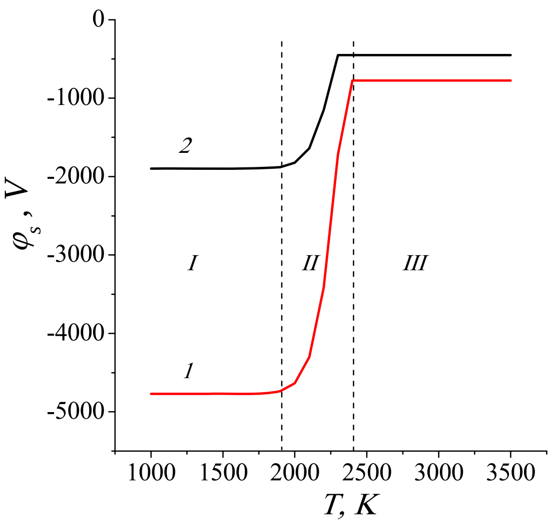

Fig. 1. The dependence of tungsten macroparticle φ_s with the size $a = 10^{-4}\,cm$ on temperature. Plasma density is $n_0 = 10^9\,cm^{-3}$, electron beam density is $n_b = 10^9\,cm^{-3}$ and electron beam energy is ε_b =10 keV (1); ε_b =5 keV (2),

Taking into account the possible limitation of the current of electrons emitted from the macroparticle by spatial charge I_{em} in the formula (1), it is determined by expression:

$$I_{em} = \begin{cases} I_{th}, & j_{th} < j_{3/2} \\ I_{3/2}, & j_{th} > j_{3/2}. \end{cases}$$

Fig. 1 shows the numerical solution for the equation (1) for two energies of an electron beam. Temperature range I in Fig. 1 corresponds to insignificant thermionic emission. Thus, the macroparticle potential is defined by interaction with beam electrons and plasma ions. The range II corresponds to increasing contribution of the thermionic current in increase of macroparticle charge that leads to decrease of its potential. Range III corresponds to formation of a layer of electron spatial charge around the macroparticle and, consequently, limit of a current of thermionic emission to value defined by the Child-Langmuir law.

Fig. 2 shows the dependence of potential of a macroparticle on energy of the electronic beam, obtained by the numerical solution of equation (1) for three temperatures of a macroparticle. The common trend of all three solutions is growth of macroparticle potential with increase of the electron beam energy. However, growth rate macroparticle temperature decreases with increase of the temperature. This effect is related to increase of the thermal emission of a macroparticle. At small temperatures (curve 1) and high macroparticle potential, there is no limitation of the emission current by the electron spatial charge in all range of the beam energy.

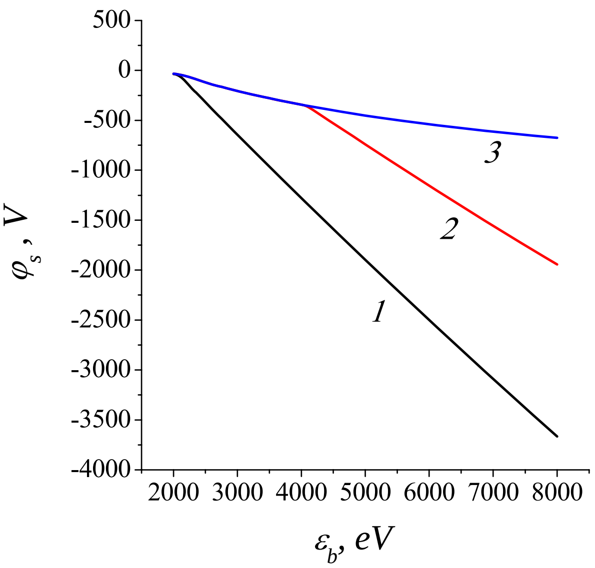

Fig. 2. The dependence of tungsten macroparticle φ_s with the size $a = 10^{-4}\,cm$ on ion beam energy. Plasma density is $n_0 = 10^9\,cm^{-3}$, electron beam density is $n_b = 10^9\,cm^{-3}$. The macroparticle temperature is: $T = 1000\,K$ (1); $T = 2250\,K$ (2); $T = 3000\,K$ (3).

When macroparticle temperature increases (curves 2 and 3) the dependences of potential from electron beam energy becomes similar in energy range 2000…4200 eV and at various temperatures. At these parameters electron emission from a macroparticle does not depend on its temperature and it is defined by the Child-Langmuir law.

When the macroparticle potential is increased, the thermal emission is not limitation by the spatial charge any more (a curve 2 at $\varepsilon_b > 4200\,eV$). Thus, the dependence of potential on the beam energy becomes similar to curve 1. For the highest temperatures of macroparticles (curve 3) the thermal emission current is limited by the spatial charge in all range of the investigated beam energy.

3. CONCLUSIONS

The macroparticle potential in plasma-beam system is studied in dependence of its characteristics. When the macroparticle temperature increases, the thermal emission of the ions has the significant effect on potential of a macroparticle. Steady-state potential of a macroparticle is strongly influenced by thermal emission, which is limited by spatial charge according to Child-Langmuir law.

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ПРОЦЕССЫ ЗАРЯДКИ МЕТАЛЛИЧЕСКИХ МАКРОЧАСТИЦ НИЗКОТЕМПЕРАТУРНОЙ ПЛАЗМЫ В ПРИСУТСТВИИ ВЫСОКОЭНЕРГЕТИЧНОГО ЭЛЕКТРОННОГО ПУЧКА

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Изучена зависимость потенциала макрочастицы в пучково-плазменной системе от ее параметров и характеристик макрочастицы. Моделирование процесса зарядки проводилось в приближении орбитальной модели движения ионов и электронов плазмы, а также электронов пучка. Исследовано влияние электронной эмиссии с макрочастиц, разогретых до высоких температур, на величину потенциала с учетом ограничения эмиссионного электронного тока собственным объемным зарядом.

ПРОЦЕСИ ЗАРЯДКИ МЕТАЛЕВИХ МАКРОЧАСТИНОК В НИЗЬКОТЕМПЕРАТУРНІЙ ПЛАЗМІ В ПРИСУТНОСТІ ВИСОКОЕНЕРГЕТИЧНОГО ЕЛЕКТРОННОГО ПУЧКА

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Вивчено залежність потенціалу макрочастинки в пучково-плазмовій системі від її параметрів та характеристик макрочастинки. Моделювання процесу зарядки проводилося в наближенні орбітальної моделі руху іонів й електронів плазми, а також електронів пучка. Досліджено вплив електронної емісії з мікрочасток, розігрітих до високих температур, на величину потенціалу з урахуванням обмеження емісійного електронного струму власним об'ємним зарядом.