# INVESTIGATION OF THE EHD EFFECT IN LIQUID NITROGEN

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*The operation of a liquid nitrogen EHD converter has been studied. A number of specific features of the cryogenic EHD effect have been revealed.*

Electrohydrodynamic converters (EHDC), which convert the energy of the electrostatic field to a directed flow of a weakly conductive (dielectric) liquid, have wide prospects for application in science and engineering [1, 2]. Liquefied gases (nitrogen, hydrogen, helium, ammonia, etc.) are related to the class of dielectric liquids [3], and for this reason an EHD flow may be anticipated to originate in them. However, regardless of the great practical significance of the cryogenic EHDCs (foremost as refrigerant transport devices without moving parts), no information directly concerning investigations of the EHD effect in cryogenic liquids has been discovered in literary sources.

The goal of the present study is to investigate the existence and distinctive features of the EHD effect in liquid nitrogen.

The object under consideration is a multistage EHDC with grid electrodes made of thin wire. Figure 1 gives the structure of one stage of such an EHDC. Into tube 1 (inner diameter, 22 mm) of dielectric material (plexiglas, teflon, etc.), rings 2 of the same material are closely inserted. A high potential is applied through leads 4, to wire grid 3, which is stretched in rings 2. The distance between adjacent wires of the grid is $l$ = 2 mm. The distance $L_{in}$ = 4 mm between the pairs of heteropolar grids is fixed with the aid of inserts 5 of the same material of width $L_{ex}$ = 6 mm. We will refer to the first grid in the pair in the flow direction as the emitter, and to the second as the collector.

Experiments with high-temperature dielectric liquids (kerosene, freons, etc.) demonstrated that the EHDC structure considered possesses higher specific characteristics and efficiency as compared with other known structures having, for example, needle- or knife-shaped electrodes.

Let us derive theoretical relationships for the EHD characteristics.

After the voltage U is applied to the electrode system, a charge emerges thereon

$$Q = CU, \tag{1}$$

where

$$C = N\varepsilon_0\varepsilon S\left(\frac{1}{L_{in}} + \frac{1}{L_{ex}}\right) \tag{2}$$

is the capacitance of the electrode system and N is the number of grid pairs (stages). Here, the following conditions must be ensured

$$N \gg 1;\ l < L_{in} < L_{ex};\ L_{in} < \sqrt{S}. \tag{3}$$

If U exceeds a certain threshold value $U_c$ (the voltage of corona onset), the entire charge Q cannot concentrate at the electrodes, and its part

$$\Delta Q = CU - CU_c \tag{4}$$

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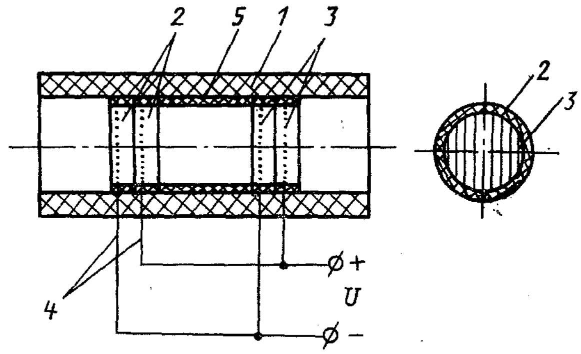


Fig. 1. Structure of an EHD converter with grid electrodes.

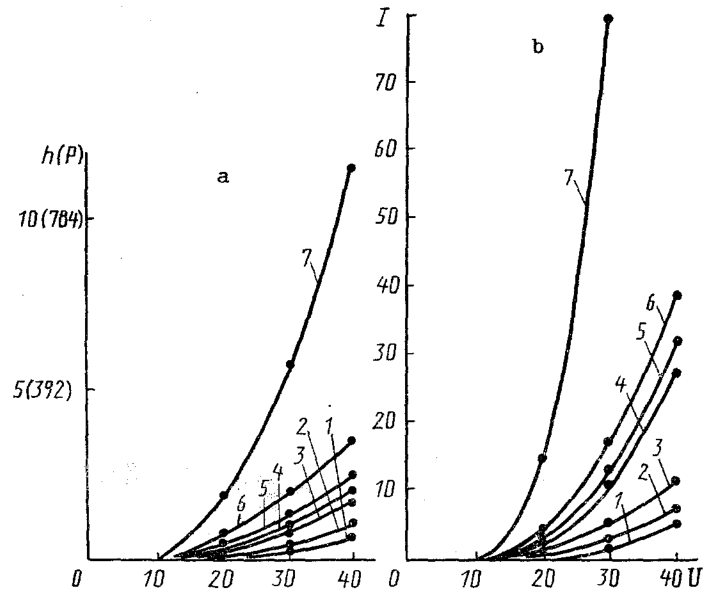


Fig. 2. Pressure head characteristics of the cryogenic EHD flow as functions of the radius of the grid electrodes and of the number of stages (a), and volt–ampere characteristic of the cryogenic EHD flow (b): 1) ∅ 0.4 mm emitter and collector, N = 1; 2) ∅ 0.05 mm emitter, 0.4 mm collector, N = 1; 3) ∅ 0.05 mm emitter and collector, N = 1; 4) ∅ 0.4 mm emitter and collector, N = 2; 5) ∅ 0.05 mm emitter, ∅ 0.4 mm collector, N = 2; 6) ∅ 0.5 mm emitter and collector; N = 2; 7) ∅ 0.05 mm emitter and collector, N = 7. h, cm; P, Pa; U, kV; I, μA.

is transferred to the liquid. It is the hydrodynamic drift of the charge that generates the current through the EHDC. We may then write the following expression for the pressure developed by the EHDC:

$$P_0 = \frac{1}{2}\frac{\Delta Q(U - U_c)}{V}, \tag{5}$$

where $V = NSL_{in}$ is the overall volume of the charged liquid in the EHDC.

Equations (2), (4), and (5) yield

$$P_0 = \frac{N\varepsilon_0\varepsilon}{2}\left(1 + \frac{L_{in}}{L_{ex}}\right)\left(\frac{U - U_c}{L_{in}}\right)^2. \tag{6}$$

The above expression disregards incompleteness of the liquid recharge on the second grid in the flow direction grid in the pair, as well as some other factors. Therefore, the exit pressure P will differ from $P_0$ by an empirical multiplier K

$$P = K\frac{N\varepsilon_0\varepsilon}{2}\left(1+\frac{L_{in}}{L_{ex}}\right)\left(\frac{U-U_c}{L_{in}}\right)^2, \tag{7}$$

where K is the efficiency. On the other hand, neglecting the hydrodynamic resistance of the EHDC, we have

$$P = \rho g h = \frac{1}{2}\rho v^2, \tag{8}$$

where g is the acceleration due to gravity and h is the height of a fountain produced by the upright EHDC. From Eqs. (7) and (8) we find:

$$h = K\frac{N\varepsilon_0\varepsilon}{2\rho g}\left(1+\frac{L_{in}}{L_{ex}}\right)\left(\frac{U-U_c}{L_{in}}\right)^2, \tag{9}$$

$$v = \left[\frac{KN\varepsilon_0\varepsilon}{\rho}\left(1+\frac{L_{in}}{L_{ex}}\right)\right]^{1/2}\frac{U-U_c}{L_{in}}. \tag{10}$$

The current traversing the EHDC is determined from the relation:

$$I = \frac{\Delta Q}{V}Sv.$$

Substituting the quantities C and ΔQ we obtain

$$I = \frac{S}{2L_{in}}\sqrt{\frac{K}{\rho}}\left[N\varepsilon_0\varepsilon\left(1+\frac{L_{in}}{L_{ex}}\right)\right]^{3/2}\left(\frac{U-U_c}{L_{in}}\right)^2. \tag{11}$$

Since

$$P_0 = \frac{IU}{Sv};\quad K = \frac{P}{P_0},$$

then, in accordance with Eq. (8), the efficiency constitutes

$$K = \frac{\sqrt{2}\rho S\,(gh)^{3/2}}{IU}. \tag{12}$$

Thus, the sought EHDC characteristics appear as

$$\begin{gathered} P \sim h \sim KN(U-U_c)^2, \\ I \sim \sqrt{K}N^{3/2}(U-U_c)^2, \\ v \sim \sqrt{KN}(U-U_c). \end{gathered} \tag{13}$$

It should be noted that in deriving these equations the liquid nature and temperature were not concretized. Consequently, in respect to the presence of the EHD effect, normal and cryogenic dielectric liquids must be equivalent.

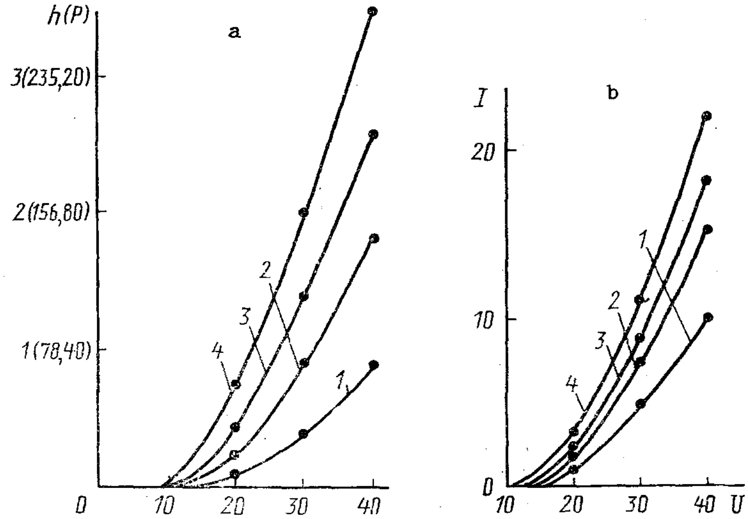


Fig. 3. Pressure head characteristic of the cryogenic EHD flow (a) and volt–ampere characteristic of the cryogenic EHD flow for a two-stage structure (b): 1) platinum-iridium alloy RII-10; 2) copper; 3) tinned copper; 4) stainless steel ÉI-708.

The cryogenic EHD effect was investigated experimentally for liquid nitrogen. The EHDC was placed vertically in a metal cryostat, with the upper end flush with the surface of liquid nitrogen. The use of a quartz glass cryostat is undesirable because the electric breakdown of the EHDC can give rise to a hydrodynamic shock, which can result in cracking of the EHDC.

The EHDC was connected to a high voltage source through a 360 MΩ limiting resistor. Having the resistance 4-5 times lower than that of the EHDC proper, in the case of the EHDC breakdown, it terminates the current accordingly to a 4-5-fold value of the normal current, and thereby prevents a fracture of the wire grids. This allows the EHDC to be tested at high voltages of up to 45 kV, with no risk of its failure.

After a high voltage was switched on, the flow developed spontaneously upward from the positively charged emitter grids, to the negatively charged collectors. The flow velocity v and pressure P, generated by the EHDC, were determined from the fountain height h.

Figure 2 presents correspondingly the characteristics P = P(U) and I = I(U) for the EHDC with grids made of wire (stainless steel ÉI-708) of different cross sections, i.e., of ∅ 0.05 and 0.4 mm. The given data make clear that the pairs with ∅ 0.05 mm wire grids have better characteristics compared with the pairs with ∅ 0.4 mm wire grids. Asymmetric pairs with one grid made of ∅ 0.05 mm wire and the other of ∅ 0.4 mm wire occupy an intermediate position.

The results are easily elucidated by a high corona activity of thin wires due to their greater surface curvature.

The form of the experimental relations P = P(U) and I = I(U) is consistent with Eqs. (13). Mean values of the efficiency, calculated from Eq. (12) for each type of the electrode pairs, fall within 15-20% (∅ 0.05 mm), 13-16% (asymmetric ∅ 0.05 and 0.4 mm grids), and 11-12% (∅ 0.4 mm).

Results interesting from the physical viewpoint have been obtained in studying the EHDC with electrode grids of various materials, viz., of stainless steel, tinned copper, and of the platinum-iridium alloy RII-10 (∅ 0.05 mm wire, N = 2) (Fig. 3).

Attention is called to the lamination of the characteristics P = P(U) and I = I(U) depending on the material of the electrode surface. In this connection, there are reasons to presume that the lamination is associated with the work function of metals: the smaller the work function, the greater the emission current from the metal surface and, accordingly, the higher the intensity of the corona processes governing the amount of charge injected to the liquid.

The metals used in the experiments have the following work functions [4]: 4.30 eV for Fe, 4.40 eV for Cu, 4.38 eV for Sn, 5.32 eV for Pt, and 4.70 eV for Ir. Thus, the above presumption is not devoid of foundation, but calls for additional experimental verification.

In the experiments, we noted instability of the liquid nitrogen EHD flows. It manifested itself in two ways. First, the fountain height underwent random variations from one test to another with the experimental conditions unchanged, and second, a gradual decrease in the fountain height was observable in some cases during continuous operation of the EHDC.

The following features are characteristic of the variations in the fountain height:

a) the fountain height in various tests differed by 1.5-2 times;

b) newly manufactured electrode grids of clean wire give the highest flow rate;

c) after the EHDC operates for 1-2 h daily for several days the flow rate falls, and a grey deposit becomes noticeable on the initially bright grid wires;

d) the flow rate grows, when the array of electrode grids been cleaned and dried in a stream of a hot air;

e) the flow rate is higher at a low atmospheric humidity.

Instability of the flow rate over time revealed itself thus:

1. Sluggishness of the flow development. After the voltage had been applied, the fountain height settled at a value after some time (up to 5-7 sec) elapsed rather than immediately. This was sometimes followed by a further slow increase in the fountain height, lasting for 12-15 min.

2. Dependence of the time of flow development on the time of interruption in the EHDC operation. When the voltage is switched off for a short time (10-15 sec) and subsequently reapplied, the flow is established at once. However, if the voltage is switched off for not shorter than 10-15 min, sluggishness of the flow development becomes noticeable.

3. Progressive reduction in the breakdown strength of interelectrode gap. In some cases, when the EHDC operated over several hours (irrespective of interruptions of the operation), a progressive reduction in the breakdown strength of the interelectrode gaps and frequent breakdowns were registered. On long-term (not shorter than a day) interruptions of the EHDC operations, the previous electric strength was hardly ever restored.

The reason for the above-described phenomena of instability of the liquid nitrogen EHD flow must, apparently, be sought in the alteration of the physicochemical properties of the electrode grid surface, directly contacting the cryogenic liquid. This is likely to result in a change of the work function of the electrode metal. However, a complete explanation of these effects requires a further accumulation of experimental data.

In conclusion we should remark that to verify the hypothesis of a convective, rather than thermal, mechanism of the liquid nitrogen flow in the EHDC we executed the following experiment. Instead of the electrode grids, we installed an electric heater coil in the EHDC casing. With thermal power of an order of magnitude greater than the EHDC power input, an elevation of liquid nitrogen above the upper cut of the EHDC casing, caused by its boiling, was an order of magnitude smaller than a corresponding fountain produced by the EHDC. Here, bubbles were visible clearly in the liquid nitrogen ejections, which was not the case with the EHDC operation.

Thus, the performed investigations confirm the existence of the cryogenic EHD effect, and at the given developmental stage the EHDCs may already be utilized as low-power pumping devices for nonaggressive, stable cryogenic liquid. A further study of specific features of the cryogenic EHD effect will permit a significant improvement of the characteristics for relevant converters.

## NOTATION

$l$, distance between adjacent grid wires; $L_{in}$ distance between grids in a pair; $L_{ex}$, distance between the nearest grids of neighboring pairs; Q, charge; $\varepsilon$, dielectric constant; $\varepsilon_0 = 8.85 \cdot 10^{-12}$ F/m; S, area of electrode grids; P, pressure, $U_c$, voltage of corona onset; V, volume of a grid pair; $\eta$, dynamic viscosity of liquid; $\rho$, liquid density; $g = 9.8$ m/sec$^2$; v, flow velocity of liquid; I, current; U, voltage.

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