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Study of charge and temperature of copper particles, produced in the gas-plasma generator. II. Calculation of the charge.

The charge of copper particles, obtained in the gas-plasma generator is calculated. It is shown that the experimentally measured charge equals to sum of a particle charge and emitted electrons remaining near a particle surface.

The experimental data on the electric charge of hot copper particles are presented in the first part [1]. When calculating the charge, it is obviously necessary to consider the parameters of the surrounding medium, which determines the particle charge along with thermomission.

After interception from the wire the drop of copper under action of the surface tension gets spherical shape and is moving in plasma of the jet of the air-propane flame. For such flame the dependences on temperature and concentration of the ions is known, see Fig. 1, thus the Debye radius λ_D can calculated, which at the flame front is of the order of tenths of a micrometer, which is significantly higher than the mean free path $\lambda_{i(e)}$ of the charged particles in the flame, $\lambda_D >> \lambda_{i(e)}$. This gives reason to use the theory of particles charging in the diffusion regime [3]. Charge of the particle is defined by the electron I_e and ion I_i flows on its surface, and the thermoemissional one from the surface of I_{th} [4]:

$$I_i + I_{th} = I_e, \tag{1}$$

where:

$$I_i = 4\pi r^2 \left[n_i \mu_i \frac{d\varphi}{dr} + D_i \frac{dn_i}{dr} \right], \tag{2}$$

$$I_e = 4\pi r^2 \left[n_e \mu_e \frac{d\varphi}{dr} + D_e \frac{dn_e}{dr} \right], \tag{3}$$

$$I_{th} = 4\pi A (RT_s)^2 \exp\left(-\frac{W}{kT_s} \right) \cdot \begin{cases} 1, & \varphi_s < 0, \\ \left(1 + \frac{e\varphi_s}{kT_s} \right) \exp\left(-\frac{e\varphi_s}{kT_s} \right), & \varphi_s > 0. \end{cases} \tag{4}$$

Where: A – constant, for pure metal it is equal to $6 \cdot 10^5$ – 10^6 A/(m^{2}K^2); k – Boltzmann constant; r – radial coordinate, n_i and n_e – respectively concentration of the ions and the electrons; μ_i and μ_e – respectively mobility of the ions and the electrons; D_i and D_e – diffusion coefficients of the ions and the electrons, respectively; $\varphi = \varphi(r)$ – the electric potential of the particles; T_s – temperature of the particle surface; φ_S – electric potential in the vicinity of the particle; e – electron charge; W – work function of the particles from the surface (for copper about 4.55 eV); R – radius of the

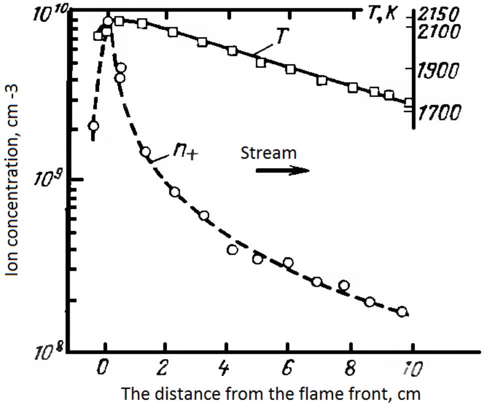

Fig. 1. *Some characteristics of air-propane flame. [2]*

particle; h – Planck's constant. Equations (1) and (2), (3) and (4) are supplemented by the Poisson equation

$$\nabla^2\varphi = -\frac{1}{\varepsilon\varepsilon_0} e(n_i - n_e) \tag{5}$$

and boundary conditions

$$\varphi(R) = \varphi_S, \quad \varphi(\infty)=0; \tag{6}$$
$$n_i(R) = n_e(R) = 0, \quad n_i(\infty) = n_e(\infty) = n_0 ,$$

where ε and ε_0 – dielectric permittivity and dielectric constant, respectively.

Furthermore, by motion of the particles in the air, the particle charge is defined similarly. Thermionic emission current is given by (4). As a result of the thermoemission, around the particle the space charge with the density $\rho = \rho(r) = e\cdot n_e(r)$.

At the surface of the particle electrons with spatial density ne cause a current to the particle surface $I_{ba} = 4\pi R^2 j_b$, with density

$$j_b = \frac{n_e v_e e}{4} . \tag{7}$$

The electron velocity v_e is given by

$$v_e = \sqrt{\frac{8kT_S}{\pi m_e}} , \tag{8}$$

where m_e – electron mass. In equilibrium, the currents of electrons from the surface and the surface of the particle are equal

$$I_{th} = I_{ba} . \tag{9a}$$

Dependence of the potential φ on the distance from the particle is described by the Poisson equation

$$\Delta\varphi = -\frac{1}{\varepsilon\varepsilon_0}\rho . \tag{9b}$$

In case of the equilibrium distribution, the electron density near the particle ρ(r) is determined by the Boltzmann equation

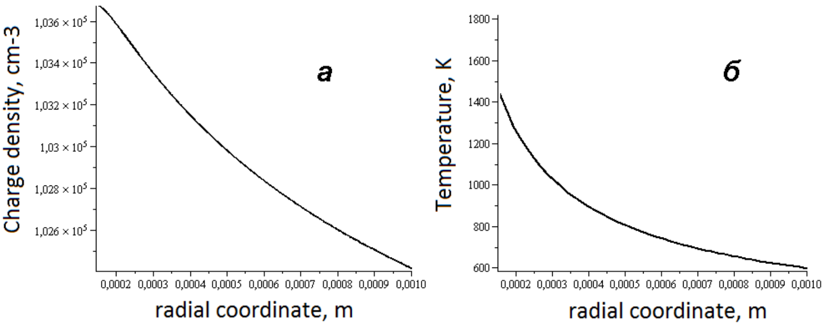

Fig. 2. *Calculated dependence of the charge density of the radial coordinate (a) and calculated dependence of the air temperature around the copper particle (b).*

$$\rho = C \exp\left(-\frac{e\varphi}{kT}\right) . \tag{10}$$

C – coefficient, which can be calculated from the boundary conditions

$$C = \rho_0 \exp\left(-\frac{e\varphi_S}{kT}\right) , \tag{11}$$

where ρ_0 – the charge density at the surface of the particles, the temperature of the surrounding gas $T = T(r)$. The boundary conditions for the electric potential for the convenience of calculation, can be selected [5]

$$\varphi\big|_{r=R} = 0 , \tag{12}$$

$$\varphi\Big|_{r=\infty} = \frac{q}{R} - \int \frac{\rho(r)}{r} dV , \tag{13}$$

where q – the charge of the particle. In (13) the integral is taken with respect to the volume around the particle. Additional condition of charge preservation

$$q = \int \rho(r) dV , \tag{14}$$

where the integral is taken with respect to the volume around the particle.

The solution of the system of equations (1) – (6) and (7) – (14) showed that the charge of the particle in the flame has a lower value than in the air. This is explained by the presence of free electrons in the plasma with higher mobility than the ions, and create an additional stream of charge on the particle surface [6], which is shown by equations (1) and (9).

One outcome of the solutions of equations (7) – (14) is the value of a positive charge of the copper particle with a surface temperature of 1475 K in air (equal to $4 \cdot 10^{-17}$ Cl), which up to experimental error corresponds to the measured value of the charge. In the calculation of the charge, the data on determining of the temperature field of a hot particle from [7] were used. Another result is the distribution of the electron density as a function of the radial coordinate, as shown in Fig. 2. Electron density at the surface of the particles was $1.04 \cdot 10^5$ cm^{-3}.

Obviously, by capturing the heated particle by the measuring device [1], in a Faraday cup the particle enters with its electronic "cloud". Herewith, the total charge

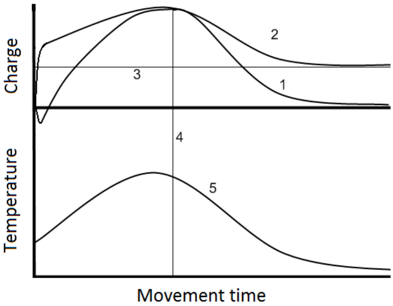

Fig. 3. *Qualitative understanding of the evolution of the particle charge in different environments.*

of the particle and its "cloud." is measured. Since the electrons of the "cloud", leaving the surface of the particles, make it positive charged (in absolute value, which is equal to the total electron charge of the "cloud"), it would be expected that the charge of the particle is zero. So it would be by moving in vacuum, where all the emitted electrons with termination of the thermoemission would return to the surface of the particle, as well as in the gas phase without presence of convection and particle motion in regard to the gas medium The relative motion of the gas medium and the particle leads to loss of the electrons of the "cloud" of the particle, so that the meter is captured the particle with a positive charge due to all of the emitted electrons, and the negative charge of the rest of the "cloud". I.e., not true charge of the particle but the total charge of the particle and the rest of the emitted electrons is measured. Obviously, this charge will depend on the relative velocity of the particle and the gas environment. Based on these ideas in Fig. 3 the evolution of the charge of the moving heated particle is presented. The total charge of the particle and the "cloud" the motion in the air, curve 1, and in vacuum, curve 2, respectively, would be approached asymptotically to a positive, line 3, and zero values (after crossing boundary between the plasma - gas medium line 4), as the temperature drops particles, curve 5. The two curves of the charge on the left from the line 4 show that the charge of the particle by motion in the plasma of the flame can be either positive or negative, depending on the degree of ionization of the flame, parameters of the material of the particle.

Thus, an assessment of the charge of the heated copper particle in the air was carried out. For the particle with the temperature of 1475 K the charge is equal to $4\cdot10^{-17}$ Cl. Herewith, the electron density at the surface of the particle was $1.04\cdot10^{5}$ cm^{-3}. The analysis of the charge transfer processes showed that the experimentally measured charge is not a true charge of the particle (charge, which is localized on the surface of the particle), but is a net charge of the particle and the residue of emitted electrons from the particle carried along with it.

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Семенов К.І.

Вплив дифузійно-дрейфової нестійкості межі утворення к- фази у поверхні нагрітої макрочастинки на її заряд. II. Розрахунок заряду.

АНОТАЦІЯ

Приведено розрахунок заряду частинок міді, отриманих в газоплазмовому генераторі. Показано, що експериментально вимірюваний заряд не є дійсним зарядом частки, а є сумарним зарядом частки і залишку емітованих електронів.

Семенов К.И.

Исследование температуры и заряда частиц меди, получаемых в газоплазменном генераторе. II. Расчет заряда.

АННОТАЦИЯ

Приведен расчет заряда частиц меди, полученных в газо-плазменном генераторе. Показано, что экспериментально измеренный заряд является суммой зарядов частицы и остатка эмитированных электронов вблизи её поверхности.