6. A. I. Grigor'ev and S. O. Shiryaeva, Zh. Tekh. Fiz., 59, No. 5, 6-13 (1989).
7. A. I. Grigor'ev, S. O. Shiryaeva, and E. I. Belavina, Zh. Tekh. Fiz., 59, No. 6, 27-34 (1989).
8. A. I. Grigor'ev and S. O. Shiryaeva, Izv. Akad. Nauk SSSR, Mekh. Zhidk. Gaza, No. 2, 5-15 (1988).
9. L. Tonks, Phys. Rev., 48, 562-568 (1935).
10. G. Taylor, Proc. R. Soc. London, A280, 383-397 (1964).
11. A. Wagner and T. M. Hall, J. Vac. Sci. Techn., 16, No. 6, 1871-1874 (1979).
12. J. J. Nolan, Proc. Irish Acad., A37, 28-39 (1926).
13. G. A. Ostroumov, Interaction of Electric and Hydrodynamic Fields [in Russian], Moscow (1979).
14. A. V. Pogorelov, Differential Geometry [in Russian], Moscow (1969).
15. M. L. Aleksandrov, L. N. Gall', V. Ya. Ivanov, et al., Izv. Akad. Nauk SSSR, Mekh. Zhidk. Gaza, No. 6, 165-167 (1983).
16. J. Zeleny, Phys. Rev., 10, No. 1, 1-6 (1971).
17. J. Reilly, Theory of Sound [Russian translation], Vol. 2, Moscow (1955).
18. Ya. I. Frenkel', Zh. Éksp. Teor. Fiz., 6, No. 4, 347-350 (1936).
19. L. D. Landau and E. M. Lifshits, Electrodynamics of Continuous Media [in Russian], Moscow (1982).
20. L. Éizenberg and V. Kautsman, Structure and Properties of Water [in Russian], Leningrad (1975).
21. G. Birkhof and E. Sarantonello, Jets, Wakes, and Caverns [Russian translation], Moscow (1964).
22. P. Appel', Equilibrium Figures of a Rotating Liquid [in Russian], Moscow—Leningrad (1936).
23. E. V. Lozanskii and O. B. Firsov, Theory of the Spark [in Russian], Moscow (1975).
24. A. G. Baily, Sci. Prog. Oxf., 61, 555-581 (1984).
25. A. I. Grigor'ev and O. A. Sinkevich, Zh. Tekh. Fiz., 54, No. 7, 1276-1283 (1984).

EFFECT OF ELECTRODE CONFIGURATION ON EFFICIENCY OF INDUCTION ELECTRIFICATION OF DROPLETS

V. I. Bezrukov, V. D. Spiridonov, and Yu. V. Syshchikov

UDC 537.29:532.522

Numerical calculation of the electric field in an induction electrification unit is used to determine the charges of droplets formed for various axisymmetric electrode systems.

In electrodroplet-jet equipment the charge of the droplets is the basic parameter controlling transverse deviations of drops in the chain and, thus, formation of the image on the substrate [1]. Therefore calculation of this parameter is an important stage in the design of such devices. Theoretical calculations are based on determination of the electric field in the interelectrode gap. Analytical calculations usually make use of a number of assumptions for which quantitative estimates are lacking, as a result of which they are uncontrolled, and in a number of cases, incorrect. Among these assumptions are: that the droplet charge is determined by a section of the jet the length of which is equal to the wavelength of the disturbance; neglect of electrode edge effects; neglect of charge redistribution on the electrode surfaces due to interaction with jet charges and detached droplets; use of the thin bar approximation for the jet, which produces the largest error near its end (i.e., the spot of droplet formation), etc.

The present study has as its goal the calculation of the electric field in the interelectrode space of an axisymmetric charging system in an electrodroplet-jet device with its subsequent use to calculate the charges upon the droplets formed. Special attention was

"Electrodroplet-Jet Technology" Institute, Leningrad Institute of Precision Mechanics and Optics. Translated from Inzhenerno-fizicheskii Zhurnal, Vol. 60, No. 4, pp. 641-645, April, 1991. Original article submitted July 31, 1990.

 0022-0841/91/6004-0488$12.50

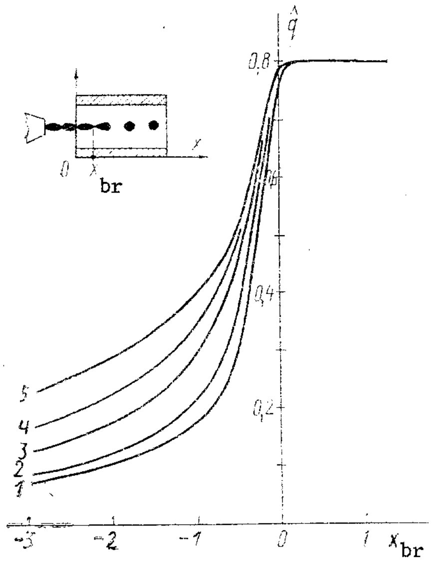


Fig. 1

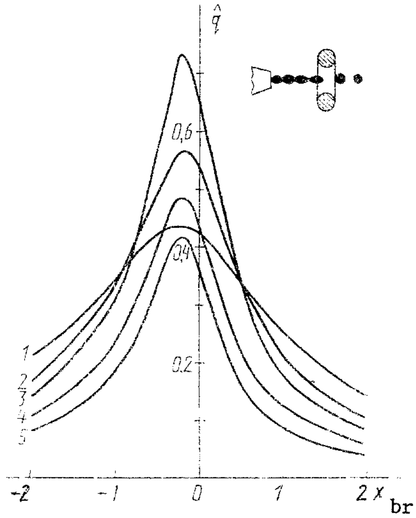


Fig. 2

Fig. 1. Electrification in field of a cylindrical electrode. Dimensionless charge $\hat{q}$ vs longitudinal coordinate of breakup point x_{br}, mm ($d_e = 0.45$ mm, $\ell_e = 4$ mm): 1) $h_e = 0$; 2) 0.1 mm; 3) 0.5; 4) 1.0; 5) 2.0.

Fig. 2. Electrification in ring field: 1) R = 1.05 mm; 2) 0.65; 3) 0.475; 4) 0.50; 5) 0.45; 1-3) r = 0.25 mm; 4) 0.10; 5) 0.05.

given to the effect of electrode form and dimensions on the charges of the droplets produced.

The electric field in the interelectrode gap was calculated by the finite element method using an equation for surface charge density [2]. The electrostatic problem was solved for the potential φ of the electric field:

$$\Delta\varphi = 0,$$
$$\varphi|_{S_c} = U_c, \quad \varphi|_{S_e} = U_e.$$

It was assumed that the liquid was electrically conductive and the charge relaxation time was less than the characteristic time of change in jet surface.

We will consider axisymmetric jet surfaces S_j and electrode surfaces S_e, which we divide, respectively, into N_j and N_e finite annular elements. The mutual capacitances of the finite elements are calculated with the expression

$$B_{ik} = \frac{1}{S_i S_k} \iint \frac{dS_i dS_k}{|\mathbf{r}_i - \mathbf{r}_k|}, \tag{1}$$

where S_i, S_k are the areas of finite elements i and k. With consideration of the axial symmetry of the problem the integration in Eq. (1) can be reduced to twofold:

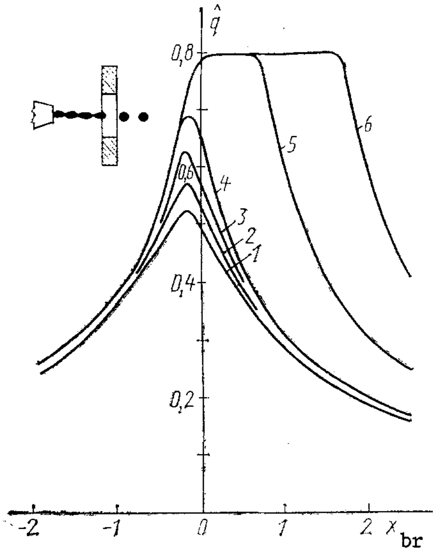
$$B_{ik} = \frac{8}{\pi} \frac{1}{(R_{i+1} + R_i)(R_{k+1} + R_k)} \int_0^1\int_0^1 \mathrm{K}\left(\sqrt{\frac{4r_i r_k}{(z_i - z_k)^2 + (r_i + r_k)^2}}\right) \frac{r_i r_k dt_i dt_k}{\sqrt{(z_i - z_k)^2 + (r_i + r_k)^2}}. \tag{2}$$

Here R_i, R_k, z_i, z_k are cylindrical coordinates of the finite element boundaries; $r_i = R_i + (R_{i+1} - R_i)t_i$; $z_i = Z_i + (Z_{i+1} - Z_i)t_i$ (the variables r_k and z_k are defined similarly).

The charges of the finite elements are found from the system of linear equations

$$\sum_k B_{ik} q_k = U_c, \quad i = 1, \ldots, N_c;$$
$$\sum_k B_{ik} q_k = U_e, \quad i = N_c + 1, \ldots, N_c + N_e.$$

In the present study the dependence of droplet charge on characteristics of the electrode system was studied, therefore the form of the jet and droplets in the calculations was



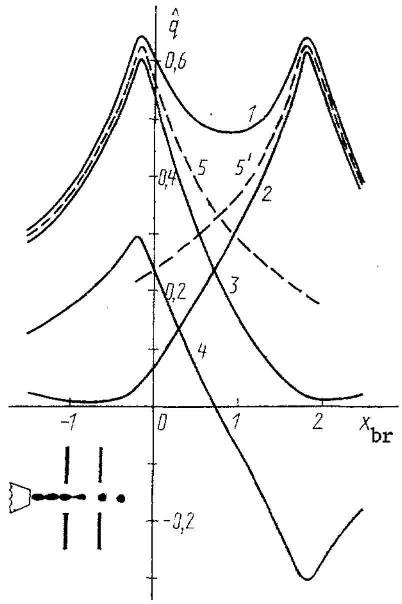


Fig. 3 Fig. 4

Fig. 3. Electrification in field of disk with orifice, D_e = 4 mm: 1) d_e = 0.8 mm; 2) 0.6; 3-6) 0.45; 1-3) h_e = 0; 4) 0.1 mm; 5) 1.0; 6) 2.0.

Fig. 4. Electrification in field of transverse planar capacitor, d_e = 0.6 mm, D_e = 4 mm, h_e = 0, H_e = 2 mm (jet grounded): 1) $U_1 = U_2 = U$; 2) $U_1 = 0$, $U_2 = U$; 3) $U_1 = U$, $U_2 = 0$; 4) $U_1 = U/2$, $U_2 = -U/2$; 5, 5') single disks.

taken constant (cylindrical jet and droplet with hemispherical head and conical tail section) and the following parameters defined: jet diameter d_j = 80 μm, disturbance wavelength λ = 500 μm, jet length ℓ_j = 4 mm, droplet length ℓ_d = 330 μm, spherical droplet head diameter d_d = 160 μm.

The droplet charge q is characterized by the dimensionless parameter

$$\hat{q} = \frac{q}{2\pi\varepsilon_0 l_d U}.$$

We will present the basic results obtained below. The figures show calculated dependences of droplet charge on longitudinal coordinate of the breakup point x_{br}, which is measured from the leading edge of the electrode.

The graphs of Fig. 1 correspond to droplet electrification in the field of a cylindrical electrode. If the breakup is submerged in the depths of the electrode (region $x_{br} > 0$), then the droplet charge depends solely on the internal diameter of the electrode and is independent of the other parameters. For these intervals the droplet charge can be described approximately by the expression

$$q = \alpha_c \frac{2\pi\varepsilon_0 l_d U}{\ln(d_e/d_j)},$$

where for a droplet of the form considered α_c = 1.35. The effects of the electrode walls and the form of the leading edge manifest themselves in the region $x_{br} < 0$, where the breakup point is moved outside the electrode.

Figure 2 characterizes electrification in the field of a ring electrode. Comparison with approximate analytical calculation [3] shows that the droplet charges can be calculated with the expression

$$q = \alpha_r \frac{2\pi^2\varepsilon_0 l_d U}{\sqrt{1 + (x_{br}/R)^2}\,(\ln(4l_j/d_j) - 1)\ln(8R/r)}.$$

For a droplet of the form considered, α_r = 1.48.

Results of electrification calculations for the field of a disk with orifice and two disks with orifices perpendicular to the jet are shown in Figs. 3 and 4, respectively. A

TABLE 1. Comparison of Calculated (I) and Experimental (II) Values of Droplet Charge (U = 250 V, d_e = 0.6 mm, D_e = 4 mm, h_e = 0.1 mm)

x_{br}, mm	q, pC			
	single plate		two plates H_e = 2 mm, $U_1 = U_2 = U$	
	I	II	I	II
—2,00	1,23	1,37	—	—
—1,00	1,95	2,01	2,08	2,19
—0,75	2,29	2,29	2,39	2,35
—0,50	2,71	2,70	2,79	2,72
—0,25	2,93	2,88	3,04	2,88
0,0	2,58	2,47	2,82	2,70
0,25	—	—	2,50	2,45
0,50	1,73	1,69	2,32	2,33
0,75	—	—	2,28	2,29
1,00	1,32	1,33	2,34	2,33
1,25	—	—	2,49	2,44
1,50	—	—	2,74	2,65
1,75	—	—	3,02	2,97
2,00	0,96	0,87	2,85	2,88

comparison of the graphs shows that of the two configurations the two planes with identical potential produce the highest charging efficiency; the single disk produces almost the same efficiency. We stress that for curves 2-4 (Fig. 4) the potential difference between the plates is the same, but the potential distributions between the jet and the electrodes are different. Correspondingly there are significant differences in the droplet charges.

Analytical calculations [3] of droplet charge for the given configuration correspond to curve 2 (Fig. 4) and lead (in our notation) to the expression

$$q = \frac{2\pi\varepsilon_0 l_d x_{br} U}{H_e (\ln (4x_{br}/d_j) - 1)}.$$

Calculations show that for the linear interval $0.25 \leqslant x_{br}$ (mm) $\leqslant 1.5$ the error of this expression does not exceed 10-15%.

To verify the numerical results a comparison was performed with an experimental study of electrification of droplets with the apparatus of [4, 5]. Since in those experiments the droplet form differed from that considered here, an individual series of calculations was performed. A comparison of numerical and experimental results is presented in Table 1. For the entire data set the maximum relative error is 10%, with mean square of 2%.

On the basis of these results we may state that for a given electrode orifice diameter highest electrification efficiency is achieved for electrodes in the form of a cylinder (see Fig. 1) or a thick plate (Fig. 3). Another shortcoming of the other electrode forms is the intense dependence of droplet charge on breakup point coordinate. In this case any fluctuation of the breakup point leads to corresponding scattering in droplet charges and reduction in the accuracy of droplet positioning in electrodroplet-jet devices.

The results obtained can be used to develop a class of electrodroplet-jet devices suitable for mass production [6].

NOTATION

D_e, disk outer diameter; d_e, electrode orifice diameter; He, distance between planar capacitor disks; h_e, electrode thickness; $K(x)$, type I elliptical integral; ℓ_e, electrode length; q, droplet charge; $\hat{q}$, dimensionless droplet charge; R_i, Z_i, cylindrical coordinates of finite element boundaries; R, radius of ring electrode; r, wire radius of ring electrode; S_j, S_e, jet and electrode surfaces; U_j, U_e, jet and electrode potentials; $U = |U_c - U_e|$, power supply voltage; U_1, U_2, potentials of planar capacitor plates; x_{br}, coordinate of jet breakup point (measured from front edge of electrode); α, correction coefficient; ε_0, dielectric constant.

LITERATURE CITED

1. V. I. Bezrukov, Izv. Vyssh. Uchebn. Zaved., Priborostr., No. 12, 58-65 (1986).
2. P. Sylvester and R. Ferrari, Finite Element Method for Radio and Electrical Engineers [Russian translation], Moscow (1986).

3. V. V. Blazhenkov, A. V. Bukharov, and A. A. Vasil'ev, Physical Problems in the Study of Monodispersed Systems [in Russian], No. 147, Moscow (1987).
4. V. I. Bezrukov, V. D. Spiridonov, and Yu. V. Syshchikov, XV All-Union Conference "Practical Questions in the Physics of Aerodispersed Systems" [in Russian], Vol. 1, Odessa (1989), p. 47.
5. V. I. Bezrukov and V. D. Spiridonov, Electrodroplet-Jet Technology in the Realization of the "Intensifikatsiya-90" Program [in Russian], Leningrad (1989), pp. 9-17.
6. V. I. Bezrukov (ed.), Flexible Automatic Electrodroplet-Jet Systems for Part Marking in Ship Construction [in Russian], Leningrad (1988).

INDUCTIONAL CHARGING OF MONODISPERSED DROPS FORMED IN THE INDUCED CAPILLARY BREAKDOWN OF LIQUID JETS

V. V. Blazhenkov, A. V. Bukharov,
A. A. Vasil'ev, and S. N. Panasov

UDC 621.319.7.001:517.958

Theoretical and experimental data on the inductional charging of monodispersed liquid drops formed in the induced capillary breakdown of liquid jets are given.

The preparation of fluxes of monodispersed drops with dosed electric charges which may be controlled by means of electric and magnetic fields is one of the basic elements of electrodrop-jet [1] and cryodisperse [2] technology.

The method of inductional charging of monodispersed drops of conducting liquids formed as a result of the induced capillary breakdown of liquid jets (ICBJ) is investigated in the present work. The results of analytical and numerical calculations are given, as well as experimental data on the charges induced at the drops in electric fields of various configurations. The experimental and theoretical data are compared.

In inductional charging, the potential applied between the electrodes (the charging electrode most often takes the form of a plane with a hole, a ring, or a cylinder; the second electrode is an attachment to the ICBJ generator and the intact part of the jet itself) induces some charge distribution along the jet; this distribution depends on the concentration and mobility of the charge carriers in the liquid volume and also on the time of drop formation in ICBJ.

The charge induced at the drop may be expressed in terms of the its equivalent capacitance and the potential at the charging electrode V: $Q = -C\alpha V$; here α takes account of the correction for the local value of the potential at the point of breakdown.

The capacitance of the drop is determined by its size and shape. For a spherical drop, the capacitance is $C = 4\pi\varepsilon\varepsilon_0 R_d$. It must be taken into account that the shape of the surface of the intact part of the jet and the charges at all the previously formed drops in the flux influence the magnitude of the charge.

The influence of the shape of the drop may be estimated from the change in capacitance of an ellipsoid of revolution as a function of its eccentricity, since the drops take this form at the instant of breakaway from the jet in ICBJ. Data on the charges at the drops as a function of the eccentricity obtained by experiment (points) and calculation (continuous curve) are shown in Fig. 1.

Because of the finite electrical conductivity of the liquid, the inductional charging of the drop does not occur instantaneously. To describe the dynamics of the charging process, it is expedient to represent the charged section of the jet and the charging device as a series RC circuit in which the resistance R is determined by the electrical conductivity of the liquid being dispersed ρ, the diameter D_j, and the length of the intact part of the jet L_j:

Moscow Power Institute. Translated from Inzhenerno-fizicheskii Zhurnal, Vol. 60, No. 4, pp. 646-651, April, 1991. Original article submitted July 31, 1990.

 0022-0841/91/6004-0492$12.50