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POSITIVELY CHARGED MICROPARTICLES IN PLASMA

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The processes of recharging and changing the temperature of a positively charged microparticle (MP) introduced into plasma are considered. It is assumed that the MP is charged to a positive charge outside the plasma, and then enters the plasma due to the accelerating field. For various values of plasma density and temperature, a numerical solution of the energy and current balance equations of a MP is obtained. The equation that determines the evaporation of particles is solved numerically. The time dependence of the radius of a MP during evaporation has been obtained.

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INTRODUCTION

The usual way to obtain plasma from a substance that is in a solid state under normal conditions is to evaporate it in a crucible, followed by ionization of the previously created plasma. This method of obtaining vapors of a substance is not economical, and in some cases, for example, for a radioactive substance, it is dangerous. An alternative to this method of obtaining plasma from a given substance can be the introduction of MP of a given substance into the previously obtained plasma, followed by their evaporation and ionization. Such a scheme, for example, is implemented in devices for controlled thermonuclear fusion, in which fuel is introduced in the form of solid hydrogen pellets using a high-velocity injection system to achieve and maintain ignited plasma [1, 2]. Once in the plasma, the granules evaporate, and the resulting gas is ionized.

A similar scheme was proposed for devices with technological plasma used to create coatings on a substrate and created by a vacuum arc discharge. Here there is a problem of microdroplets that fly out from the cathode and, falling on the substrate, worsen the properties of the coatings. To eliminate this problem, it was proposed to evaporate microdroplets with a high-energy electron beam [3, 4], which is additionally introduced into the plasma, since the energy of the plasma itself is not enough to evaporate microdroplets. The created negative potential of the particles leads to a strong flow of plasma ions onto them and, as a result, to heating and evaporation of these MP. This not only eliminates the problem of interfering microdroplets, but also increases the flux of neutral atoms and ions onto the substrate due to their evaporation.

Thus, there are certain achievements in increasing the plasma density using solid-state or liquid MP that evaporate and ionize in pre-prepared plasma.

In [5], to obtain plasma of this substance, it was proposed to introduce into the plasma MP charged to a high positive potential. The high positive potential plays a dual role. On the one hand, a high potential makes it possible to introduce MP not mechanically, but electrostatically, accelerating them in an electric field. On the other hand, a particle with a high potential leads to a significant influx of electrons to the MP, heating them. Thus, an additional source of energy is created, that contributes to the evaporation of the MP. Interest in positively charged particles is due to the absence of thermionic emission during particle heating, as well as the field emission of electrons. In addition, MP introduced at a given rate, which are then evaporated and ionized, make it possible to obtain plasma with a given distribution function, for example, to create a plasma flow rotating in a magnetic field with axis-encircling ions, and also to obtain helical ion beams in a magnetic field without the use of additional methods. To introduce particles with a large positive charge into the plasma, one can use the method developed in [6, 7]. Here, positively charged particles of micron and submicron sizes are used to simulate the flow of micrometeorites in the laboratory. These particles are accelerated by high voltages up to 2 MV. The speed and charge of such particles reach 80 km/s and 10^7 proton charges, respectively [6, 7].

In this paper, which is a development of [5], the equations describing the processes of recharge and heating of MP charged to a significant positive potential are solved numerically at various values of plasma density, and temperature, as well as various parameters of MP, their size and potential. The equation that determines the conditions for the evaporation of a charged MP due to the flow of electron energy from the plasma is solved. The time of evaporation of MP is calculated depending on the plasma density.

1. HEATING OF MICROPARTICLES

On a MP placed in plasma, flows of plasma ions and electrons occur. The absorption of plasma ions and electrons is accompanied by the transfer of energy from the plasma to the MP surface. In addition, due to these flows, secondary electron emission, as well as with strong heating of the MF, thermionic emission occurs. In the case of strongly positively charged MPs, plasma ions are scattered in the MP electric field, and the charging and heating of the MP is determined only by the flow of accelerated plasma electrons. In the OML approximation, the electron and energy fluxes on the MP are described by the system of equations

$$\begin{cases} I_e^{pl} = dQ_{mp}/dt; \\ P_e^{pl} - P_r = mc \cdot dT/dt, \end{cases} \qquad (1)$$

where $I_e^{pl} = e\Gamma_e$ is the electron current on MP, $P_e^{pl} = \Gamma_e(2kT_e + e\varphi_a)$, is the electron power flux on MP, $\Gamma_e = \sqrt{8\pi}a^2 n_0 v_{Te}\left(1 + \frac{|e\varphi_a|}{kT_e}\right)$, φ_a is the potential of MP, n_0 is the plasma number density, $P_r = \sigma T^4$ is the power flux of thermal radiation from the MP, T is the MP temperature, c is the heat capacity of a substance MP, m is the mass of MP.

We assume that the value of the initial potential φ_0 of MP is sufficiently high, so that the potential energy of the charged MP significantly exceeds the average thermal energy of plasma ions and electrons $e\varphi_0 >> T_e > T_i$.

The system of equations (1) was solved numerically for a copper MP. The dependences of the temperature of MP on time were obtained for various values of its initial potential, as well as for various values of the plasma density and electron temperature. The initial temperature of the MP is 300 K, its radius is 1 μm.

Fig. 1 shows the dependences of the temperature of a copper particle on time for various values of its initial potential φ_0 with a radius of 1 μm.

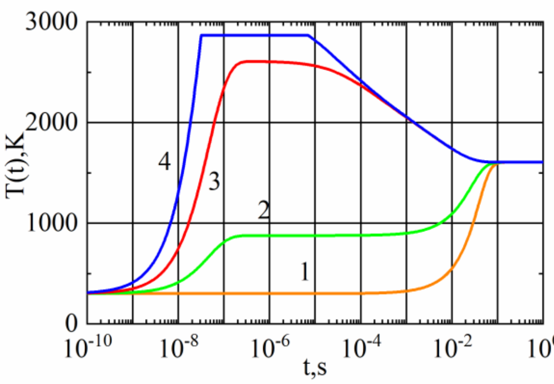

Fig. 1. The temperature of MP versus time at different values of φ_0: 1 – φ_0 = 0; 2 – φ_0 = 10kV; 3 – φ_0 = 20 kV; 4 – φ_0 = 30 kV; $n_0 = 10^{10}$ cm^{-3}, T_e = 50 eV

Curve 1 in Fig. 1 shows the dependence *T(t)* at $\varphi_0 = 0$. The particle temperature begins to increase due to the plasma electron flow approximately 10^{-3} *s* after the appearance of the particle in plasma and reaches an equilibrium value due to the equality of the incoming and outgoing energy flows. Curve 2 shows dependence *T(t)* at φ_0 = 10 kV. At the first stage, heating occurs due to the influx of electrons during the recharge of the particle. A further increase in temperature occurs due to the flow of thermal electrons. Curves 3 and 4 show this dependence at φ_0 = 20 kV and φ_0 = 30 kV, respectively. At φ_0 = 30 kV, the temperature of the particle reaches the boiling point of the material and after some time decreases, reaching the equilibrium value. At φ_0 = 20 kV (curve 3), the potential energy of the charged MP turns out to be insufficient to heat it up to the boiling point. Note that in all cases the final temperature of the particle turns out to be equal to the same value, which is determined by the equality of the incoming and outgoing energy from the particle.

The results of studying the effect of plasma number density on the MP temperature are shown in Fig. 2.

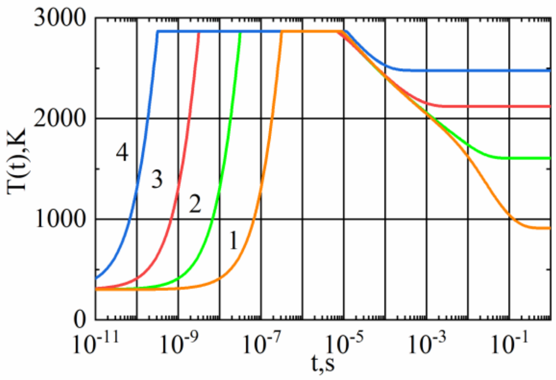

Fig. 2. The temperature of MP versus time at different values of n_0: 1 – $n_0 = 10^9$ cm^{-3}; 2 – $n_0 = 10^{10}$ cm^{-3}; 3 – $n_0 = 10^{11}$ cm^{-3}; 4 – $n_0 = 10^{12}$ cm^{-3}; T_e = 50 eV, φ_0 = 30 kV

For all considered values of number density, the temperature of the MP reaches the boiling point. It can be seen that the denser the plasma, the shorter the time to reach the temperature of boiling, and the longer the time spent at this temperature. This effect is explained by a larger flux of plasma electrons on the MP and, as a result, a larger flux of energy from the plasma. This can also explain the greater value of the equilibrium temperature at the final stage of the process, which is determined by the equality of the incoming and outgoing energy flows.

Fig. 3 shows the dependence *T(t)* for various electron temperatures.

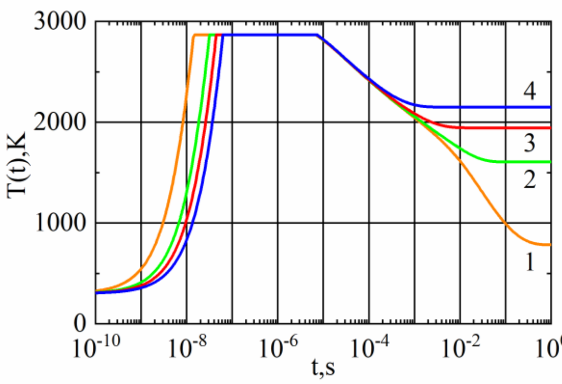

Fig. 3. The temperature of MP versus time at different values of T_e: 1 – T_e = 10 eV; 2 – T_e = 50 eV; 3 – T_e = 100 eV; 4 – T_e = 200 eV; φ_0 = 30 kV

As can be seen from the Fig. 3, the time during which the MP temperature reaches the boiling point is somewhat longer for plasma with hot electrons than for plasma with cold ones. This effect can be explained by the fact that in the model under consideration, hotter electrons fly past the particle to a greater extent than colder ones. The time during which the temperature of the particle remains equal to the boiling point also does not differ much. However, the equilibrium temperature at the final stage for plasma with hotter electrons is higher, which is explained by a larger energy flux on particle.

Let us estimate the speed of MP assuming that it is accelerated by the same potential to which it is charged. Equating the kinetic energy of the particle and the electrostatic energy of the charged sphere, we obtain

$$v = \frac{\varphi_0}{a}\sqrt{\frac{3\varepsilon_0}{\rho}}\,, \tag{2}$$

where ε_0 is the electric constant, ρ is the particle matter density. For a copper particle with a radius a =1 µm and an initial potential φ_0 = 30 kV we get from (2) $v = 1.6 \cdot 10^{3}$ m/s, and thus, during the time when the particle stays in the heated to the boiling point, the particle moves over a distance of about 2 cm.

2. EVAPORATION OF MICROPARTICLES

The additional energy flow from the plasma onto the MP surface due to the initial positive charge of the MP causes heating and vaporization of the MP substance. The quantity of the evaporated substance that associated with the initial potential is determined by $\Delta m = \varepsilon / H_v$, where ε is the energy related with the initial charge of the MP, H_v is the heat of vaporization. In the general case, the MP in plasma evaporates partially, that is, the spherical shell evaporates, and the final radius of MP is

$$r_f = \sqrt[3]{a^3 - \frac{3\varepsilon}{4\pi\rho H_v}}\,. \tag{3}$$

Assuming r_f (3) to be equal to zero, we obtain a relation for the energy ε (4) and size a of MP, which can be completely evaporated

$$\varepsilon = \frac{4}{3}\pi a^3 \rho H_v\,. \tag{4}$$

In order to find the time of complete evaporation of the MP we calculate the energy that transferred from the plasma to the MP taken into account the initial MP charge. When the MP entered into the plasma the process of heating starts immediately, as the heating is being, the power flux is getting smaller. The vaporization of the MP is possible when the power influx on the MP surface greater than power radiated from the MP.

The time interval τ_v when vaporization of the MP is possible can be found from the condition of equality energy flows on the MP surface $P_e^{pl}(\tau_v) - P_r(\tau_v) = 0$:

$$\tau_v \approx \frac{1}{2\alpha a}\ln\frac{\alpha\varphi_0^2}{4\pi\sigma T_b^4}\,, \tag{5}$$

where $\alpha = 4\pi e^2 n_0 v_{Te}/T_e$. We neglect the cooling associated with evaporation of the MP substance, since the energy that has spent on evaporation leads to losses of the mass and it will be further taken into account.

The energy transferred to the MP in the time interval τ_v (5) has been spent on vaporization, can be evaluated as:

$$\varepsilon = \int_0^{\tau_v}\left(P_e^{pl}(t) - P_r(T_b)\right)dt =$$
$$= \frac{\varphi_0^2 a}{2} - \frac{2\pi\sigma T_b^4}{\alpha} a\left(1 + \ln\frac{\alpha\varphi_0^2}{4\pi\sigma T_b^4}\right). \tag{6}$$

The energy required for the complete evaporation of the MP radius is determined by (4). Equating this value to (6), we obtain the condition for the evaporation of the MP of initial radius a in the case of a positively charged MP

$$\frac{\varphi_0^2}{2} - \frac{2\pi\sigma T_b^4}{\alpha}\left(1 + \ln\frac{\alpha\varphi_0^2}{4\pi\sigma T_b^4}\right) = \frac{4}{3}\pi a^2 \rho H\,. \tag{7}$$

Equation (7) determines the relationship between characteristic properties of MP substance such as heat of vaporization, boiling point as well as initial magnitude of MP potential and its radius. Defined such way relation between the parameters determines which MP can be vaporized. The numerical solution of the equation (7) was performed for copper and tungsten MPs (Fig. 4). Obtained curves represent critical values of electric potential and MP radius and define regions of the parameters (MP size and its electric potential) where MP can be vaporized completely and where is not.

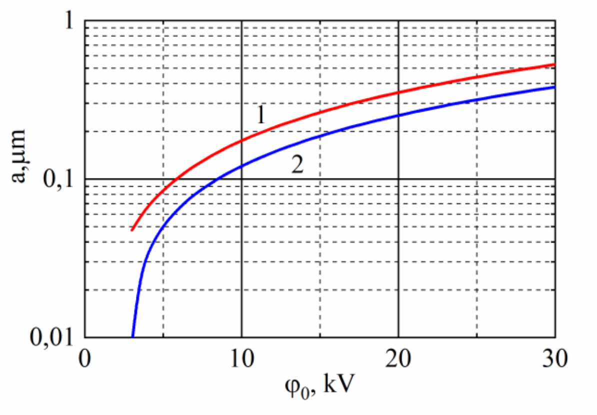

Fig. 4. The critical MP radius versus the initial MP potential: 1 – copper, 2 – tungsten; $n_0 = 10^{10}$ cm^{-3}, T_e = 50 eV, T_i = 1 eV

The MP which sizes and initial electric potential are in the region of the parameters that is under the curve can be vaporized completely. This graph shows the energy possibility of vaporization, but the time needed for complete vaporization of MPs is differ. For MPs which parameters are closer to the curve the time needed to vaporization is greater than for those ones which parameters are further from the curve. The MPs from the upper region depending on their size and initial potential can be vaporized partially and their final size is determined by (3).

The change in the MP radius during evaporation is governed by the equation

$$\alpha\varphi_0^2 e^{-2\alpha r t} - 4\pi\sigma T_b^4 = 4\pi\rho H \frac{dr}{dt}. \qquad (8)$$

To study the vaporization process the initial parameters of the MP in (8) was taken close to curve 1 in Fig. 4. The results of numerical solution of equation (8) for a copper MP are shown in Fig. 5.

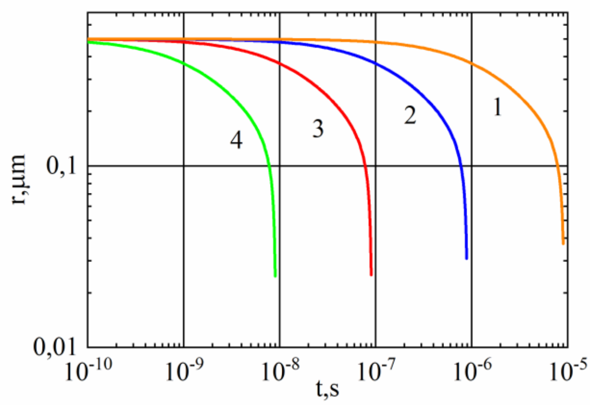

Fig. 5. The radius of MP versus time at different n_0: $1 - n_0 = 10^9\ cm^{-3}$; $2 - n_0 = 10^{10}\ cm^{-3}$; $3 - n_0 = 10^{11}\ cm^{-3}$; $4 - n_0 = 10^{12}\ cm^{-3}$; $T_e = 50$ eV, $T_i = 1$ eV; $\varphi_0 = 30$ kV; $a = 0.5\ \mu m$

As can be seen from the Fig. 5 the cooper MP with the radius 0.5 μm evaporates completely, moreover, the denser the plasma, the faster the evaporation. However, calculations show that MPs with an initial size 1 μm evaporate only partially. This is consistent with the graph in Fig. 1. Thus we conclude that the introducing positively charged MP to high enough potential can lead to it partially or complete vaporization.

CONCLUSIONS

Positively charged to a potential of 30 kV a copper MP with a size of 1μm, entering the plasma, can be heated to the boiling point and partially evaporate due to the energy influx by the plasma electrons during recharging, while a particle 0.5 μm in size evaporates completely.

It is shown that an increase in the plasma density leads to a decrease in MP recharging time, which leads to an increase in the residence time of the particle at the boiling temperature. An increase in the temperature of plasma electrons does not lead to an increase in the residence time of MP at the boiling temperature; however, to enhance the subsequent ionization of the evaporated substance of the MP, the electron temperature should be increased.

The speed of a charged particle in plasma is estimated under the assumption that it is accelerated by the same potential to which it is charged. It is shown that the time during which the particle is at the boiling temperature, it moves over a distance of about 2 cm.

The equation relating the initial potential and the critical radius of MP, when it can be completely evaporated, is derived and solved numerically. Diagram critical radius – initial potential for copper and tungsten is drawn (Fig.4).

The equation for changing the MP radius during vaporization is derived and numerically solved. It is shown that at an initial MP potential of 30 kV and various number densities of plasma, partial evaporation of particles 1 μm in size occurs, while particles 0.5 μm in size evaporate completely.

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ПОЗИТИВНО ЗАРЯДЖЕНІ МІКРОЧАСТИНКИ В ПЛАЗМІ

Д.В. Чібісов, О.Д. Чібісов, О.А. Жерновникова, Г.В. Дейниченко, В.В. Масич

Розглянуто процеси перезарядки та зміни температури позитивно зарядженої мікрочастинки (МЧ), введеної в плазму. Передбачається, що МЧ заряджається до позитивного заряду поза плазмою, а потім потрапляє в плазму в результаті прискорювального поля. Для різних значень густини та температури плазми отримано чисельний розв'язок рівнянь балансу енергії та струму МЧ. Чисельно розв'язано рівняння, яке визначає можливість випаровування таких частинок. Отримано часову залежність радіусу МЧ при випаровуванні.