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POSITIVELY CHARGED MACROPARTICLES IN LOW-TEMPERATURE PLASMA†

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The evolution of a positively charged metallic macroparticle placed into the low-temperature plasma is considered. The influence of the value of the initial macroparticle charge on the dynamics of the electrical potential and temperature of the macroparticle, as well as the possibility of evaporation of a macroparticle due to its interaction with plasma particles are studied. The system of equations of the energy balance and the current balance based on the OML theory, that takes into account the changing of macroparticle potential and its temperature over the time is solved numerically. The solution of the system of equations shows the evolution of the macroparticle potential and temperature within the time interval from the moment when the macroparticle is placed in the plasma until the moment the macroparticle has charged to the floating potential. The positive charge of the macroparticle excludes the thermionic emission and secondary electron emission from the macroparticle surface, as well as the mechanisms of cooling of the macroparticle associated with these emission processes. Analytical expressions that determine the macroparticle potential, the electron current on the macroparticle, as well as the power transferred by plasma electrons in the case when the energy of attraction of electrons to the macroparticle strongly exceeds the energy of thermionic electrons, the energy of secondary electrons and the energy of plasma ions are obtained. A simplified system of equations of the energy balance and the current balance for a positively charged macroparticle is solved; the solution of the simplified equations matches with the solution of the general equations in the region of positive values of the macroparticle potential. Calculations show that during the charging of the macroparticle, its temperature increases up to the boiling point of the macroparticle substance. An equation that determines the conditions under which evaporation of macroparticles is possible has been obtained and solved numerically. The possibility of evaporation of macroparticles of a given size (critical value of the radius) due to initial charging to high positive values of potential is shown. The dependencies of the critical value of the radius on the initial value of the potential for tungsten and copper macroparticles that can be evaporated in a low-temperature plasma are obtained. These solutions bound the region of the parameters where evaporation of a macroparticle is possible and where it is not. The critical values of the potential for copper and tungsten particles with sizes of 0.1 and 1 μm are calculated. The dependence of the radius of a macroparticle on time during the process of vaporization is obtained.
Keywords: macroparticles, dusty particles, dusty plasma, floating potential, vaporization
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The investigations of plasma with charged dust particles (dusty plasma) are aimed at various technological and scientific applications [1-5]. Charging of the dust particles or macroparticles (MPs) negatively is performed by the electron beam. It was experimentally and theoretically shown that the charge of micron-sized particles can reach 10^6 electrons [1]. In this case, the particle charge is limited by the effects of thermionic and field emission of electrons. The high negative potential of the particle leads to intensive flow of plasma ions on it and, as a result, to the heating and vaporization of this particle. In paper [3], the processes of charging and vaporization of macroparticles in a low-temperature plasma in the steady state approximation have been studied; it was considered the effect of plasma-beam system parameters on the floating potential and temperature. The transient processes were neglected; it has been shown that interaction of the MPs with low-temperature plasma leads to partial or complete vaporization of MPs. This effect can be used to eliminate microdroplets generated in a vacuum-arc discharge, which is used to thin film coatings. In paper [4] the interaction of MP with a high energy electron beam has been studied. It was shown that intense charging by an electron beam may cause develop of Rayleigh instability that lead to disruption of the MPs into smaller ones and their further decay is possible.

Thus, the behavior in plasma of MPs charged with a high negative potential for their heating and evaporation is well studied. At the same time, the behavior of a positively charged particle in plasma is of interest, which is due to the absence of thermionic emission, as well as the field emission of electrons from the particle.

To introduce a particle with a large positive charge into the plasma, one can use the method developed in the works [6,7]. In those works, positively charged particles of micron and submicron sizes are used to reproduce the flow of micrometeorites in laboratory conditions. These particles are accelerated by high voltages of up to 2 MV. The speed and charge of such particles reach values of 80 km/s and values 10^7 of proton charges, respectively [6,7].

In this work, transient processes of charge and heating of positively charged particles in low-density plasma are studied. The possibility of evaporation of such particles, caused by the flow of energetic electrons from the plasma, is also discussed.

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MODEL DESCRIPTION

MP placed into the plasma interacts with the plasma in different ways. In such system the following charging processes are take place: absorption of plasma ions and electrons, secondary electron emission, thermionic emission. The process of MP charging by flows of electrons and ions is also accompanied by heating of the MP. The processes of charging and heating of the MP act on each other through the process of thermionic emission from the MP surface.

In general, the floating potential and the temperature of the MP are described by the set of equations [4]:

$$\begin{cases} I_i^{pl} + I_e^{pl} - I_e^{s} - I_e^{th} = dQ_{mp}/dt\,; \\ P_e^{pl} + P_i^{pl} - P_s - P_r - P_{th} - P_{vap} = mc\,dT/dt\,. \end{cases} \tag{1}$$

The first equation of (1) describes the changing of the MP charge and includes the following charging processes: I_i^{pl} and I_e^{pl} are the ion and electron currents from the plasma onto the MP surface, I_e^{s} is the secondary electron emission current from the MP surface, I_e^{th} is the thermionic emission current from the MP surface.
Absorption of plasma particles is described by the OML theory and has the form

$$I_\alpha^{pl}\left(\varphi_a\right) = e < n_0 v_\alpha \sigma_\alpha^{OML} >= e\cdot\Gamma_\alpha\,,$$

where $\alpha = i, e$ denote the particle species.

$$\Gamma_\alpha = \sqrt{8\pi} a^2 n_0 v_{T\alpha}\left(1 + \frac{|e\varphi_a|}{kT_\alpha}\right),$$

is the current of particles α in a case of attractive MP potential and

$$\Gamma_\alpha = \sqrt{8\pi} a^2 n_0 v_{T\alpha}\exp\left(-\frac{|e\varphi_a|}{kT_\alpha}\right)$$

in a case of repulsive MP potential, n_0 is the plasma number density, $v_{T\alpha}$ is the thermal velocity of particles α, a is the initial MP radius, φ_a is the MP potential. Secondary electron emission is described by the relation:

$$I_e^{s} = \delta I_e\,,$$

where

$$\delta = \delta_{\max}\frac{|e\varphi_a|}{E_m}\exp\left(2(1-\sqrt{\frac{|e\varphi_a|}{E_m}})\right)$$

is the secondary electron emission yield: E_m is the electron energy which corresponds to the maximum of secondary emission yield $\delta_{\max}$. Thermionic emission current is described by the Richardson's law

$$I_e^{th} = 4\pi a^2 A T_a^2 \exp\left(\frac{e\Phi - \Delta W}{k_B T_a}\right),$$

where, $A = \frac{4\pi m_e k_B^2 e}{h^3}$, h is the Planck constant, k_B is the Stefan–Boltzmann constant, $e\Phi$ is the work function, T_a is the temperature of the MP. $\Delta W = \sqrt{e^3\varphi_a / a}$ is the decreasing of the electron work function (Schottky effect).

The second equation of (1) describes the changing of MP temperature caused by energy flows the following processes: $P_{i(e)}^{pl}$ is the energy flow of plasma particles to the MP; P_r is the energy radiated from the MP surface, P_{vap} is the cooling due to vaporization of MP substance, P_{th} is the energy flow from the MP surface is transferred by the electrons of thermionic current, P_s is the energy flow due to the secondary electron emission. The values of the respective energy flows are determined by the following relations: $P_e^{pl} = \Gamma_e\cdot(2kT_e + e\Phi)$, $P_i^{pl} = \Gamma_i\cdot(2kT_i + e\varphi + I + e\Phi)$, $P_r = \sigma T^4$, $P_{th} = \Gamma_e^{th}\cdot(2k_b T_a)$, $P_e^{s} = \Gamma_s\cdot(<\varepsilon_s> + e\Phi)$, $P_{vap} = \Gamma_a\cdot(2k_B T_a + p)$, where I is the ionization energy, $\Gamma_a = n'\sqrt{\frac{k_B T_a}{2\pi m_a}}\exp\left(-\frac{p}{k_B T_a}\right)$ is the atom flow of vaporized MP substance, n' is the concentration of atoms in metal, p is the energy of vaporization an atom, $\Gamma_e^{th} = I_e^{th} / e$, $\Gamma_s = I_s^{e-e} / e$, $< \varepsilon_s >$ is the averaged energy of the secondary electrons.

SPECIFIC OF CHARGING AND VAPORIZATION OF POSITIVELY CHARGED MP

We consider the case of positively charged MP placed into the plasma. We suppose plasma number density n_0 is $10^9 cm^{-3}$ electron T_e and ion T_i temperatures are $10eV$ and $0.03eV$ respectively. Calculations was performed for the residual gas pressure $10^{-4} torr$, under this conditions the boiling point of the copper is close to the melting point and approximately equal 1350K [8]. The processes of charging and heating of the positively charged MP occurs the different way than the negatively charged MP. We suppose that the magnitude of MP charge is high enough such that $|e\varphi_a| >> e\Phi$, $|e\varphi_a| >> \varepsilon_s$, $|e\varphi_a| >> T_e > T_i$, that is thermionic electrons and secondary electrons are captured by the electric field of the MP, the plasma ions are scattered on the positive potential of the MP. Therefore the ion current on the MP surface and the processes of thermionic emission and the secondary emission from the MP surface can be neglected as well as the energy flows related with these processes. Therefore charging of the MP is entirely as a result of absorption of plasma electrons. Thus, the set of equation (1) in the case of positively charged MP can be simplified:

$$\begin{cases} I_e^{pl} = dQ_{mp}/dt; \\ P_e^{pl} - P_r - P_{vap} = mc \cdot dT/dt. \end{cases} \tag{2}$$

Figure 1a represents the positive part of the MP potential which is solution of the first equation of the sets of equations (1) and (2). From the Figure 1a it can be seen, that typical time of full (except the time interval where $\varphi \le -T_e / e$) charging τ_{ch} of MP depending on its size is $10^{-6} \div 10^{-4} s$.

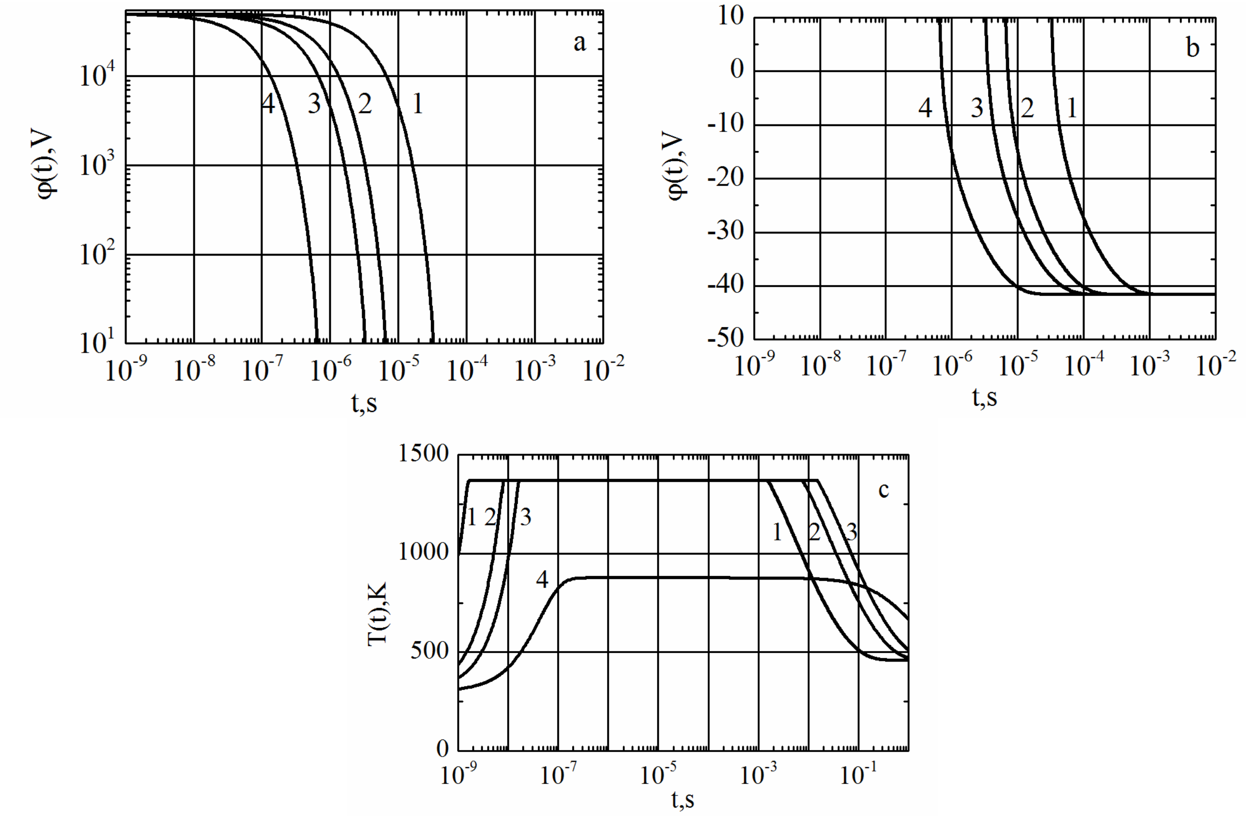

Figure 1. The dependence of the MP potential on the time (a) $\varphi >> -T_e / e$, (b) $\varphi < -T_e / e$ and related temperature (c), the MP substance is copper initial value of MP potential is $\varphi_0 = 50kV$, initial MP temperature is $T_0 = 300K$: 1 – $a = 0.1\mu m$, 2 - $a = 0.5\mu m$, 3 – $a = 1\mu m$, 4 – $a = 5\mu m$.

Figure 1b shows the part of the solution where the MP potential is lower than $10V$ including negative values of the MP potential as well as steady state values (floating potential), which is obtained by solving of the set of equation (1). This result is consistent with previous work [4]. Further we will consider the case $\varphi >> -T_e / e$ that is described well by the set of equation (2).

The Figure 1c shows the numerical solution of the second equation of the sets of equations (1) and (2) that represents the changing of the MP temperature on the time. The MP temperature grows until reaches the boiling point T_b for the MPs sized $0.1 \div 1 \mu m$ it takes $4 \cdot 10^{-9} \div 4 \cdot 10^{-8} s$, then temperature stays constant for some time interval during which the vaporization of the MP occurs. During simulation the dependence the heat capacity on the temperature as well as the process of melting was neglected.

In order to evaluate the parameters MP and plasma when the vaporization of the MP is possible we obtain analytical relations for the basic parameters such as electric potential of the MP, electron and power flows on the MP surface. From the first equation of (2) we obtain MP potential as a function of time:

$$\varphi(t) = \varphi_0 e^{-\beta a t}, \tag{3}$$

where $\beta = 4\pi e^2 n_0 v_{Te} T_e^{-1}$. Obtained function (3) described MP potential shown in Figure 1a. Electron flow and power associated with this flow on the MP surface in approximation OML theory under condition $\varphi >> -T_e / e$ have the form

$$I(t) = \beta a^2 \varphi = \beta a^2 \varphi_0 e^{-\beta a t}, \tag{4}$$

$$P_e^{pl}(t) = \beta a^2 \varphi_0^2 e^{-2\beta a t}. \tag{5}$$

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

$$\tau_b \approx \frac{1}{2\beta a} \ln \frac{\beta \varphi_0^2}{4\pi\sigma T_b^4}. \tag{6}$$

The process of cooling related with vaporization of the MP substance excluded from the equality (6), since the energy losses related with the vaporization lead to mass changing and it will be further taken into account.

The energy transferred to the MP in the time interval τ_b cause the MP vaporization and can be evaluated as:

$$\varepsilon = \int_0^{\tau_b} \left(P_e^{pl}(t) - P_r(T_b) \right) dt = \frac{\varphi_0^2 a}{2} - \frac{2\pi\sigma T_b^4}{\beta} a \left(1 + \ln \frac{\beta \varphi_0^2}{4\pi\sigma T_b^4} \right). \tag{7}$$

The energy required to complete vaporization of the MP of radius a is $\varepsilon_{vap} = m_a H = \frac{4}{3}\pi a^3 \rho H$, where H is the heat of vaporization, ρ is the density of MP substance. Substituting this value into (7) gives the condition of vaporization of MPs of radius a in the case of positively charged MP:

$$\frac{\varphi_0^2}{2} - \frac{2\pi\sigma T_b^4}{\beta} \left(1 + \ln \frac{\beta \varphi_0^2}{4\pi\sigma T_b^4} \right) = \frac{4}{3}\pi a^2 \rho H. \tag{8}$$

This equation gives the relation between specific parameters of MP substance such as density and heat of vaporization, the critical initial value of the MP potential and the critical MP radius that can be vaporized. Critical means that the obtained parameters separate two regions of the parameters where MPs can be vaporized and where is not. The numerical solution of the equation (8) is shown in the Figure 2.

Figure 2 shows the critical curves for copper (1) and tungsten (2), the region of the parameters that lies under the curve corresponds to conditions the vaporization of the MP is possible.

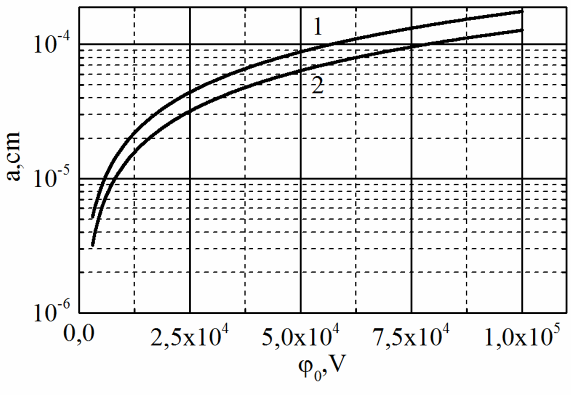

Figure 2. The dependence of the critical MP radius on the critical initial value of the MP potential which can be vaporized: 1 - copper, 2 – tungsten.

The closer to the curve parameters are the longer the process vaporization is, and vise verse the far the parameters from the curve the faster the process vaporization is. In the table 1 some critical values of initial MP potential and MP radius is shown.

Table 1. Some critical values of initial MP potential and MP radius

	$0.1\mu m$	$0.5\mu m$	$1\mu m$
Cu	$6kV$	$28.5kV$	$57kV$
W	$8.5kV$	$39.5kV$	$78.5kV$

When the vaporization of the MP is possible the changing of the MP radius r is described by the equation:

$$\beta\varphi_0^2 e^{-2\beta rt} - 4\pi\sigma T_b^4 = 4\pi\rho H \frac{dr}{dt}. \tag{9}$$

Numerical solution of the equation (9) for the copper MP is shown in the Figure 3.

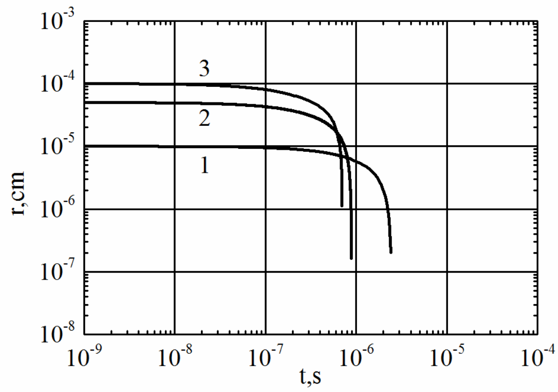

Figure 3. The dependence of the radius on the time at different initial radii a and initial potential φ_0 of the copper MP, initial MP temperature is $T_0 = 300K$: 1. $a = 0.1\mu m, \varphi_0 = 10kV$, 2. $a = 0.5\mu m, \varphi_0 = 40kV$ 3. $a = 1\mu m, \varphi_0 = 70kV$.

To simulation of vaporization process the initial parameters of the MP was taken close to the curve 1. From the Figure 3 it can be seen that at given parameters the time of vaporization of the MP with the radius $0.1 \div 1\mu m$ is $0.7\mu s - 2\mu s$. This result correlate with the simulation MP potential and MP temperature (see Figure 1a and Figure 1c) in this time interval the MP temperature is at boil point and MP potential still high enough ($\varphi_0 \sim 5\cdot 10^3 \div 4\cdot 10^4 kV$). Thus we can conclude that the placing preliminarily positively charged MP to high enough potential can lead to it partially or complete MP vaporization.

CONCLUSIONS

For the preliminarily positively charged metallic macroparticle placed into the low-temperature plasma the set of equations energy and current balance has been solved numerically. The transient values of the MP potential as well as relative temperature have been obtained.

The particle is charged by the flow of electrons from the plasma. It is shown that the time of full (up to values of $\varphi = -T_e / e$) charging τ_{ch} of MP depending on its size is $6\cdot 10^{-7} \div 3\cdot 10^{-5} s$.

The electron current from the plasma heats up the particle. In the case of $\varphi << -T_e / e$ analytical relations for the MP potential, electron flow and power associated with this flow have been obtained. It was found that the MP heating time up to the boiling point for the MPs sized $0.1 \div 1\mu m$ is $4\cdot 10^{-9} \div 4\cdot 10^{-8} s$.

The equation for the initial value of the MP potential and its critical radius at which the particle can be vaporized has been derived and solved numerically. The critical values of radius and potential for copper and tungsten particles, which determine the region of the parameters where MPs can be vaporized, have been obtained. It is found that the initial potentials of the particles of radius $a = 1\mu m$ for the copper and tungsten MP that evaporated are equal $57kV$ and $78.5kV$ respectively.

The equation describing the change in the MP radius during evaporation is derived and solved numerically. It is shown that for given initial potential of MP the time of vaporization of MP with the radius $0.1 \div 1\mu m$ is $0.7\mu s - 2\mu s$. Thus the possibility of partially or complete vaporization in plasma of the preliminarily positively charged metallic MP has been shown.

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REFERENCES

[1] A. V. Filippov, A. F. Pal', A. N. Starostin, A. V. Gavrikov, V. E. Fortov, O. F. Petrov, and M. N. Vasil'ev Physics of Plasmas, **16**, 093702 (2009), https://doi.org/10.1063/1.3227646
[2] Yu.S. Akishev, V.B. Karal'nik, A.V. Petryakov, A.N. Starostin, N.I. Trushkin, and A.V. Filippov, Plasma Phys. Rep. **42**, 14 (2016), http://dx.doi.org/10.1134/S1063780X16010013
[3] A.A. Bizyukov, K.N. Sereda, and A.D. Chibisov, Problems of atomic science and technology. Series: Plasma physics, **1**(17), 107 (2011), https://vant.kipt.kharkov.ua/ARTICLE/VANT_2011_1/article_2011_1_107.pdf
[4] A.A. Bizyukov, A.D. Chibisov, E.V. Romashchenko, and Yu.E. Kolyada. Problems of atomic science and technology. Series: Plasma physics, **1**(23), 163 (2017), https://vant.kipt.kharkov.ua/ARTICLE/VANT_2017_1/article_2017_1_163.pdf
[5] S.I. Kopnin, T.I. Morozova, and S.I. Popel. IEEE Transactions on Plasma Science, **46**(4), 701 (2018) https://doi.org/10.1109/TPS.2017.2748378
[6] A, Mocker, S, Bugiel, S, Auer, et al. Rev. Sci. Instrum. **82**, 095111 (2011). https://doi.org/10.1063/1.3637461
[7] J.D. Kerby, R.T. Daly, and D.E. Austin, Earth Planets Space, **65**, 157 (2013). http://dx.doi.org/10.5047/eps.2012.08.005
[8] T. Iida, and R.I.L. Guthrie, *The Physical Properties of Liquid Metals*, (Oxford, 1988), pp. 86-87, https://www.amazon.com/Physical-Properties-Liquid-Metals/dp/0198563310

ПОЗИТИВНО ЗАРЯДЖЕНІ МАКРОЧАСТКИ В НИЗЬКОТЕМПЕРАТУРНІЙ ПЛАЗМІ

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Розглянуто еволюцію позитивно зарядженої металевої макрочастинки, яка поміщена в низькотемпературну плазму. Досліджено вплив значення початкового заряду макрочастинок на динаміку електричного потенціалу та температуру макрочастинки, а також можливість випаровування макрочастинки внаслідок її взаємодії з частинками плазми. Чисельно розв'язана система рівнянь балансу енергії та балансу струмів, яка заснована на OML теорії та враховує зміну потенціалу макрочастинок та її температури з плином часу. Розв'язок системи рівнянь показує еволюцію потенціалу та температури макрочастинок протягом інтервалу часу з моменту розміщення макрочастинки у плазмі до моменту, коли макрочастинка зарядилася до плаваючого потенціалу. Позитивний заряд макрочастинки виключає появу термоелектронної емісії та вторинної електронної емісії з поверхні макрочастинок, а також механізми охолодження макрочастинок які пов'язані з цими процесами. Отримано аналітичні вирази, що описують потенціал макрочастинки, електронний струм на макрочастинку, а також потужність, що передається електронами плазми у випадку, коли енергія притягання електронів до макрочастинки значно перевищує енергію термоелектронів, енергію вторинних електронів та енергію іонів плазми. Розв'язано спрощена система рівнянь балансу енергії та балансу струмів для позитивно зарядженої мікрочастинки, розв'язки спрощених рівнянь збігаються з розв'язками загальних рівнянь в області позитивних значень потенціалу макрочастинок. Розрахунки показують, що під час заряджання макрочастинки її температура зростає аж до температури кипіння речовини макрочастинок. Отримано та чисельно розв'язане рівняння, яке визначає умови, за яких можливе випаровування макрочастинок. Показано можливість випаровування макрочастинок заданого розміру (критичне значення радіуса) внаслідок початкової зарядки до високих позитивних значень потенціалу. Отримано залежності критичного значення радіуса від початкового значення потенціалу для макрочастинок вольфраму та міді, які можна випарувати в низькотемпературній плазмі. Отримані розв'язки обмежують область параметрів, де випаровування макрочастинки можливе, а де ні. Розраховано критичні значення потенціалу для частинок міді та вольфраму з розмірами 0,1 і 1 мкм. Отримано залежність радіусу макрочастинки від часу в процесі випаровування.

Ключові слова: макрочастинки, пилові частинки, пилова плазма, плаваючий потенціал, випаровування.