Interaction of Nonequilibrium Plasma with an Evaporating Metal Drop[1]

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Abstract – The theoretical model of process of metal drop evaporation in plasma vacuum arc was created. The model predicts a new mode of drop heating when the drop temperature and its evaporation rate increase as a result of ionization of the evaporated material. It is shown, that the given mode exists for substances with high melting temperature (Zr, W, Ta) and for easily fusible materials (Cu, Al, Ni, Ga, Ti). The greatest evaporation rate of drop takes place when increase of plasma concentration in a vicinity of a drop is accompanied by intensive thermionic electron emission from a surface of a drop.

1. Introduction

Presence of drop fraction in vacuum arc plasma limits technical application of such plasma [1–6]. The first time it is experimentally established, that some metal drops flying from the cathode during arcing intensively evaporate and turn to plasma clots [1]. The drop with surrounding plasma represents new object named a "droplet spot". Studying of the "droplet spot" opens new opportunities for decrease of drops concentration in arc plasma.

As a rule, the theoretical analysis of drop interaction with plasma is spent in the assumption of insignificant evaporation of the drop material [3–5]. Recently the model considering evaporation of a drop material and two modes of drop heating (a "high temperature mode" with high intensive thermionic emission and a "low temperature mode" with low intensive thermionic emission) has been offered for the description of "droplet spot" [2, 7]. It has been shown [8] that ionization of the substance evaporated from a drop under certain conditions leads to increase of local concentration of plasma near to the metal drop.

The given work develops the approach to the description of metal droplet behavior in nonequilibrium plasma presented in papers [2, 7, 8] earlier. In particular, influence of increase of local plasma concentration on the drop heating and its evaporation was analyzed.

2. Theoretical model

Let us consider a spherical droplet of radius R, which evaporates in an unbounded nonequilibrium plasma with known parameters (m is the electron mass; M is the ion mass; Z is average ion charge; n_0 is background ion plasma density far from drop; T_i is the ion temperature; T_e is the electron temperature, $T_e \gg T_i$).

The droplet radius R is assumed to be significantly smaller than the mean free path of the plasma particles, but much greater than the Debye screening distance.

We assume that neutral atoms, the concentration n_a of which depends only on the radial coordinate, are evaporated from the spherical surface and are ionized as a result of interaction with the plasma electrons.

The ionization of the vapor takes place due to a high thermal conductivity of the electron gas, and a certain gradient of the electron temperature must exist in order to provide for the necessary energy supply. This gradient is assumed to be small, and the ionization constant $K_i(T_e)$ dependent on the electron temperature is assumed to have the known constant value.

The system of three differential equations was considered. The dynamic of the drop potential φ_d was defined by balance of charged particles fluxes

$$4\pi\varepsilon_0 R\frac{d\varphi_d}{dt} = 4\pi R^2 q\left(\Gamma_e^{pl} - Z\Gamma_i^{pl} - \Gamma_e^{em}\right), \qquad (1)$$

here $4\pi\varepsilon_0 R$ is the capacitance of the droplet; q is the elementary charge; Γ_e^{pl} and Γ_i^{pl} are the fluxes electrons and ions on the drop from plasma; Γ_e^{em} is the flux of thermionic electrons. In stationary condition, the right part of equation (1) is equal to zero and it is possible to define the floating potential of a drop.

The drop temperature T_d was defined by the equation for the energy fluxes

$$\frac{R\rho C}{3}\frac{dT_d}{dt} = W_1\Gamma_e^{pl} + W_2\Gamma_i^{pl} - W_3\Gamma_e^{em} - W_4\Gamma_a^{ev} - \sigma T_d^{\,4}, \qquad (2)$$

here c and C are the density and specific heat of droplet material; Γ_a^{ev} is the flux of evaporating atoms; σT_d^4 is the radiation energy flux; W_1, W_2, W_3, and W_4 are the elementary exchange energies of the interaction between the droplet and plasma:

$$W_1 = W_e + 2kT_e\,,\; W_2 = Zq\varphi_d + I_Z - ZW_e + W_a\,;$$
$$W_3 = W_e + 2kT_d\,,\; W_4 = W_a + 2kT_d\,.$$

Here W_e is the electron work function of droplet material; I_Z is the total ionization energy of an ion

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of the charge state Z; W_a is the evaporation energy of a single atom.

The drop radius is described by the equation for balance ion flux from plasma onto the drop and flux of the evaporated atoms from a drop

$$\frac{dR}{dt} = \frac{M}{\rho}(\Gamma_i^{pl} - \Gamma_a^{ev}), \quad (3)$$

$$\Gamma_a^{ev} = P_s(T_d) \Big/ \sqrt{2\pi M k T_d},$$

where $P_s(T_d)$ is the temperature dependence of the vapor saturation pressure for the drop material, which is considered known.

Fluxes electrons and ions from plasma on the drop have been estimated considering ionization of a cloud vapor near the drop according to [8]:

$$\Gamma_e^{pl} = \frac{1}{4} Z n_0 \eta_{\max}(\alpha)\sqrt{8kT_e/\pi m}\exp\left(-q\varphi_d/kT_e\right);$$

$$\eta_{\max}(\alpha) = \frac{\alpha - \arctan\alpha}{\sin(\alpha - \arctan\alpha)}; \quad (4)$$

$$\Gamma_i^{pl} = \begin{cases} \Gamma_i^B, & T_d \le T_{d\min} \\ \Gamma_i(\alpha), & T_d > T_{d\min} \end{cases}. \quad (5)$$

Here $\Gamma_i^B = \frac{1}{2} n_0 \sqrt{ZkT_e/M}$ is the Bohm flux; $\Gamma_i(\alpha)$ is the ion flux taking into account ionization of a drop material vapor:

$$\Gamma_i(\alpha) = n_0\sqrt{\frac{kT_e}{M}}\sqrt{\frac{T_e}{T_i}}\left(\frac{\lambda}{R}\right)\frac{\alpha^3/3}{\sin\alpha - \alpha\cos\alpha};$$

$$\alpha^2 = 3Z\sigma^*\left(n_a(R)R\right)^2\frac{K_i(T_e)}{\sqrt{kT_e/M}}\sqrt{\frac{T_i}{T_e}},$$

here $\lambda = 1/\sigma^* n_a(R)$ is the mean ion range; σ^* is the transport cross section (doubled charge exchange cross section). Concentration of a material vapor near to a drop is approximately equal to concentration of saturation vapor: $n_a(R) \approx n_s = P_s/kT_d$. Physically correct solutions of a problem are possible only at parameter $\alpha < 4.49$. The temperature $T_{d\min}$ in expression (5) have been considered by minimization of residual for fluxes Γ_i^B and $\Gamma_i(\alpha)$.

We used radial distribution of vapor concentration $n_a(r)$, which corresponds to the approximation of a constant velocity of expansion of the vapor cloud:

$$n_a(r) = n_a(R)\left(\frac{R}{r}\right)^2.$$

We assumed that the ionization degree of vapor always remains small. This assumption allows ignoring influence of the charged particles on the diffusion coefficient of ions. At the same time, the ionized gas is assumed to be sufficiently dense so as to obey the condition of quasi-neutrality for the concentrations of ions $n_i(r)$ and electrons $n_e(r)$ in vapor cloud too, according to which $n_e(r) = Zn_i(r)$.

The ionization constant can be estimates as

$$K_i = \langle\sigma_i v_e\rangle = \bar{\sigma}_i\sqrt{kT_e/m}\exp\left(-I/kT_e\right),$$

where I is the ionization energy for atoms of the droplet; $\bar{\sigma}_i$ is the effective electron-impact ionization cross section. The characteristic ionization cross-section in the expression for the ionization constant can be selected on the order of $\bar{\sigma}_i \sim 10^{-16}$ cm^2.

Earlier it has been shown [2, 7], there are two possible modes of heat exchange of a drop with nonequilibrium plasma. Modes differ from each other intensity of thermionic emission from a surface of a drop.

At the “lower temperatures mode” the emission flux obeys the Richardson–Dushman law

$$\Gamma_e^{em\,R-D} = AT_d^2\exp\left(-W_e/kT_d\right),$$

here $A = 120$ A/cm^2 K^2 is the Richardson–Dushman constant.

At the “high temperatures mode” the electron flux from drop is formed in a double electric layer. In this case, the electrons flux from drop is proportional to ions flux from surrounding plasma on a drop.

As a result, we have two expressions of the thermionic electrons flux for two modes

$$\Gamma_e^{em} = \begin{cases} \Gamma_e^{em\,R-D}, & \Gamma_e^{em\,R-D} \le \sqrt{ZM/m}\,\Gamma_i^{pl}, \\ \sqrt{ZM/m}\,\Gamma_i^{pl}, & \Gamma_e^{em\,R-D} > \sqrt{ZM/m}\,\Gamma_i^{pl}. \end{cases} \quad (6)$$

On the one hand, such formulation of new model allows passing continuously to results of old model for the plasma undistorted by the vapor [2, 7]. On the other hand, the model described above allows illustrating features of the drop evolution in a vicinity of temperature $T_{d\min}$ when ionization of a drop material vapor appears significant.

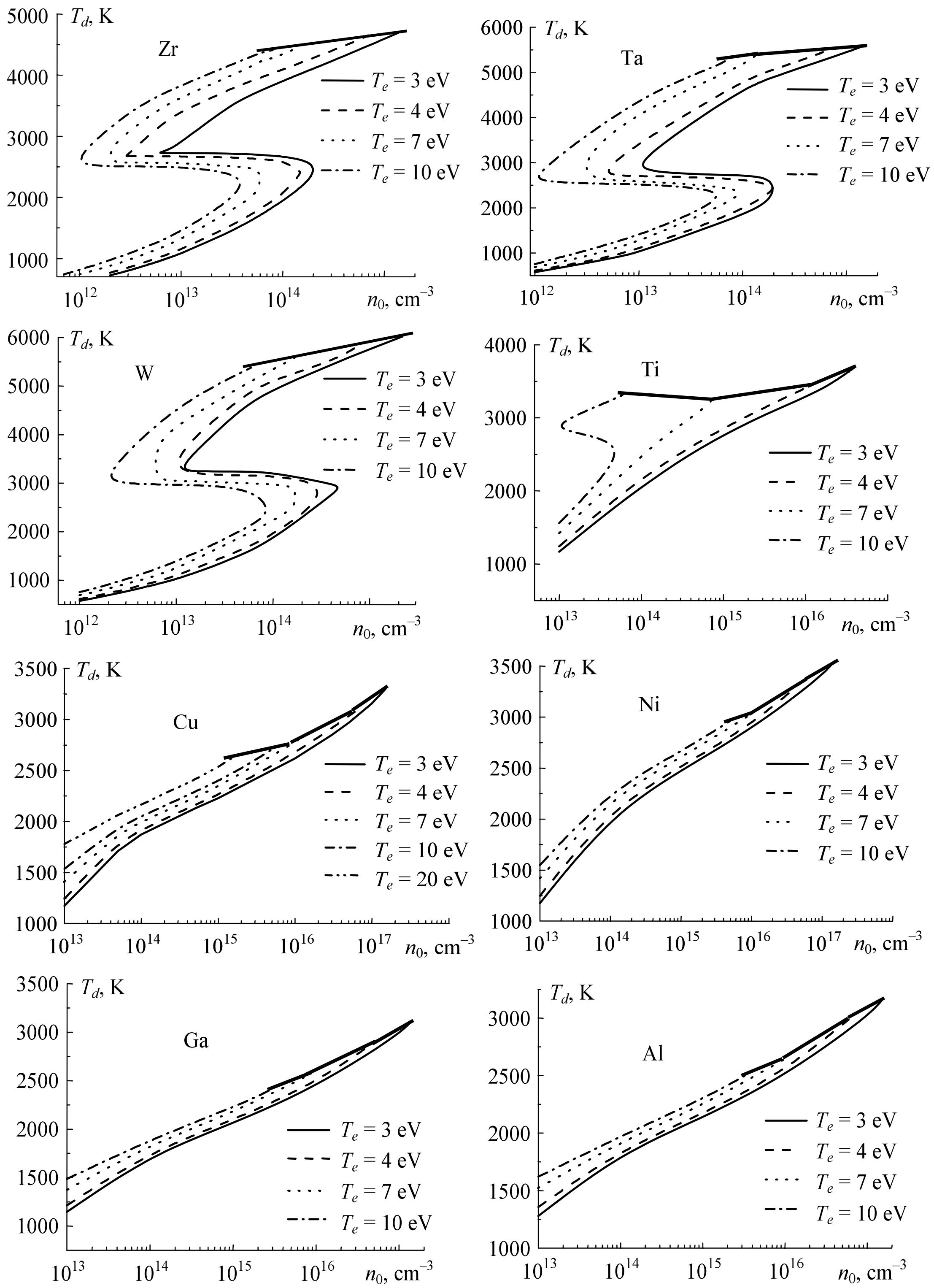
3. Discussion

In calculations, we have used typical values of plasma parameters in a vacuum arc (the average ion charge $Z = 2$, the ion temperature $T_i = 0.4$ eV, the electron temperature $T_e = 3 \div 20$ eV, the background ion plasma density $n_0 = 10^{12} \div 10^{18}$ cm^{-3}). We have made calculations for some drop materials (Zr, W, Ta, Cu, Al, Ni, Ga, Ti).

The analysis of equations (1) and (2) for the drop potential φ_d and its temperature T_d has shown that stationary solutions there are not for all range of concentration n_0.

Figure shows the calculated dependences of the stationary drop temperature T_d on the background ion plasma density n_0 for the drop radius $R = 1$ μm.

The area of stationary solutions is limited from above to a heavy line for each curve. It is not possible to receive stationary drop temperature above this heavy line.



Dependences of the stationary droplet temperature T_d on the plasma density n_0 at different electron temperature T_e

Crossing of dependence $T_d(n_0)$ with a heavy line gives value of concentration $n_0 = n_\alpha$. Above concentration n_α the drop heating will always prevail of its cooling, and heat exchange of the drop and plasma will go in a non-stationary mode.

As can be seen from the figure, the new model, as well as the old model [2, 7], describes two modes differing from each other intensity of thermionic emission. The drops from substances with the higher fusion temperature (Zr, W, Ta) have higher stationary drop temperature than drops of more fusible materials (Cu, Al, Ni, Ga) at identical plasma density n_0.

Titan occupies intermediate position. It can be observed both of modes in a considered range of concentration n_0 at the Ti. Distinctive feature of new model is prediction of the new general mode of heating both for the fusible metal drop and for the refractory metal drop. This mode takes effect at the vicinity of background plasma density $n_0 \approx n_\alpha$.

Ionization of a evaporating material cloud leads to significant increase the plasma density in a vicinity of the drop under the condition $n_0 > n_\alpha$. In this case, the drop temperature cannot accept stationary value and increases with time. Growth of the drop temperature contributes to acceleration of evaporation process of drop. This mode can be named a "self-enhancement evaporation mod".

It is possible to make the assumption, that the "self-enhancement evaporation mod" should be observed near to the cathode spot of a vacuum arch at all materials. In this region of the discharge, the plasma density is high and slow drops may evaporate completely.

The greatest acceleration of evaporation process should be expected for substances at presence both "high temperatures mode" with intensive thermionic emission and the "self-enhancement evaporation mod" simultaneously. It is visible in the figure, such substances are zirconium, tungsten, tantalum and titan.

For fusible substances, such as copper, gallium, aluminum and nickel, influence of the evaporated vapor ionization on the drop evaporation process occurs only at background plasma density more 10^{15} cm^{-3}.

For titan at $T_e < 7$ eV the drop temperature basically depends on heat removal by the evaporated atoms from a drop surface, and process of thermionic emission is not significant. Mod with intensive thermionic emission and the "self-enhancement evaporation mod" increasing drop temperature should operate for titan at $T_e > 7$ eV. In this case, both of modes operate in the range $n_0 = 10^{13} \div 10^{14}$ cm^{-3} typical for experiments presented in [7].

It is necessary to note, unlike model in [2, 7], in new model the stationary drop temperature depends on its radius as consequence of dependence of parameter α from radius.

4. Conclusion

The new theoretical model of metal drop evaporation in plasma vacuum arc is suggested.

Dependence of a stationary mode of heat exchange of the drop and plasma on drop radius, electronic temperature and substance of the cathode has been revealed.

The model predicts a new "self-enhancement evaporation mod". Evaporation process of the drop in plasma is accelerated at action of this mode.

The model allows estimating the parameters of plasma necessary for start of "self-enhancement evaporation mod".

It is necessary to solve a non-stationary problem for calculation of drop evaporation rate in the "self-enhancement evaporation mod".

References

[1] A.V. Batrakov, B.J. Juttner, S.A. Popov, D.I. Proskurovsky, and N.I. Vogel, Pis'ma Zh. Eksp. Teor. Fiz. **75**/2, 76 (2002).
[2] D.I. Proskurovsky, et al., IEEE Trans. Plasma Sci. **35**/4, 1052 (2007).
[3] R.L. Boxman and S. Goldsmith, J. Appl. Phys. **52**/1, 151 (1981).
[4] A.G. Gnedovets and A.A. Uglov, Teplofiz. Vys. Temp. **29**/6, 1184 (1991).
[5] Xi Chen, Ji Chen, Yandan Wang, J. Phys. D Appl. Phys. **27**, 1637 (1994).
[6] A. Anders, J. Appl. Phys. **82**/8, 3679 (1997).
[7] A.V. Kozyrev and A.N. Shishkov, Pis'ma Zh. Tekh. Fiz. **28**/6, 504 (2002).
[8] A.V. Kozyrev and A.G. Sitnikov, Pis'ma Zh. Tekh. Fiz. **34**/4, 313 (2008).