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ELECTROGAS- AND ELECTROHYDRODYNAMIC CONTROL OF GAS AND LIQUID JETS AND FLOWS.

2. PHYSICAL PRINCIPLES

V. S. Nagornyi

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The paper deals with the electrophysical principles of the method of electrogas- and electrohydrodynamic conversion of electric signals to pneumatic (hydraulic) signals and vice versa for the control of gas and liquid jets and flows in electropneumohydraulic systems, including problems of formulating requirements for the working media and electric circuits of converters, estimating the limiting ranges of pressure, velocity, and temperatures of the working media and limiting dynamic possibilities, and determining conditions for production of potential signals, stable control, and extension of the control ranges.

1. In a previous paper [1], it is shown that the bulk force in EHD control of gas and liquid jets and flows cannot be arbitrary, and this limits the gas- or hydrodynamic outlet power of EHD converters.

Both the force produced in EHD control and the gas- or hydrodynamic outlet power depend on the dimensionless parameter of EHD interaction N, which is the ratio of the volume density of electric energy to the volume density of gas- or hydrodynamic energy. In mathematical models of EHD converters, this parameter enters the right side of the Navier–Stokes equation [1, Eq. (2.7)]. The dependence of the characteristics of converters on N can be explained by the following examples.

As follows from formulas (3.1) in [1], even for the largest possible values of E_0 and ρ_{e0}, the maximum velocity v_0 of the working liquid flow in EHD control cannot exceed 3–4 m/sec, and the gas-flow velocity cannot exceed 6–10 m/sec. Therefore, the parameter N [1, Eq. (2.7)] also has limiting values. However the larger the N for jet and throttling electrohydraulic (electropneumatic) EHD converters, the more efficient the EHD control. For example, the deflection x at the exit from a homogeneous electric field for an element of a free-fall jet (or a liquid drop) which is previously imparted bulk charge ρ_e in a sharply inhomogeneous field is directly proportional to N:

$$x = Nl^2/(2h), \tag{1.1}$$

where l and h are the length of the deflecting plates and the distance between them, respectively. In the expression for N, $l_0 = h$ and E is the strength of the homogeneous electric field between the deflecting electrodes. Therefore,

$$N = \rho_e Eh/(\rho v^2) = \rho_e U/(\rho v^2).$$

For particular types of converters [2–5], the range of N (as well as the ranges of the dimensionless parameters G, Re_e, and Pe_e [1, formulas (2.7) and (2.9)–(2.11)]) depends on the electrophysical parameters of working media (ε, b, and D) in the indicated ranges [1], the chosen characteristic linear dimension l_0, and the working range of interelectrode voltage E_0 (electrodes of the needle–plane type, coaxial, plate,

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etc.). For example, in controlling working liquid flows ($2 \leqslant \varepsilon < 3$) and imparting them bulk electric charge $\rho_e = 10^{-1}$–10^{-2} C/m^3 in a sharply inhomogeneous field, we obtain $0 < E_0 < (10^7$–$10^8)$ V/m. For deflection of charged free-fall jets or drops in a homogeneous electric field, $0 < E_0 < 10^6$ V/m, and the maximum bulk charge density in the drop $\rho^{\text{dr}}_{e\max}$ is limited and is determined from the Rayleigh stability criterion for a charged spherical drop [2]:

$$\rho^{\text{dr}}_{e\max} \leqslant 16.97\sqrt{\varepsilon_0\alpha/d^3_{\text{dr}}},$$

where d_{dr} is the diameter of the drop, which is, as a rule, in the range $(30$–$300) \cdot 10^{-6}$ m, and α is the surface-tension coefficient of the working liquid.

In all cases, however, the strength E_0 should be lower than the breakdown strength E_{br} of the entire interelectrode gap. In the control of gas flows, the maximum value of E_0 decreases by an order of magnitude or more, and the limiting bulk charge density ρ_{e0} also decreases by one or two orders of magnitude.

In EHD changes of jet and flow modes and changes in velocity profiles in EHD flowmeters using a component of the total current as the informative parameter [1, formulas (2.5) and (2.11)], the Reynolds number Re does not exceed 2300. However, in other applications, for example, in label EHD flowmeters [5], an ionic label is introduced into a developed turbulent flow of a working liquid or a gas with $\text{Re} \gg 2300$ (to increase the accuracy of signal conversion). At the moment the ionic label is produced, the EHD-interaction parameter N should be as small as possible, lest the EHD effect be exerted on the flow-velocity profile and an additional error be introduced into measurements of the liquid- or gas-flow rate.

The normal operation of EHD converters with deflection of a charged jet is effective when the ion velocity acquired in the transverse electric field of the deflecting electrodes is much lower than the average jet velocity:

$$bE \ll v_0, \tag{1.2}$$

and the time constant of the decrease in the bulk charge in an elementary liquid volume along the jet length is much larger than the time of residence of the charge in the field of the deflecting electrodes:

$$\varepsilon_0\varepsilon/\sigma \gg l/v_0. \tag{1.3}$$

In (1.2) and (1.3), v_0 is the average velocity of the jet between deflecting electrodes of length l.

Condition (1.2) for the above-mentioned ranges v_0 and the strength of the deflecting electric field is not satisfied in the control of charged submerged gas (air) jets because of the high ion mobility in gases [$b \sim 10^{-4}$ m^2/(V $\cdot$ sec)], and in this case, EHD control is not feasible.

In working dielectric liquids such as mineral oils, the ion mobility is four orders of magnitude lower than that in air, and, by virtue of (1.2), the liquid-jet velocity in the field of deflecting electrodes should be $v_0 \gg (10^{-1}$–$10^{-2})$ m/sec, which is attainable with satisfaction of condition (3.1) from [1]. In addition, satisfaction of (1.3) is ensured because the conductivity σ of the working liquid media is low [about 10^{-14}–10^{-11} $1/(\Omega\cdot$m)].

Although EHD control of charged submerged gas jets is impossible according to (1.2), use of EHD compressors [3, 4], in which the control gas pressure and flow rate are produced by the unipolar ion flow in the peripheral area of a corona discharge, allows one to control the deflection of uncharged submerged gas (air) jets. In turn, by subjecting a laminar gas flow to a longitudinal inhomogeneous field of the same direction as the gas flow and producing a unipolar bulk charge in the flow, it is possible to change the velocity-flow profile, thus changing the hydraulic resistance on this pressure pipeline segment. The ionic diffusion coefficient in gases ($D \approx 10^{-5}$ m^2/sec) is five orders of magnitude higher than that in working dielectric liquids ($D \approx 10^{-10}$ m^2/sec). Therefore, in the throttling EHD conversion of an electric signal into a pneumatic signal with a longitudinal control electric field, diffusion generally favors a nonuniform charge distribution over the pipeline cross section and influences variations in the velocity profile and gas-flow rate on the present pressure pipeline segment. This influence can be estimated using the system of dimensionless equations (2.7)–(2.12) from [1], written in cylindrical coordinates for a steady, charged, laminar gas flow in a dielectric pipe of diameter $d = 2R$ with a longitudinal electric field. In the derivation of these equations, gravity forces were ignored since for high ion mobility in gases, the electric Reynolds number $\mathrm{Re_e} \ll 1$ [3]. Then, for example, for the dimensionless gas flow rate through the present pipeline segment with variation in the flow-velocity profile in the electric field, we obtain

$$Q' = \frac{2N\mathrm{Re}\,G}{\mathrm{Pe_e}}\left[\left(1+\frac{8G}{\mathrm{Pe_e}}\right)\ln\frac{1+8G/\mathrm{Pe_e}}{8G/\mathrm{Pe_e}} - 1\right] - \frac{\mathrm{Re}\,\mathrm{Eu}\,\delta p'}{8\,\delta z'}. \tag{1.4}$$

Here $Q' = Q/(\pi R^2 v_0)$, $p' = p/p_0$ is the dimensionless pressure drop on the pipeline segment $z' = z/R$, Q and p are the current flow rate and pressure drop, respectively, and p_0 is the feed pressure from the pump. In the expressions for the parameter N, the electric Peclet number $\mathrm{Pe_e}$, and the number G, the characteristic linear dimension is the radius R of the pipeline, and in the expression for the Reynolds number Re, this is the diameter d of the pipeline. As follows from (1.4), the larger the EHD interaction parameter N, the greater the change in the gas-flow rate under the action of the longitudinal electric field.

Similarly, it is possible to show that in vortical EHD converters, which can be modeled as a first approximation by coaxial cylindrical electrodes, the input signals (variations in the flow rate or pressure) also increase with increase in N.

The limited power of the output signal of electrohydraulic (electropneumatic) EHD converters used in electrohydraulic (electropneumatic) control systems leads to the necessity of using hydraulic (pneumatic) power amplifiers to control powerful actuators. The unquestionable advantage of the EHD control of working-liquid drops in electric dispersed-jet devices is that the drop itself and its deflection in the field according to (1.1) function as an actuator, and, hence, it is not necessary to use additional power amplifiers and complicated actuators. This motivates the wide use of electric dispersed-jet technologies in various fields: engineering, the light and food-processing industries, shipbuilding, medicine, etc.

2. The input signal of EHD devices is frequently a unified output signal of 0–5 V from the control microcomputers or corresponding probes. Therefore, EHD converters must incorporate a high-voltage amplifier, at whose input the unified control electric signals are delivered and whose output is connected directly to the electrodes of the converters.

Let us formulate the requirements for the high-voltage amplifiers in the circuits of EHD pumps and EHD compressors with a single-phase dielectric and a consumption load. In these converters, the electrodes located in a liquid or gas are of the needle–tube type. Voltage applied to the electrodes gives rise to a unipolar flow of ions of the same sign as the corona point potential, and this flow determines the interelectrode current I. Transferring momentum to the ambient working medium, the ions initiate motion of the liquid or gas with velocity v and produce pressure p_1 at the exit from the tube. Then for the one-dimensional case, taking into account (2.1)–(2.6) from [1] and ignoring diffusion currents, surface charges on the walls of the pipeline, friction pressure losses, and turbulence according to [6], we obtain

$$\left.\frac{dp_1}{dv}\right|_{I=\mathrm{const}} = -\frac{\varepsilon\varepsilon_0 E(E-E_\mathrm{c})}{bE+v}; \tag{2.1}$$

$$\left.\frac{dp_1}{dv}\right|_{U=\mathrm{const}} = \frac{E(E-E_\mathrm{c})^2}{2bE^2+4bEE_\mathrm{c}+8Ev+4E_\mathrm{c}v+6v^2/b}. \tag{2.2}$$

Analysis of expression (2.1) for $bE + v > 0$ shows that an increase in the velocity v due to hydraulic (pneumatic) load, with the current amplitude maintained constant, leads to a decrease in pressure p_1 and, hence, in the velocity v, and vice versa. This is equivalent to negative feedback, and, therefore, in this case, EHD converters (EHD pumps or EHD compressors) are a stable source of consumption.

When a voltage of constant amplitude is maintained at each working point of an EHD pump or EHD compressor, this ideal system according to (2.2) is unstable toward velocity fluctuations. In real systems, the hydro- or gas-dynamic losses in channels are a damping factor of this stability, and when the voltage amplitude is maintained constant at each working point, the pressure can vary asymptotically with variation in v to a certain fixed value determined by the parameters of the system.

From the aforesaid, it is possible to formulate the following requirement on the design of the electric part of EHD converters. When EHD pumps and EHD compressors operate on a consumption load and in circuits of analog conversion of electric signals to hydraulic or pneumatic signals, it is expedient to use the variation in voltage U as the electric signal on the electrodes, but at each working point, the electric circuit should ensure maintenance of a current of constant amplitude between the electrodes of such converters.

If EHD converters are used for discrete conversion of electric signals to hydraulic or pneumatic signals, the spread permissible in hydropneumatic for the signal levels corresponding to logical "zero" and "unity" is, as a rule, much larger than the range of variation in the output signals of EHD due to variation in the interelectrode current. In this case, it is expedient to use simpler high-voltage amplifiers that are not stabilized toward the output currents and work in a discrete mode.

3. We formulate the main requirements on the individual parameters of EHD converters that operate using a gas corona discharge.

Within the framework of the currently adopted Townsend–Rogowski theory, the number of ionizations performed in a corona layer by electrons on a unit path along the electric-field lines is characterized by the electron ionization coefficient α_e, which is defined as the product of the average number of collisions on a unit length and the probability of ionization by electron impact during collision. In this case, the condition $w_e > w_i$ should be satisfied, where w_i is the ionization energy of the working gases and w_e is the energy of the electrons.

In electronegative gases and their mixtures, for example in air, atoms and molecules can attach a superfluous electron to form a stable, negatively ionized atom. Therefore,

$$\alpha_{\text{eff}} = \alpha_e - \alpha_{\text{att}}, \tag{3.1}$$

where α_{eff} is the effective coefficient of ionization by electron impact, which determines the multiplication of electrons during impact ionization and α_{att} is a coefficient that describes the attachment of electrons. For $\alpha_{\text{eff}} > 0$, impact ionization begins. In this case, in EHD converters using a corona discharge in electronegative gases (air), the normal mode of operation that maintains impact ionization conditions is described by the relation

$$E/p \geqslant c, \tag{3.2}$$

where c is a constant value for the selected working gas. For air, $c = 23.8$–26.3 V/(m · Pa) [7, 8].

When the curvature radius of needle electrodes is about 10^{-5} m, the electric-field strength in the corona layer is approximately (3–5) · 10^7 V/m. Therefore, from (3.2) it follows that the pressure range in which electrogas-dynamic converters can operate is more than twice the working range of pneumoautomatic devices, which is usually 0.6 MPa and rarely 1 MPa.

Let us determine the applicability conditions for the method of EHD control of gas flows under variations in the flow temperature. The effective coefficient of impact ionization (3.1) is a function of the electric-field strength E in the corona discharging layer and the ambient pressure p. For most gases near the threshold value, as a first approximation we can write [3, 9]

$$\alpha_{\text{eff}} = \frac{aT_0}{\rho_0 p_0 T}\Big(E - c\,\frac{\rho_0 p_0 T}{T_0}\Big)^2, \tag{3.3}$$

where the coefficient a together with the exponent determines the rate of increase in α_{eff}/p with increase in E/p after the threshold value and ρ_0 is the relative gas density.

For the beginning of ionization by electron impact, it is necessary that the impact ionization coefficient become larger than zero. Setting $\alpha_{\text{eff}} \approx 0$ and taking into account that $aT_0/(\rho_0 p_0 T) \neq 0$, from (3.3) we obtain the following condition for the applicability of EHD control with variations in the temperature of the working gas of converters (ambient temperature):

$$\frac{ET_0}{\rho_0 p_0 T} \geqslant c. \tag{3.4}$$

From (3.2) and (3.4) it follows that the method of EHD conversion of the type of energy of signals is applicable over wide ranges of pressure and temperature and the working gas and the ambient medium.

For example, for converters working in air, at $E \approx 10^7$ V/m, $T_0 = 293$ K, $\rho_0 = 1$, $p_0 = 101.3$ kPa, and $c = 23.8$ V/(m·Pa) from (3.4) we infer that the air temperature can vary within several thousands of Kelvins. In this case, one should take account of thermoautoelectron emission [8]. However, for EHD converters, as well as for conventional converters, the unfavorable effect of ambient temperature on their characteristics must be compensated for by well-known methods.

To produce not only dynamic (pulsed) but also potential output signals without complication of EHD converters, it is first of all necessary to ensure a flow of unipolar ions during the lifetime of electric signals at the converter input. This is achieved by satisfying the condition of independence of the corona discharge, i.e., the condition that the discharge is maintained without additional external ionizing agents. This condition is written in analytic form as [3, 7, 9]

$$\int\limits_0^{l_c} \alpha_{\text{eff}}\, dx = K \simeq \text{const}, \tag{3.5}$$

where l_c is the length of the line field line within the corona layer and x is the path of the electron avalanche (from the cathode for a negative corona and from the external boundary of the corona layer to the anode for a positive corona). In this case, the values of K in (3.5) for different signs of the corona electrode can differ by factor of 2 or 3 [8]: for a positive potential (positive corona), $K \approx 18$–20, and for a negative corona, $K = \ln[(1+\gamma)/\gamma] = 8$–$9.2$. Here γ is a generalized coefficient of secondary ionization that characterizes the average amount of electrons that form in the corona layer as a result of ionization by secondary electrons (secondary ionization) released from the cathode by impact of the initial avalanche on the surface of the positive ions, or as a result of photoionization on the cathode surface by radiation from the initial avalanche, or as a result of photoionization in the gas volume by the short-wave radiation of the avalanche.

With satisfaction of condition (3.5), in EHD converters there is a stable corona discharge with the corresponding electric-field strength at the needle electrode and the electrode voltage, which are called the initial strength E_c and initial voltage U_c of the corona.

The considerable difference between the values of K in (3.5) for different polarity of the corona electrode has little effect on E_c and U_c [8] because of the strong dependence of α_{eff} on the field intensity E [see, for example, (3.3)]. Therefore, even a small change in $E(x)$ leads to a significant change in the integral on the left side of expression (3.5). As follows from experiments, the values of E_c for negative and positive coronas in air differ only slightly; for a negative corona, the value of E_c is somewhat smaller than that for a positive corona.

Determining E_c and U_c is of great significance in an analysis of the static and dynamic characteristics of EHD converters. At present there are a great number of semiempirical formulas for E_c and U_c, which differ strongly from each other because E_c are defined differently [3]. They are applicable in the case of large interelectrode gaps, where the inner area of the corona with $\alpha_{\text{eff}} > 0$ is many times smaller than the interelectrode zone and the field on most of the interelectrode gap can be considered quasihomogeneous, as, e.g., in high-voltage transmission lines. In EHD converters, however, the distance between the corona electrodes are small and are several millimeters with satisfaction of condition (3.5). The dimension of the peripheral area of the corona becomes commensurable with the interelectrode gap, and practically over the entire interelectrode gap there is an inhomogeneous electric field with strength increasing sharply at the electrode with a small curvature radius. Because of this, the well-known formulas of the initial field strength are mostly inapplicable for calculations of the characteristics of electropneumatic (air-to-electric) EHD converters. The expressions for E_c and U_c given below are obtained with allowance for the design features of the converters.

For engineering applications, we obtained a semiempirical formula for E_c that fits experimental data well and allows for the dependence of E_c on the distance h between electrodes of the needle–plane type for small interelectrode gaps:

$$E_c = A\rho_0 + B\sqrt{h\rho_0/r_0}. \tag{3.6}$$

Here $A = cp_0T/T_0$, $B = \sqrt{Kp_0T/(adT_0)}$, the coefficients a and c are determined from (3.3), K is determined from condition (3.5) of the independence of the corona discharge in the working gas, and d is an empirical coefficient that characterizes the distance from the electrode with small curvature radius r_0 within which the electric field E has a pronounced nonuniformity along the length of the interelectrode gap until the occurrence of a corona discharge.

In the case of coaxial electrodes, relation (3.6) can be written as

$$E_c = A\rho_0 + B\sqrt{(R/r_0 - 1)\rho_0}, \tag{3.7}$$

where R is the curvature radius of the electrode that does not display a corona. For example, for $R = 5$ mm and a radius of the corona electrode of $r_0 = (0.5\text{–}9.0) \cdot 10^{-2}$ mm, in expression (3.7) for air, we have the coefficients $A = 34.2$ kV/cm and $B = 11.799$ kV/cm.

Formula (3.7), in contrast to the well-known similar formulas for E_c [7–9], takes into account the dependence of E_c on the interelectrode spacing. Calculations of E_c using formula (3.7) for the above-mentioned range of r_0 are in good agreement with experimental data for both negative and positive coronas, whereas results of calculations using the well-known semiempirical formulas of Pick, Townsend, Lösh, Razevig, Engel, Stenbeck, et al., which ignore the dependence of E_c on the interelectrode spacing for such small interelectrode gaps, differ greatly from experimental data.

The initial corona voltage U_c is determined from (3.7) by the formula

$$U_c = E_c r_0 \ln{(R/r_0)}. \tag{3.8}$$

For EHD converters using a corona discharge, the working electrode voltage varies within the limits

$$U_c \leqslant U < U_{\text{br}}, \tag{3.9}$$

where U_{br} is the voltage at which there is spark breakdown of the interelectrode gap.

Hence, the lower bound of the working range of electrode voltage U_c for electrogas-dynamic converters is determined by processes occurring in the inner area of the corona (in the corona layer). In turn, the peripheral area of the corona discharge determines the EHD effect, since a unipolar (having the sign of the corona point) bulk electric charge is formed precisely in this area. The upper limit of the working voltage range U_{br} is characterized by conditions of spark breakdown of the peripheral area of the corona. To soften the requirements on the electric part of converters, it is desirable to select the maximum possible range of voltage (3.9). In an optimal EHD converter, the design and other parameters ensure minimum corona voltage U_c and maximum spark breakdown voltage U_{br}.

For electropneumatic and air-to-electric EHD, the possible range of electrode voltage can be extended primarily by an appropriate choice of the corona electrode polarity.

The significant difference in the values of the right side of expression (3.5) for positive and negative coronas has little effect on the value of E_c [8]. This value is smaller for a negative corona than for a positive corona [8]. Accordingly, the value of U_c is smaller for a negative corona than for a positive one.

For a positive potential of a needle electrode, the width of the high field strength region is greater [3] than that for a negative potential. Therefore, with increase in the electrode voltage in EHD converters, the development of streamers for a negative potential of the needle occurs on a smaller length of the interelectrode gap. As a result, in the case of a positive corona, spark breakdown occurs at a lower electrode voltage U_{br} than in the case of a negative corona. Since, the voltages U_c of occurrence of positive and negative coronas are identical, as a first approximation, it is concluded that the working range of positive corona voltage is narrower.

When the corona point is in gas flow, the bulk charge formed in the inner area of the corona is partly blown off from the point, the effect of the charge on the resulting field decreases, and the conditions of formation of streamers change. Therefore, with increase in the velocity of working gas flow around the corona electrode, the breakdown voltage U_{br} also increases. The initial corona voltage U_c practically does not depend on the flow velocity, and this increases the range of electrode voltage for electrogas-dynamic converters.

By selecting the design parameters of EHD converters (first of all, the curvature radius r_0 of the needle electrode), one can significantly change the working voltage range [see, for example, (3.6)–(3.9)] and the value of the unipolar charge imparted to the working gas (liquid) flow. The last statement follows, for example, from formula (3.4) in [1], since the value of r_c is determined primarily by r_0 [1, formula (3.5)].

With decrease in the electrode spacing h, the quantity U_{br} decreases faster than U_c, which leads to a decrease in the working range of $U_c \leqslant U < U_{br}$. Therefore, with a further decrease in h, beginning from a certain critical electrode spacing h_0, a corona does not appear, but spark breakdown occurs at once, i.e., the working voltage range U is equal to zero. Hence, for EHD converters, the ratio h/r_0 should be larger than the particular value: $h/r_0 > h_0$. For example, for coaxial electrodes, the ratio of radii at which a corona discharge occurs in air should satisfy the condition [3, 7] $R/r_0 = (h + r_0)/r_0 > 2.718$.

For air-to-electric EHD converters with specified geometric dimensions of the interelectrode gap, the working range of electrode voltage $U_c \leqslant U < U_{br}$ increases for higher gas pressure p. This is explained by the fact that with increase in p, the value of U_{br} increases faster than U_c.

The physical processes involved in the selected method of conversion of the type of energy of signals in essence do not limit the necessary response of electrogas-dynamic converters since the upper bound of the frequency of variation in the electrode voltage for which a steady corona discharge still occurs is several orders of magnitude higher than the passband of pneumoautomatic devices. Only at very high rates of increase in the input voltage (hundreds of kilovolts in a microsecond [3]), which do not arise in EHD converters, do streamers arise with attainment of the voltage U_c.

The dynamics of formation of a corona discharge in EHD converters, as in a number of other devices (e.g., high-voltage apparatus [7]), is determined by the statistical delay time of the discharge t_{st} with attainment of U_c (which characterizes the time a free electron capable of impact ionization occurs) and the time t_f of formation of a corona discharge. For electro-gas-dynamic converters with short interelectrode spacings, $t_f \ll t_{st}$, as a rule, and the time of formation of a corona discharge is $t_d = t_{st} + t_f \approx t_{st}$. In this case, t_d does not exceed several microseconds, whereas in the best pneumoautomatic devices, the operation time is about milliseconds. Therefore, in an analysis of the dynamics of EHD converters it can be ignored.

4. The mechanisms of imparting charges to dielectric liquids in strong electric fields have been studied less extensively than the mechanisms of imparting charges to gases. At present, there is no universally adopted theory of ionization of liquids [3], because of the variety of phenomena involved in the passage of an electric current through a dielectric liquid.

The studies performed showed that in sharply inhomogeneous fields (as in the case of a corona in air) the charge in a dielectric liquid is unipolar in most of the interelectrode gap and its sign coincides with the sign of the potential of the acute electrode. Moreover, unipolar conduction in the liquid arises when the voltage across electrodes of the needle–plane type reaches a certain value, as is the case in a corona discharge in gases with attainment of the initial corona voltage U_c. In this sense, the EHD effect on dielectric liquid flow is similar in mechanism to a corona discharge in gases, although the physics of formation of a bulk unipolar charge is different in these cases.

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