t, temperature; m, particle mass; g, acceleration of gravity; F_r, aerodynamic resistance force; η, ν, dynamic and kinematic viscosities of gaseous medium; r, particle radius; Pr, Prandtl number; c, specific heat; σ, Stefan–Bolzmann constant; ε, emissivity of particle surface; λ, gas thermal conductivity; γ, gas density; R, radius of substrate cylinder; H, height of substrate cylinder; T_{eff}, effective temperature; χ, thermal diffusivity; T, temperature; ρ, z, cylindrical coordinates; r_s, radius of contact spot between droplet and substrate; n, normal vector; T_{Cu}, T_{Mo}, temperatures of copper and molybdenum particles.

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LIMITING PARTICLE CHARGE FOR ELECTRIFICATION IN A CORONA DISCHARGE FIELD

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An experimental study is performed of electrification of objects from a dielectric fluid within a corona discharge field. Use of jet monodispersion permits comparison of data on charging of a cylindrical surface and spherical particles, elimination of the effect of dynamic factors, refinement of the electrification mechanism and limiting charge value. It is shown that aside from other factors, the limiting charge is defined by the cross sectional area of the electrified object, and is approximately 30% less than previously accepted values.

A most important factor in electron–ion and droplet jet technology is the study of conditions for electrification of material and the physical processes which accompany this phenomenon. One of the most studied and widely used methods is charging of material in the field of a corona discharge [1]. This method is universal in the sense that it can be applied to both conductive and dielectric materials.

Depending on the dimensions of the particles being charged, the physical kinetics of charging under corona conditions can be described by two different methods: for particles with diameter $\leqslant 1$ μm the major role is played by diffusion charging, while for particles with diameter $\geqslant 10$ μm shock ionization dominates, in accordance with which the particle charging dynamics are described by the equation

$$q(t) = q^* \frac{en_0kt}{4\varepsilon_0 + en_0kt}.$$

In this expression the value of the limiting particle charge q* plays a most important role, since it in fact determines the efficiency of device operation. The widely accepted method of determining q* is based on the condition of equality to zero of the field intensity on the surface of the particle turned toward the corona electrode:

$$\mathbf{E}_c + \mathbf{E}_p + \mathbf{E}_q = 0,$$

where $\mathbf{E}_c$ is the field intensity of the corona discharge; $\mathbf{E}_p$ is the polarization component of the field; $\mathbf{E}_q$ is the field of the charges deposited on the surface.

To determine $\mathbf{E}_p$ it was assumed that particle electrification occurs with a uniform distribution of the accumulating charge over the surface and the value of the charge is such that the field created by this charge at all points of the surface corrsponds to the highest intensity. Based on this, the maximum charge of a conductive spherical particle, for example,

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can be determined from the condition $3E_c - q^*/4\pi\varepsilon_0 R^2 = 0$. In determining E_c we assume that within the limits of the jet or droplet diameter the external field is homogeneous. This condition is also extended to the dielectric. It is assumed that on the spherical dielectric particle an initially nonuniform charge distribution over the surface leads to disordered rotation of the particle due to the leverage effect of electrostatic forces, which is the basis of the assumption of final uniformity of the charge distribution, and in such a situation charging dynamics are described by the expression

$$q(t) = q_j^* F(t) = 4\pi R_d^2 \varepsilon_0 E_c \left(1 + 2\frac{\varepsilon_\ell - 1}{\varepsilon_\ell + 2}\right) F(t).$$

We write the expression for charging of an infinite dielectric cylinder in the form

$$q(t) = q_j^* F(t) = 2\pi\varepsilon_0 R_j \lambda E_c \frac{2\varepsilon_\ell}{\varepsilon_\ell + 1} F(t).$$

Commencing from this, we compare the efficiency of using a corona discharge for charging of a jet and a sequence of monodispersed droplets formed therefrom.

The experimental stand on which the studies were performed was described in detail in [2], while among the unique features of the experimental technique we may note the fact that to improve accuracy the position of the corona electrodes and the jet relative to the electrodes were maintained constant. The objects being electrified were changed since at some moment in time oscillations of a certain frequency formed on the jet surface and the latter decayed into monodispersed droplets [3]. Comparison of removal currents for ion beam irradiation of a jet and a droplet sequence of identical diameter permits some conclusions as to charging dynamics. As was shown in [4], for monodispersed decay of a cylindrical jet the surface area ratio

$$S_j/S_d = 0{,}76 \sqrt[3]{\frac{\lambda}{D_j}}.$$

Performing a precise calculation with consideration of the expressions presented above, we obtain

$$I_j/I_d = q_j/q_d = \frac{2}{3}\sqrt[3]{\frac{4}{9}}\left(\frac{\varepsilon_\ell + 2}{\varepsilon_\ell + 1}\right)\sqrt[3]{\frac{\lambda}{D_j}}.$$

With consideration of the dielectric constant of the vacuum oil used as the working liquid, for jet diameters $D_j' = 0.375$ mm and $D_j'' = 0.295$ mm over a wide escape velocity range the calculated ratios for removal currents are equal to

$$(I_j/I_d)' = 0{,}93\sqrt[3]{\lambda} \text{ and } (I_j/I_d)'' = 1{,}01\sqrt[3]{\lambda}. \quad (1)$$

Figure 1 shows experimental data and corresponding theoretical curves. Comparison will show obvious divergence which exceeds the experimental uncertainty (~1%).

To analyze this divergence we will evaluate the assumptions made in deriving the removal current ratio for a jet and droplet train. We will define the correction needed to refine the voltage on the charged cylinder surface for a field calculated with the assumption of an infinite stream and constant surface charge density. If the rate of motion of surface charge along the jet is significantly less than the escape velocity (which the experiemnts performed confirm), then the charge acquired by an uncharged jet upon its entrance into ion current region will be carried along the jet with a gradual increase in surface charge density to an amount determined by the highest external field value. It is obvious that the point of highest external field intensity E_c will be point A of Fig. 2. We assume that this point is a boundary: thereabove the linear charge density changes by a linear law

$$\tau(\eta) = \tau\left(\frac{\eta}{l} + 1\right),$$

where η is an integration variable, $-l \leqslant \eta \leqslant 0$, and for $\eta > 0$ $\tau(\eta) = \tau$, τ is the linear charge density, a constant quantity.

The problem can then be formulated in the following manner: we must determine the field intensity on the surface of a semiinfinite cylinder of radius R_j with varying linear surface charge density.

We replace the cylinder by a linear charge with the same distribution and find the field potential at the point A(0, a − R, 0) [5]:

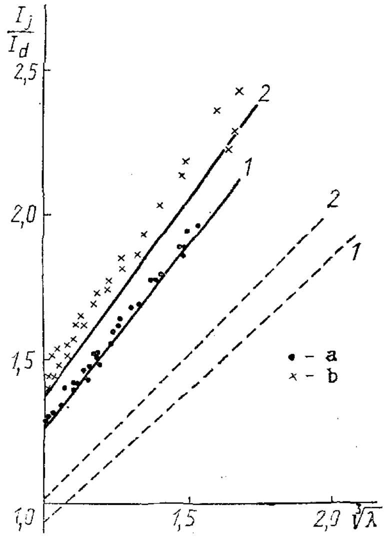

Fig. 1

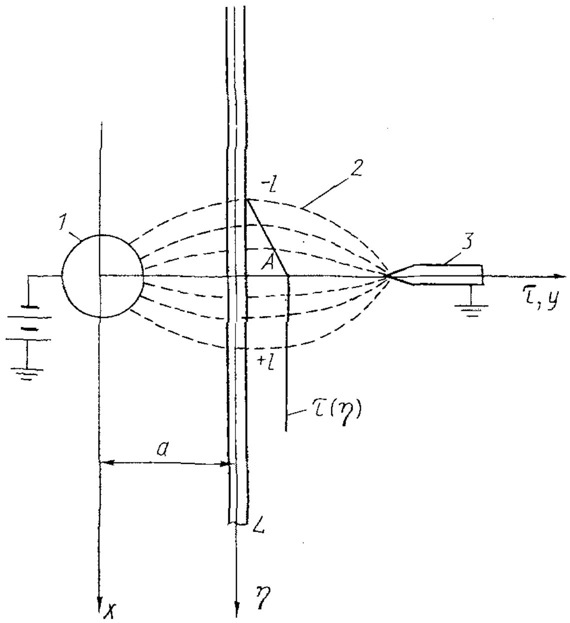

Fig. 2

Fig. 1. Efficiency of charging of jet I_j compared to charging of droplet flow I_d vs wavelength of surface excitation for monodispersed decay: a) experimental data for 0.295 mm diameter jet; b) same, 0.375 mm; 1, calculated values for 0.375 mm diameter jet; 2, same, 0.295 mm; dashed lines, calculation by limiting charge [1]; solid, calculation by method proposed in present study.

Fig. 2. Schematic representation of the conditions of electrification of the jet and the interelectrode space: 1) spherical electrode; 2) outer boundary of the field; 3) corona electrode.

$$U = \frac{1}{4\pi\varepsilon_0}\int_{-l}^{L}\frac{\tau(\eta)\,d\eta}{r}.$$

We denote by r the distance from a point on the linear charge to an arbitrary point of space M(x, y, z):

$$U = \frac{1}{4\pi\varepsilon_0}\int_{-l}^{L}\frac{\tau(\eta)\,d\eta}{\sqrt{(x-\eta)^2+(y-a)^2+z^2}} =$$

$$= \frac{\tau}{4\pi\varepsilon_0}\left\{\int_{-l}^{0}\frac{(\eta/l+1)\,d\eta}{\sqrt{(x-\eta)^2+(y-a)^2+z^2}}+\int_{0}^{L}\frac{d\eta}{\sqrt{(x-\eta)^2+(y-a)^2+z^2}}\right\}.$$

Integration yields the following expression for the potential:

$$U = \frac{\tau}{4\pi\varepsilon_0}\left\{-\frac{x}{l}\ln\frac{x+\sqrt{x^2+(y-a)^2+z^2}}{x+l+\sqrt{(x+l)^2+(y-a)^2+z^2}}+\right.$$

$$\left.+\frac{1}{l}\left(\sqrt{x^2+(y-a)^2+z^2}-\sqrt{(x+l)^2+(y-a)^2+z^2}\right)-\ln\frac{x-L+\sqrt{(x-L)^2+(y-a)^2+z^2}}{x+l+\sqrt{(x+l)^2+(y-a)^2+z^2}}\right\}.$$

Considering that the external field intensity E_c and the incident ion current are orthogonal to the jet at point A, we seek only one component of the field intensity of the charged jet:

$$E_y = -\frac{\partial U}{\partial y} = -\frac{\tau}{4\pi\varepsilon_0}\left\{-\frac{x}{l}\frac{x+l+\sqrt{(x+l)^2+(y-a)^2+z^2}}{x+\sqrt{x^2+(y-a)^2+z^2}}\times\right.$$

$$\times (y-a)\left\{\left[\frac{x+l+\sqrt{(x+l)^2+(y-a)^2+z^2}}{\sqrt{x^2+(y-a)^2+z^2}}-\right.\right.$$

$$\left.\left.-\frac{x+\sqrt{x^2+(y-a)^2+z^2}}{\sqrt{(x+l)^2+(y-a)^2+z^2}}\right]\right\}\{x+l+\sqrt{(x+l)^2+(y-a)^2+z^2})^2\}^{-1}+$$

$$+\frac{(y-a)}{l}\left[\frac{1}{\sqrt{x^2+(y-a)^2+z^2}}-\frac{1}{\sqrt{(x+l)^2+(y-a)^2+z^2}}\right]+$$

$$+(y-a)\left\{\frac{x-L+\sqrt{(x-L)^2+(y-a)^2+z^2}}{\sqrt{(x+l)^2+(y-a)^2+z^2}}-\frac{x+l+\sqrt{(x+l)^2+(y-a)^2+z^2}}{\sqrt{(x+L)^2+(y-a)^2+z^2}}\right\}\times$$

$$\left.\times\{(x+l+\sqrt{(x+l)^2+(y-a)^2+z^2})\ (x-L+\sqrt{(x-L)^2+(y-a)^2+z^2})\}^{-1}\right\}.$$

For the point A with coordinates (0, a + R, 0) the expression simplifies:

$$E_y=-\frac{\tau}{4\pi\varepsilon_0}\left\{\frac{1}{l}\left[1-\frac{R}{\sqrt{l^2+R^2}}\right]+R\frac{\dfrac{-L+\sqrt{L^2+R^2}}{\sqrt{l^2+R^2}}-\dfrac{l+\sqrt{l^2+R^2}}{\sqrt{L^2+R^2}}}{(l+\sqrt{l^2+R^2})(-L+\sqrt{L^2+R^2})}\right\}.$$

For simplification we take $\ell = L$:

$$E_y=-\frac{\tau}{4\pi\varepsilon_0}\left\{\frac{1}{l}\left[1-\frac{R}{\sqrt{l^2+R^2}}\right]+\frac{-2l}{R+\sqrt{l^2+R^2}}\right\}.$$

As $l\to\infty$ $E_y\to\tau/2\pi\varepsilon_0 R_j$, i.e., we obtain an expression for an infinite charged filament.

For the concrete geometric parameters R_j = 0.1875 mm and ℓ = 3 mm

$$(E_y^*)'=\frac{\tau}{4\pi\varepsilon_0}\,10{,}333=5{,}17\,\frac{\tau}{2\pi\varepsilon_0};\ (E_y)'=\frac{\tau}{2\pi\varepsilon_0 R}=5{,}33\,\frac{\tau}{2\pi\varepsilon_0}.$$

Thus, the refined value of the charged filament field yields an increase in the coefficient of the slope of the straight line in Eq. (1) to the values 0.96 and 1.04, which confirms the validity of the correction.

We will now evaluate the error produced by the assumption of homogeneous E_c on the jet surface and the droplets formed therefrom. If we consider that the position of these objects relative to the electrodes is fixed, change in surface intensity of the external field is possible due to its strong inhomogeneity and the difference in the radii of the cylinder and spherical droplets.

From the condition of conservation of mass upon transformation from jet to droplets, which is natural, since the vapor pressure of vacuum oil is quite low, the droplet radius is related to the jet radius:

$$R_d=R_j\sqrt[3]{\frac{3\pi}{2\varkappa}}.$$

For the value $\kappa = 0.6$, $R_d = 1.99R_j$.

Electrification in an ion discharge field was accomplished in the near field of a potential spherical electrode. An estimate made with consideration of the concrete geometry yields a minimum reduction in the field for transition from a cylinder to a sphere of 4-5%. This leads to a corresponding increase in the removal current ratio to values $(I_j/I_d)' = 1.00$, $(I_j/I_d)'' = 1.08$. Thus, consideration of both corrections permits generalization of experimental data with less error, but does not completely correspond to the physical essence of the charging process.

We will assume that the charge surface mobility is so low that over the time it is located in the corona field, of the order of $(0.5\text{-}1.0)\cdot 10000^{-3}$ sec, the charge does not "spread," remaining on the portion of the surface directed toward the corona electrode. Moreover, during flight particles are not "levered," do not rotate, etc. Then, in accordance with the well-known solution of [6] the potential on the surface and outside the dielectric sphere is

$$\varphi=-\mathbf{E}_c\mathbf{r}+R^3\frac{\varepsilon_\ell-1}{\varepsilon_\ell+2}\frac{1}{r^3}\mathbf{E}_c\mathbf{r},$$

where r is the radius vector directed from the center of the sphere. The surface polarization charge density distribution is equal to

$$\sigma = \varepsilon_0 \left(-\frac{\partial \varphi}{\partial r} \right) = E_c \cos\Theta \left(1 + 2 \frac{\varepsilon_\ell - 1}{\varepsilon_\ell + 2} \right).$$

Integration over the surface turned toward the ion flux yields

$$q_d^* = \varepsilon_0 \pi R_d^2 E_c \left(1 + 2 \frac{\varepsilon_\ell - 1}{\varepsilon_\ell + 2} \right).$$

The analogous expression for a cylindrical surface is:

$$q_j^* = \varepsilon_0 \lambda D_j E_c \frac{2\varepsilon_\ell}{\varepsilon_\ell + 1}.$$

The condition for limiting charge in a corona discharge field, equality to zero of the total field on the surface, is then realized upon compensation of the surface polarization charge by charge acquired due to irradiation by corona discharge ions. With consideration of the correction for the finite size of the charged portion of the jet and field inhomogeneity the ratios of these quantities are given by $(I_j/I_d)' = 1{,}27\sqrt[3]{\lambda}$ and $(I_j/I_d)'' = 1{,}38\sqrt[3]{\lambda}$. Comparison with the experimental data shows good agreement.

Figure 3 shows data recalculated in the dimensionless coordinates I_d/I_j and $\varkappa = 2\pi R_j/\lambda$. A characteristic feature of the graph is the merger of curves 1, 2 (Fig. 1) into a single dependence.

Thus, comparison of experimental results with theoretical estimates demonstrates the suitability of the assumptions made in determining the value of limiting charge acquired in the corona discharge field by spherical and cylindrical objects. This means that the dominant factor in electrification of particles is their cross section, and not their surface area, as was previously assumed. The surface charge acquired is distributed nonuniformly, and the efficiency of electrification must be evaluated relative to the limiting charge:

for spherical particles

$$q_d^* = A_d \varepsilon_0 \pi R_d^2 E_c \left(\frac{3\varepsilon_\ell}{\varepsilon_\ell + 2} \right);$$

for a cylindrical surface of length λ

$$q_j^* = A_j \varepsilon_0 \lambda D_j E_c \left(\frac{2\varepsilon_\ell}{\varepsilon_\ell + 1} \right).$$

NOTATION

e, electronic charge; n_0, ion flux density in discharge gap; k, ion mobility; $\varepsilon_0 = 8.85 \cdot 10^{-12}$ F/m; ε_ℓ, dielectric constant of fluid; λ, wavelength; f, excitation frequency; v_j, jet escape velocity; τ, linear charge density; q*, limiting charge acquirable by particle in corona field; R, radius; A, coefficient considering external field inhomogeneity. Subscripts: d, droplet; j, jet.

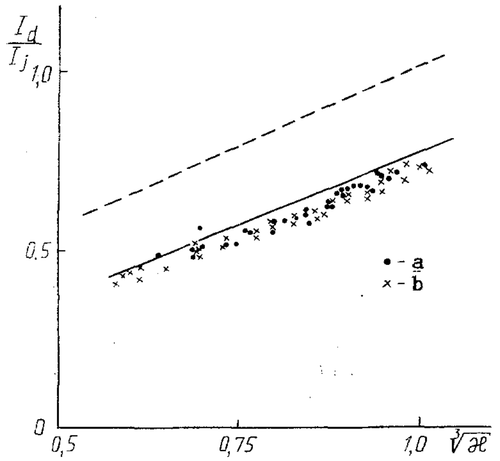

Fig. 3. Comparison of experimental data and theoretical charging efficiency I_d/I_j as function of wave number $\varkappa = 2\pi R_j/\lambda$; a, experimental data for 0.295 mm diameter jet; b, same, 0.375 mm; dashed line, calculation for limiting charge [1]; solid line, calculation by method proposed herein.

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THE MECHANISM OF CORONA DISCHARGE FROM A WATER DROPLET

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A model is proposed for electrical discharge from a water droplet, which explains the experimentally observed formation of a sharp projection at the top of the droplet and emission therefrom of highly dispersed charged droplets and ions.

1. The first studies of electrical discharge from a water droplet were performed at the start of this century [1]. After the appearance of [2] such a discharge was termed "corona," although from the data obtained in [2] it follows that such a term is incorrect (which was noted in [3]). This incorrect terminology has led to the treatment of the still incompletely studied mechanism of discharge from a water drop from the viewpoint of conventional corona discharge from a metallic point [4]. Meanwhile the study of the real mechanism of discharge from a drop of electrically conductive liquid is of significant interest because of its applications in various physical and technical problems: from power generation [4] and study of the mechanisms of explosive emission and electrode erosion in high power arcs [5] to the theory of natural storm electricity [6]. The present study was undertaken to meet this need.

It is well known that in a sufficiently intense electric field a water drop first extends into an ellipsoid of revolution oriented along the field [7], after which sharp projections appear at the ends, from which highly dispersed droplets which flow weakly in darkness are emitted [1-4, 6, 8]. The dimensions of these droplets decrease with increase in field, and finally at a sufficiently high field, droplet emission is replaced by emission of ions [1, 6, 8]. The visual characteristics of a discharge from a water drop very much recall a corona discharge from a metal point. This is evident from Figs. 1 and 2. The external similarity of the two processes is obvious. But careful examination of experimental data on the discharge from a water drop [1-4, 6, 8] shows that it cannot be identified with the discharge from the metal point: their mechanisms differ. But before discussing the mechanism of the drop discharge we should first consider the question of why the sharp projections from which the discharge commences appear upon the drop.

The classical studies of Tonks [9] and Taylor [10] on this question did not in fact provide an answer. Tonks showed that formation of such projections is possible, or to speak more precisely, does not contradict known physical laws. Taylor simply postulated existence of equilibrium projections of strictly conical form with aperture angle of the cone constant for a given liquid, and commencing from this postulate, sought the external field at which existence of that form was possible. And apparently, he was incorrect. Careful examination of available photographs of such projections, including those cited by Taylor [8, 10-13], shows that their form is not precisely conical, but is more like a half of a pseudosphere [14]: aside from the close vicinity of the top itself, the Gaussian curvature of the projection is negative everywhere. This is especially evident in the photograph

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