CHARGING PROCESSES AND PHASE STATES OF MACROPARTICLES IN LOW-PRESSURE ARC DISCHARGE

A.A. Bizyukov[1], A.D. Chibisov[1], K.N. Sereda[1], E.V. Romashchenko[2], V. Dimitrova[3]
[1] V.N. Karazin Kharkov National University, Kharkov, Ukraine;
[2] V. Dahl East Ukrainian National University, Lugansk, Ukraine;
[3] Sofia University St. Kliment Ohridski, Bulgaria
E-mail: bizyukov@mail.ru

The effects of plasma density and ionic charge on the floating potential of the solitary macroparticle (MP) in a low-pressure arc discharge have been investigated. The energy balance has been studied taking into account mutual influence on each other of the charging processes and heating of the MP. The possibility of the evaporation of the MP is shown.

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INTRODUCTION

The usage of arc vacuum discharge in technological processes requires the control of melted drops in the plasma flow. There are conditions when the drops of the cathode substance can be evaporated during its passing through the plasma from cathode of arc evaporator to substrate [1, 2]. The analysis of the charging processes and energy exchange at the MP surface denotes the possibility of the evaporation of the MP. The influence of the parameters of low-temperature collisionless plasma with singly charged ions on the floating potential and equilibrium temperature of the MP has been investigated in [2]. The authors also considered the mutual influence on each other of the charging processes and heating of the MP. In this paper, we consider a more general plasma situation in which the multi-charged ions have some streaming speed. This case corresponds to plasma of the low-pressure arc discharge. The interaction of MP with such plasma has been studied. The effects of plasma density and ionic charge on the MP floating potential have been investigated. The possibility of the evaporation of the MP in a low-pressure arc discharge has been studied.

1. FLOATING POTENTIAL OF MP

Let us consider a charging process of the MP in metallic plasma which produced by a low-pressure arc discharge. There are ions with different charges in such plasmas. Moreover, the plasma is characterized by high velocity of plasma flow [3]. The MP is immersed in plasma charges to the some floating potential φ_{mp} due to flows the plasma particles and various kinds of emission on its surface [2, 4]. The MP is mainly charged by the collection of electrons and ions from the plasma. Expressions for the charging currents flowing onto MP surface in a collisionless plasma can be derived from the OML (orbit motion limited) approximation [5]. The electron and ion currents to a MP with a negative potential are

$$I_e = \sqrt{8\pi} a^2 n_0 \left|e\right| v_{Te} \exp\left(-e\varphi_{mp}/T_e\right), \qquad (1)$$

$$I_i = \sqrt{\pi} n_0 Z \left|e\right| \sqrt{\frac{T_i}{2\pi m_i}} a^2 \left[\left(1-e^{-\chi_i}\right)\frac{\left(a+\lambda_D\right)^2}{a^2} + e^{-\chi_i}\right], \qquad (2)$$

where $\chi_i = \dfrac{Ze\varphi_{mp}}{T_i}\left[\dfrac{\left(a+\lambda_D\right)^2}{a^2} - 1\right]^{-1}$.

Here, n_0 is the plasma density, Z is the ionic charge, $T_{e(i)}$ is the electron (ion) temperature, $v_{Te(i)} = \sqrt{T_{e(i)}/m_{e(i)}}$ is the electron (ion) thermal velocity.

The interaction of MP with plasma ions incident onto the MP surface causes emissions of electrons from the MP surface. The emitted electrons are known as secondary. The value of the secondary ion-electron yield depends on ionic charge. The electron current emitted from MP surface is written as follows

$$I_s^{i-e} = I_i^b \delta_s^{i-e}, \qquad (3)$$

where δ_s^{i-e} is the secondary ion-electron yield [6]. The effective current is defined as

$$I_i^{eff} = I_i + I_s^{i-e} = I_i\left(1+\delta_s^{i-e}\right). \qquad (4)$$

There is another significant charging process at high temperature of MP – it is thermionic emission [2]. Taking into account the work function reduction by the effect of the external electric field E (Schottky effect) the thermionic current is calculated through [7]:

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

where E is the electric field on MP surface, T_{mp} is the MP temperature, ϕ is the work function.

In a case of formation of the space charge around MP surface, the thermionic current is limited by the Child-Langmuir Law [8] that in spherical geometry is given by

$$I_e^{3/2} = \frac{4\sqrt{2}}{9}\sqrt{\frac{|e|}{m_e}} \frac{\varphi_{mp}^{3/2}}{\alpha^2\left(\left(a+\lambda_D\right)/a\right)}, \qquad (6)$$

where λ_D is the Debye length, α^2 is the transcendental function [8].

Thus, using (5) and (6), the thermionic emission current from the MP surface is determined by conditions:

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

The MP floating potential is determined by the balance of charging currents (1), (4), (7) to its surface:

$$I_e\left(\varphi_{mp}\right)+I_i^{eff}\left(\varphi_{mp}\right)+I_e^{th}\left(\varphi_{mp}\right)=0\,. \qquad (8)$$

For ions with charges Z=1, 2, 3, we numerically solve Eq. (8) for some typical ion energies that are representative of low-temperature arc discharge.

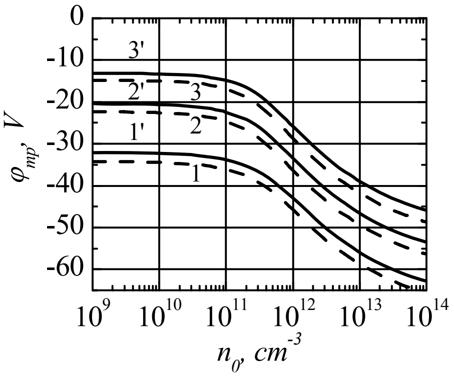

Fig. 1. The dependence of the tungsten MP potential on plasma density: 1,1′ – $Z=1$; 2,2’ – $Z=2$; 3,3’ – $Z=3$; dashed lines 1,2,3 – 20 eV, solid lines –1’,2’,3’ – 35 eV

Fig. 1 shows that the potential is considerably governed by the ionic charge. The ions carry charges to MP and cause the secondary ion-electron emission simultaneously. The increase in the ionic charge leads to increase of secondary ion-electron yield. It decreases the magnitude of MP surface potential. The ionic energy has no significant effect on the magnitude of potential in the energy region compared to effect of the ionic charge.

2. HEATING OF MP

Now consider the contribution of basic processes of energy exchange between the plasma and MP that lead to heating of MP. In the OML theory the plasma particle energy fluxes to MP are determined by:

$$P_e^{pl}=8\sqrt{2\pi}a^2n_0v_{Te}\exp\left(-e\varphi_{mp}/T_e\right)T_e\,, \qquad (9)$$

$$P_i^{pl}=I_i^{pl}(T_i+|e|Z\varphi_{mp}+\varepsilon_{rec})/\left(|e|Z\right), \qquad (10)$$

where ε_i^{rec} is the recombination energy of an ion. The values of recombination energy of tungsten ions are given in Table.

	Z=1	Z=2	Z=3
ε_i^{rec}, eV	7,131	15,72	29,6

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

$$P_a^{rad}=4\pi a^2\theta\sigma T_{mp}^4\,, \qquad (11)$$

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

The MP temperature changes in time and describes by equation:

$$cm_{mp}\,dT/dt=P_{mp}^{\Sigma}\left(T\right),$$

where c is the specific heat of MP substance, m_{mp} is MP mass, $P_{mp}^{\Sigma}\left(T\right)=P_e^{pl}+P_i^{pl}-P_a^{rad}$ is total energy flow, that includes of basic processes of the energy exchange on MP surface (9) - (11). The initially MP temperature is equal T_0, then due to energy flows on its surface the MP temperature changes until the energy equilibrium is reached. This occurs when

$$P_{mp}^{\Sigma}\left(T_{mp}^{eq}\right)=0\,. \qquad (12)$$

Hence, we obtain the equilibrium temperature T_{mp}^{eq}.

The MP temperature, 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. To consider the mutual influence of the MP temperature and potential, we numerically analyze the system of balance equations (8) and (12). The results of analysis for tungsten MP are presented in Fig. 2.

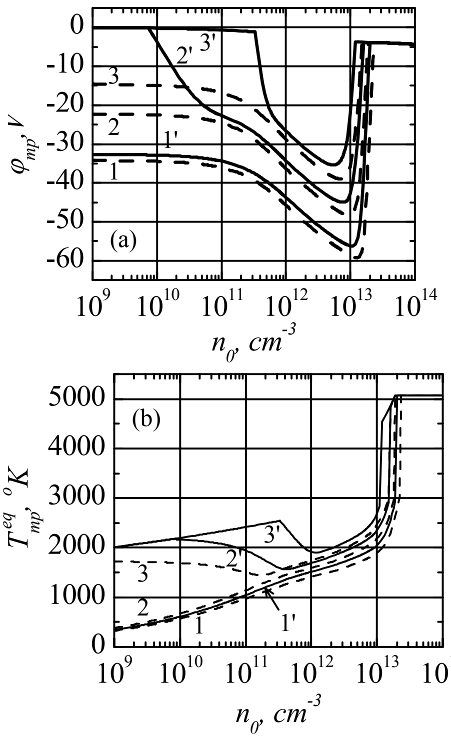

Fig. 2. The dependence of potential (a) and corresponding temperature (b) of tungsten MP on plasma density: 1,1′ – $Z=1$; 2,2’ – $Z=2$; 3,3’ – $Z=3$; dashed lines 1,2,3…20 eV, solid lines 1,2,3…35 eV

In case of ionic energy $T_i<20$ eV, the results for MP in plasma with density $n_0<10^{13}$ cm^{-3} do not differ from results for cold MP. For plasma density $n_0>10^{13}$ cm^{-3}, efficient heating of MP (see Fig. 2,b) leads to an increase of the thermionic current, and as a result the magnitude of the MP potential decreases. This case corresponds to plasma of the pulse arc discharge.

Fig. 2 illustrates that the results for MP in plasma with singly charged ions with energy $T_i\approx 30$ eV and the results for cold MP are similar. In the case of ions with charge Z=2 and Z=3 in plasma with density $n_0<10^{10}$ cm^{-3} and $n_0<3\cdot10^{11}$ cm^{-3}, respectively, the MP potential decreases to null. This effect associates with MP discharging by thermionic emission, which causes due to efficient heating of MP. The MP heating is connected to the energy release caused by recombination of ions on the MP surface. The energy released on the MP surface in a plasma with doubly and triply charged ions is larger than it of single charged ions in 2,2 and 4,15 times, respectively. For plasma with low density, the electron current does not compensate for thermionic emission. If we increase the plasma density, the electron current increases and compensates for discharging by thermionic emission, and as a result the potential increases. A further increase in the plasma density leads to increase of the energy flux from plasma and MP temperature. The effect considered above leads to an increase of thermionic emission and as result decrease of MP absolute potential, whereas the equilibrium temperature considerably increases.

The growth of MP temperature stops when it reaches the boil temperature of MP substance. The MP radius changes in time during it boiling and describes by equation:

$$\frac{dr}{dt} = -\frac{H\,P^{\Sigma}_{mp}\left(T^{b}_{mp}\right)}{4\pi r^2 \rho}, \tag{13}$$

where ρ is the substance density, H is vaporization heat.

The total evaporation time of the MP with radius a is given by:

$$t_b = 4\pi\rho \int_0^a \frac{r^2 dr}{H\,P^{\Sigma}_{mp}\left(T^{b}_{mp}\right)}. \tag{14}$$

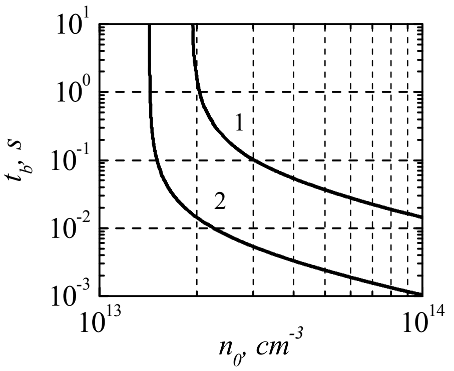

Fig. 3. The dependence of the tungsten MP evaporation time on plasma density: 1 – 1 μm; 2 – 10 μm averaged over an ionic energy

Fig. 3. shows dependence of tungsten MP's evaporation time versus plasma density. For tungsten MPs with radii 1 μm and 10 μm, immersed in plasma with density $n_0 = 10^{14}$ cm^{-3}, the evaporation time are 10^{-3} and $2\cdot 10^{-2}$ s, respectively. For plasma densities $n_0 < 10^{14}$ cm^{-3}, the evaporation time rapidly increases.

CONCLUSIONS

To summarize, we have examined the effects of ionic charge and energy as well as plasma density on the MP floating potential.

It is shown that the potential is considerably governed by the ionic charge. The ionic energy has no significant effect on the magnitude of MP potential in the typical energy region of the arc discharges.

For doubly and triply charged ions due to recombination of ions on MP surface, efficient heating takes place. Thus, MP is discharged by thermionic emission.

The MP evaporation is possible in dense plasma.

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ПРОЦЕССЫ ЗАРЯДКИ И ФАЗОВЫЕ СОСТОЯНИЯ МАКРОЧАСТИЦ В ДУГОВОМ РАЗРЯДЕ НИЗКОГО ДАВЛЕНИЯ

А.А. Бизюков, А.Д. Чибисов, К.Н. Середа, Е.В. Ромащенко, В. Димитрова

В дуговом разряде низкого давления исследуется влияние плотности плазмы и заряда ионов на плавающий потенциал уединенной макрочастицы (МЧ). Рассмотрен энергетический баланс с учетом взаимного влияния друг на друга процессов зарядки и разогрева МЧ. Показана возможность испарения МЧ.

ПРОЦЕСИ ЗАРЯДЖЕННЯ ТА ФАЗОВІ СТАНИ МАКРОЧАСТИНОК У ДУГОВОМУ РОЗРЯДІ НИЗЬКОГО ТИСКУ

О.А. Бізюков, О.Д. Чибисов, К.М. Середа, О.В. Ромащенко, В. Дімітрова

У дуговому розряді низького тиску було досліджено вплив густини плазми та заряду іонів на плаваючий потенціал відокремленої макрочастинки (МЧ). Розглянуто енергетичний баланс з урахуванням взаємного впливу один на одного процесів зарядження та розігріву МЧ. Показано можливість випаровування МЧ.