EXPERIMENTAL RESEARCH OF THERMOEMISSION CHARGING OF METAL PARTICLES[1]

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Original experimental methods of thermoemission charge determination of a spherical metallic particle surrounded by the condensed disperse phase are proposed. The analytical dependence of the particle charge on time is found, and its relaxation time is determined.

The importance of the research of the characteristics of particles at high temperatures is defined by their presence in great amounts in various natural and technical processes such as the burning of solid fuels containing metals, lightning blows at metallic objects, etc. In [1–6], the methods of calculation and the results of measurements of a charge of high-temperature metallic particles are presented. The results of studies of the thermoemission charging of particles are given in [7, 8].

Here, we propose original experimental methods of determination of a thermoemission charge on a spherical metallic particle surrounded by the condense disperse phase (CDP). The experimental dependence of the charge of a particle surrounded by CDP on its temperature in air is determined.

The analytical solution of the equation descrinbing the thermoemission charging of a spherical particle surrounded by CDP is obtained as the dependence of the particle charge on time in the positive and negative regions.

The obtained solution gives a possibility to find the relaxation time of a particle charge in the conformity with experimental values.

The experimental facility is represented in Fig. 1. The * particles researched were obtained in an impulse electric–arc generator of monodisperse particles *1* which is described in [2]. The generator was connected which power block *2*. The power block was joined to electric mains by means of separating transformer *3* (with the aim of safety while working with the generator). The generated particle moves in the volume of hermetic jar *4* which has the form of a parallelepiped. The jar had a transparent wall for observing the movement of the particle and measuring the particle temperature with the help of a pyrometer. Parallel walls of the jar covered with a thin metallic layer are covers of a flat condenser. A homogeneous electrostatic field appears between the layers, while a high voltage from high–voltage generator *6* connected with power block *7* is applied to them. A high voltage was determined with electrostatic voltmeter *5*. To study the thermoemission charging of a particle in nitrogen medium, jar *4* was filled with nitrogen beforehand. Nitrogen was transferred from jar *8* along a gas main which had regulator *9* and a meter of gas expenses *10*. The gas passed through water lock *11*. For filling jar *4* with nitrogen, moving partition *12* was used. It was lifted with lifting mechanism *13*. The lifting velocity of the partition guaranteed the filling of the whole volume of the jar with nitrogen. Partition *12* had valve *15* which can be opened with the help of stop *14*. This valve guaranteed the movement of a particle in the vertical direction. The generator of particles *1* and microscope *17* are situated on lid *16*. Microscope *17* was used in order to drive the movement of electrodes during

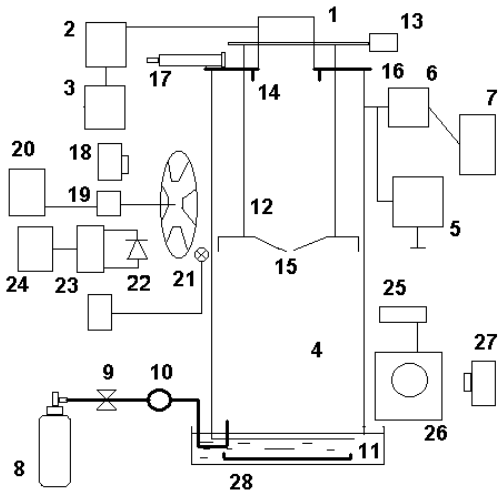

Fig. 1. Experimental facility

[1]The results of the work were reported at the 2nd International Conference "Dusty Plasmas in Applications" (August 26–30, 2007, Odesa, Ukraine).

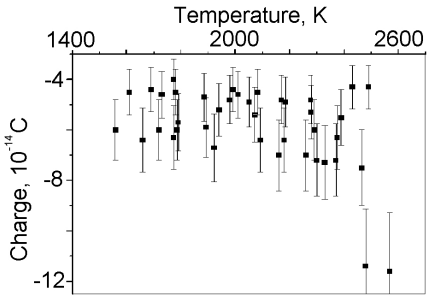

Fig. 2. Experimental dependences of the charge on a particle of tungsten

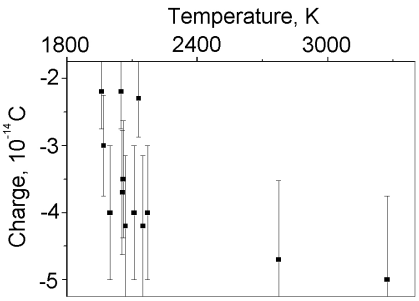

Fig. 3. Experimental dependence of the charge on a particle of molybdenum

the generation of particles. The trajectory of the movement of a particle was fixed with camera (Kiev-15) *18* with the help of chopper *19*, the engine of which was connected with current source *20*. The closing frequency of a camera objective with a chopper was measured with the help of a facility consisting of lamp *21*, photodiode *22*, comparator *23*, and frequency meter *24*. The frequency meter indicated the opening frequency of the objective. The experimental method of definition of a particle charge, applied in the given work, was based on the deviation of particles in the electrostatic field formed by vertical metal plates [1]. For the determination of a charge, the photo of a particle trajectory which was produced with the help of a turning chopper was used. Beside that, the equation of motion of a charged particle under the action of the gravity force and the force of a homogeneous electrostatic field was used. The equation was represented in finite differences [1]. The luminous trace of a moving particle was recorded with particle radiation pyrometer *25*, a signal from which passed toward storage memory oscilloscope *26*. The oscillogram was fixed with camera *27*. The particle was extracted with substrate *28*. The particle radius which was necessary for the calculation of the charge and temperature of a particle was measured after extraction.

It is known [9] that an external electrostatic field initiates the particle charging under the ion bombardment. The particle is in the region of a space charge (here, it is a cloud space charge of CDP). Under this condition, an equilibrium charge on the particle is determined by the expression

$$Q = 12\pi\varepsilon_0 E_0 R^2. \quad (1)$$

In this situation, the intensity of the electrostatic field between the plates of a flat capacitor E_0 is approximately 10^4 V/m. In such a field, according to (1), a particle gets a charge of 10^{-16} C, which is by an order of magnitude less than the thermoemission charge which is measured.

The electric charge of a particle which is formed, in particular, as a result of thermoemission from the particle itself and thermoemission from CDP which surrounds it. As the experimental researches showed, CDP is formed near warmed particles of metals and consists of nanodispersed particles of oxides of these metals. For example, CDPs which are formed around warmed particles of tungsten (W) and molybdenum (Mo) consist, respectively, of WO_2 and MoO_3. Let's denote the particle temperature by T_1 and the maximum temperature of the stable existence of CDP by T_2. For CDP of WO_2, $T_2 = 2000$ K; and, for CDP of MoO_3, $T_2 = 1613$ K [10]. At much higher temperatures, CDP is destroyed.

Under certain conditions, when the work function of an electron from a particle A_1 is more than that of an electron from the particles of CDP A_2, a metal particle can get a negative charge as the stream of a negative charge from CDP to a particle is more than the electron flow from the particle. Figure 2 shows the experimental dependences of the charge Q on a particle of tungsten (W) with the radius $r = 122$ μm, $A_1 = 5$ eV, $A_2 = 4.96$ eV on its temperature. Figure 3 represents similar dependences for molybdenum particle with the radius $r = 127$ μm, $A_1 = 4.3$ eV, and $A_2 = 4.25$ eV [11]. The experimental researches of the thermoemission charging of metallic particles in the nitrogen medium have a preliminary character. In Fig. 4, the photo of a moving warmed metallic particle surrounded with CDP is given. While describing the process of thermoemission charging of a spherical metal particle, we use the method of boundary sphere [1–6, 12–22]. In the region of negative charge of a spherical metallic particle surrounded with CDP, the

equation describing the thermoemission charging has the form [1, 5]

$$\frac{dQ}{dt} = 4\pi r^2 A T_2^2 \left[1 - \frac{\Psi(Q)}{\overline{v}_{O_2}}\right] P_2 -$$

$$-4\pi r^2 F(Q) A T_1^2 P_1 \exp\left[-\frac{\Delta A_1}{kT_1}\right], \quad (2)$$

where A is the Richardson–Deshman constant,

$$P_1 = \exp\left(-\frac{A_1}{kT_1}\right),$$

$$P_2 = \exp\left(-\frac{A_2}{kT_2}\right).$$

The first term on the right-hand side of (2) defines the flow of negative ions of oxygen O_2 from CDP to the surface of a spherical particle with radius r . The mean velocity of O_2, $\overline{v}_{O_2} = \left(\frac{8kT_2}{\pi m_{O_2}}\right)^{1/2}$. The function $\Psi(Q)$ takes the deceleration of the flow of O_2 inside the kinetic zone into account. It was derived in [13] as

$$\Psi(Q) = \frac{el_1}{(2m_{O_2}kT_2)^{1/2}\pi^{3/2}\varepsilon_0 r^2} M, \quad (3)$$

where

$$M = \left(Q^{1/2} - \frac{re^{1/2}}{2l_1}\right)^2,$$

m_{O_2} — is the mass of O_2, k is the Boltzmann constant, and ε_0 is the electric constant. When the temperature of a particle is T_1, the kinetic zone width $l_1 = l_0(T_1/T_0)$, where l_0 is the kinetic zone width at the temperature $T_0 = 273$ K . The second term on the right-hand side of (2) defines the flow of electrons from the surface of a particle. The coefficient $F(Q)$ defines a decrease of the flow of electrons from the surface of a particle due to their elastic scattering, at which a part of electrons returns to a particle. This coefficient is a function of the negative charge of a particle. The analytical expression for $F(Q)$ is derived in [13], where it was shown that $F(Q)$ varies from its minimal value equal to 0.645 to the maximal value equal to 1. In the subsequent calculations, we take $F(Q) = F$ as a constant value accepting these extreme numerical values in turn. A reduction of the work function of an electron from the surface of a particle carrying a negative charge is defined by the Schottky effect [23]: $\Delta A_1 = \frac{Q^{1/2}e^{3/2}}{4\pi\varepsilon_0 r}$. Under our conditions, the negative charge of particles $Q \sim 10^{-13}$ C. The lowering of the work function of an electron under these conditions caused by the Schottky effect is 0.01 eV. This value is lower than the error of the measurement of the work function of an electron from a particle. So, the neglect of ΔA_1 under these conditions is fully justified.

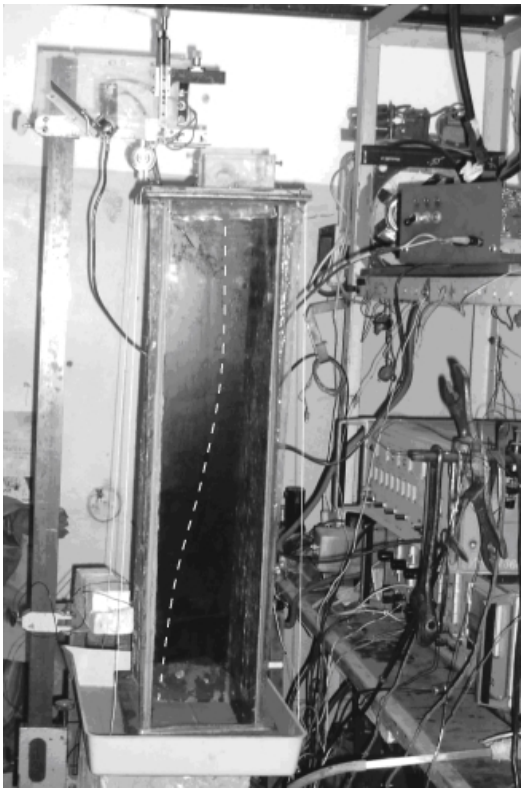

Fig. 4. Photo of a moving warmed metallic particle

We now find the dependence of the charge of a spherical metallic particle on the time t, when the temperature of the particle T_1 is fixed.

For the negative charge of a particle, whose value satisfies the inequality $0 < Q < \frac{er^2}{4l^2}$, the resulting field near the particle will be the field of attraction [1]. In this case, $\Psi(0) = 0$. The equation for the charging has the form

$$\frac{dQ}{dt} = 4\pi r^2 A T_2^2 P_2 - 4\pi r^2 F(Q) A T_1^2 P_1. \quad (4)$$

Let us assume that $F(Q) = 1$. In this case, the thermoemission current from the surface of a particle will be of maximum value. The difference between the current of a charge from CDP to the particle and the current of a charge from the particle will be minimum.

The time of the charging of the particle will reach the maximum value. When the temperature of the particle T_1 is fixed, the thermoemission current from its surface will be constant. The time of reaching the negative charge of a particle $Q = \frac{er^2}{4l_1^2}$ is given by the formula

$$t = \frac{er^2}{16\pi r^2 l_1^2 A\left(T_2^2 P_2 - T_1^2 P_1\right)}. \tag{5}$$

If the particle temperature drops from T_1 to T_2, we replace T_2 by T_1 in relation (5). For the negative charge of a spherical particle $Q \geq \frac{er^2}{4l_1^2}$ under condition when $F(Q) = 1$ and $\Delta A_1 = 0$, Eq. (2) takes the form

$$\frac{dQ}{dt} = 4\pi r^2 A T_2^2 \left[1 - \frac{\Psi(Q)}{\bar{\upsilon}_{O_2}}\right] P_2 - 4\pi r^2 A T_1^2 P_1. \tag{6}$$

We integrated the equation under the initial condition $t = 0$ and $Q = \frac{er^2}{4l_1^2}$. The dependence of the particle charge Q on the time t has the form

$$t = C_1 \ln\left[\frac{T_2^2 P_2 - T_1^2 P_1}{T_2^2 P_2 [1 - LM] - T_1^2 P_1}\right] +$$

$$+C_2 \ln\left[\frac{L^{-1/2}\left(1 - T_1^2 P_1 \left(T_2^2 P_2\right)^{-1}\right)^{1/2} + M^{1/2}}{L^{-1/2}\left(1 - T_1^2 P_1 \left(T_2^2 P_2\right)^{-1}\right)^{1/2} - M^{1/2}}.\right] \tag{7}$$

Here, the following notations are used:

$$L = \frac{el_1}{4\pi k T_2 \varepsilon_0 r^2},$$

$$C_1 = \frac{k\varepsilon_0}{el_1 A T_2 P_2},$$

$$C_2 = \left[\frac{k\varepsilon_0}{16\pi l_1^3 A^2 T_2 P_2 \left(T_2^2 P_2 - T_1^2 P_1\right)}\right]^{1/2}.$$

If the temperature of the particle T_1 drops down to T_2, we will use T_1 instead of T_2 in relation (7). The equation describing the thermoemission charging of a positive charged metallic particle surrounded by CDP is obtained in work [1] as

$$\frac{dQ}{dt} = 4\pi r^2 F A T_1^2 P_1 \exp\left[-\frac{Qe}{4\pi\varepsilon_0 r k T_1}\right] - 4\pi r^2 A T_2^2 P_2. \tag{8}$$

If the coefficient on the right-hand side of the equation is $F = 0.645$, the charge current from the particle will be minimum, and the time of its charging will be maximum. The given equation was integrated under the initial condition $t = 0$ and $Q = 0$. The dependence of the charge of a particle on the time has the form

$$t = \frac{\varepsilon_0 k T_1}{erAT_2^2 P_2} \ln \frac{FT_1^2 P_1 - T_2^2 P_2}{FT_1^2 P_1 - T_2^2 P_2 \exp\left(eQ/4\pi\varepsilon_0 r k T_1\right)}. \tag{9}$$

Values T_1 will be used instead of T_2 In relation (9), we will use T_1 instead of T_2 if the temperature of a particle falls down to T_2.

The dependence of the equilibrium charge of a particle surrounded with CDP on its temperature in the positive and negative regions was obtained in work [1].

The calculations showed that the time of the accumulation of nine tenths of the equilibrium charge by a particle under conditions of our experiment ($T_1 \sim$ 2000 K, $R \sim 100 - 200$ μm) $\tau \sim 10^{-6}$–10^{-7}s. The value of τ is significantly less than the existence time of the particle in the measuring capacitor (this time is approximately one second). The rate of cooling of the particle $\frac{\Delta T_1}{\Delta t} \sim 10^4$ K s^{-1}. During the time τ, the temperature of the particle is not practically changed. The fact allows us to consider the experimental values of a charge given in this work as equilibrium ones.

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ЕКСПЕРИМЕНТАЛЬНЕ ДОСЛІДЖЕННЯ ТЕРМОЕМІСІЙНОГО ЗАРЯДЖАННЯ МЕТАЛЕВИХ ЧАСТИНОК

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Р е з ю м е

У роботі запропоновано оригінальний експериментальний метод визначення термоемісійного заряду сферичної металевої частинки, оточеної конденсованою дисперсною фазою. Одержано аналітичну залежність заряду частинки від часу. Знайдено час релаксації заряду.