

Some Hydrodynamical Phenomena Accompanying the Passage of a Current Through Insulating Liquids

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Experiments are described, conducted with turpentine, benzene, nitrobenzene, benzine and transformer oil, which indicate that in a strong, almost homogeneous electric field these liquids are set into motion, independent of the sign of the applied voltage.

SOME theoretical considerations¹ lead to the conclusion that electro-insulating liquids in a sufficiently strong electric field cannot be at rest. The usual methods of study of the motion of a liquid are difficult to apply for the observation of the hydrodynamical phenomena arising here. In particular, the mixing of colored additives inevitably changes the dielectric permeability of the electro-conductivity of the separate parts of the liquid and hence disturbs its homogeneity. Therefore, other phenomena, as for example, electroconductive convection², will be admixed with the phenomenon under investigation. The addition of light-scattering particles leads to the occurrence of cataphoresis as a masking action, and so must also be excluded.

free as far as possible from the indicated deficiencies, and controlled, so that the method, at least in principle, would record just the process under investigation.

After numerous trials, the goal was successfully attained by the combination of an optical method of high sensitivity³ and the introduction into the liquid of a negligible (as far as possible) thermal non-uniformity. The vessel (Fig. 1), with dimensions 95 x 100 x 38 mm, has a metallic bottom and two metallic side walls. The front and back walls are of plane-parallel glass. An aluminum electrode in the form of an upside down umbrella with a maximum diameter of 50 mm is lowered into the vessel. This electrode is provided with a heater consisting of several tens of turns of enameled constantan wire, indicated in the figure by dots. The heater resistance is 12.6 ohms. The vessel is half filled with the liquid being studied, and is placed in the path of a beam of light in a partially shaded mounting with a grating. The source of light is repre-

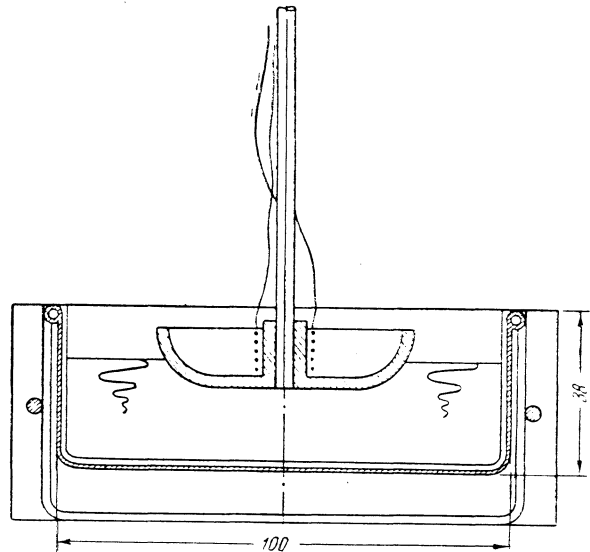


FIG. 1. Section of the model vessel

sented by a horizontal slit, with dimensions 0.7 x 11 mm, on which is focussed the filament of an incandescent lamp for an alloscope. The collimator has a focal length of 140 cm, and an objective diameter of 95 mm. The parallel rays leaving the collimator traverse the vessel and continue further through an objective with a diameter of 110 mm and a focal length of 165 cm. A grating with horizontal rods is placed in the focal plane of this objective. There are 12 rods, 1.281 ± 0.003 mm in diameter, 38 mm long, and separated by 2.95 ± 0.05 mm between their axes. A telescope with a focal length of 35 cm and with a Ramsden ocular was placed behind the grating. The vessel, which is translucent throughout, can be observed visually and photographed through the telescope and grating. The exposure time required for film with a sensitivity of 90 units GOST was of the order of 0.5 sec. The location of the grating was controlled in such a way that in the absence of the process, the liquid appeared dark.

When the electrode is heated, a temperature gradient arises in the liquid, the field becomes clear

¹G. A. Ostroumov, J. Tech. Phys. (U.S.S.R.) 24, 1916 (1954), Sec. IV, Eq. (18).

²G. A. Ostroumov, J. Exptl. Theoret. Phys. (U.S.S.R.) 29, 529 (1955); Soviet Phys. 2, 428 (1956).

³G. A. Ostroumov, J. Tech. Phys. (U.S.S.R.) 24, 2045 (1954).

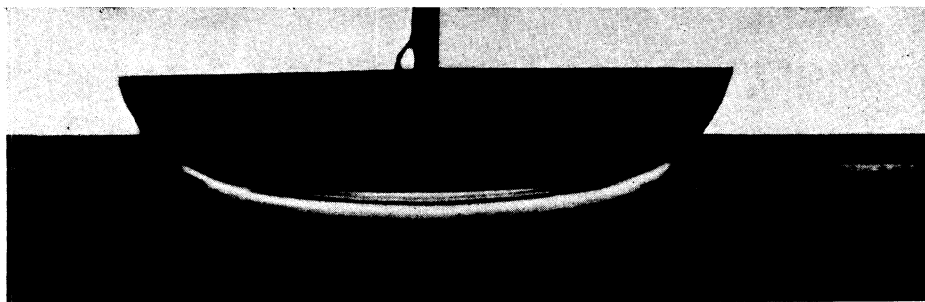


FIG. 2. Photograph of the initial stage of heating of the electrode, without high voltage

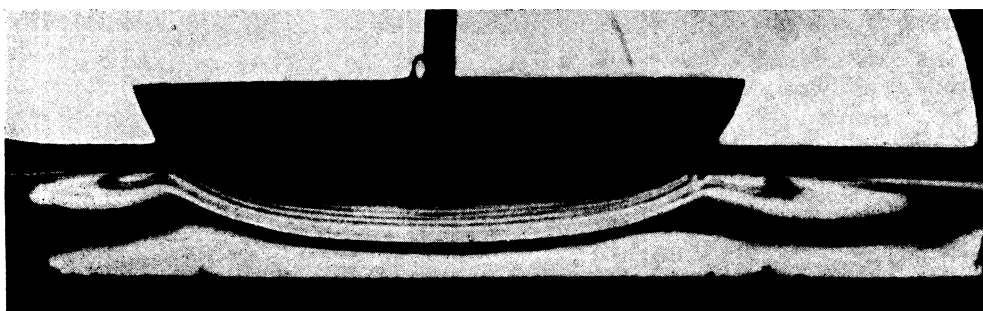


FIG. 3. Photograph of the final stage of heating of the electrode, without high voltage.
Heating power, 0.2 W.

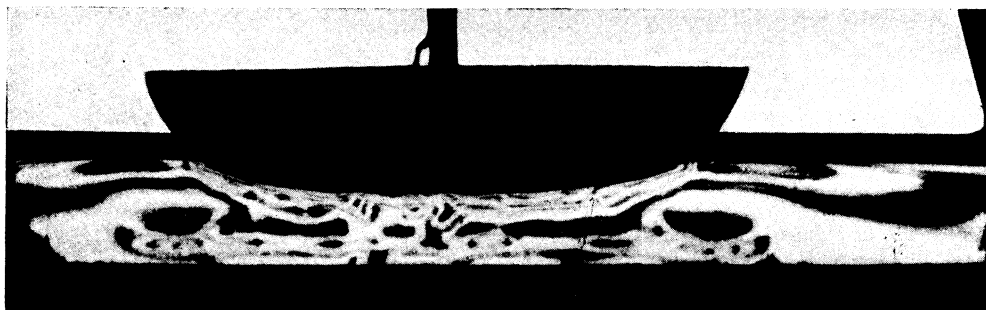


FIG. 4. Heating power, 0.2 W. High voltage around 3000 V.

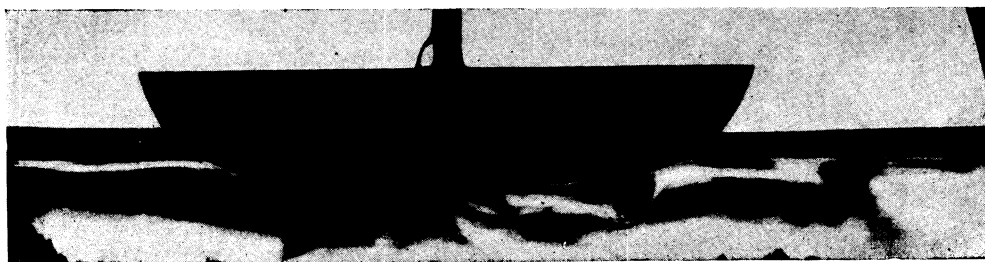


FIG. 5. Heater switched off. High voltage around 3000 V.

in certain places, and thermal convection begins. Figure 2 is a picture corresponding to an initial stage of heating of the electrode in turpentine. Fig. 3 represents the final stage of heating, the power expended being 0.20 w.

If a constant voltage of the order of several hundred volts is now applied between the electrode and the bottom of the vessel, the stable picture will be markedly distorted, as reflected in Fig. 4. The dark and light streaks move rapidly, and vigorously change their configuration, disclosing an intensive hydrodynamic process. The most vigorous motion is noticeable under the central part of the electrode.

The motion in general gives the impression of being irregular; however, certain peculiar details are noticed. In particular, through the motion of certain dust particles (the rest of the dust sticks to the electrode) it is possible to follow the general circulation of the liquid--from the free surface it constricts towards the upper electrode, generally sinks downward under it, spreads along the bottom, and rises to the surface again along the walls. The direction of this motion does not depend on the sign of the applied voltage. The intensity of the motion did not appear to depend on the sign of the applied voltage. However, the intensity of the motion of course increased with increased voltage. This general motion is comparatively slow, but it is still more rapid than the convective thermal motion which could be noticed during the heating of the electrode in the absence of the field, and which was exactly in the opposite direction.

In the course of not many seconds after the switching off of the high voltage, the normal picture of thermal convection is re-established (see Fig. 3). This lapse of time is in good agreement with the magnitude of the thermal conductivity of turpentine-- $8 \cdot 10^{-4}$ cm²/sec.⁴ The re-establishment is the resolution of thermal nonuniformities, caused by the hydrodynamic process.

It might have been expected that with the heater switched off and with a sufficiently large voltage, conduction current and Joule heating of the liquid would occur, leading to approximately the same effect of thermal convection as with a warm heater: the greatest heating being obtained under the electrode, the warmed liquid would rise upwards and spread under the free surface. Actually, things take place otherwise: large, irregular regions of translucence of the field of view in the liquid arise, move about, and fade away (Fig. 5), voltage around 3000v). The motes disclose an irregular mixing of the liquid generally in the same direction as des-

cribed above (see Fig. 4). Hence, it may be concluded that the electrical causes of the motion of the liquid are far stronger than the gravitational effects associated with uneven heating, and in general are directed opposite to the latter.

If a variable voltage at industrial frequency is applied to the electrode, the change in the picture of thermal convection (Fig. 3) is scarcely noticeable, the motion of the motes being slightly less regular. At large voltages hydrodynamic effects were noticed, produced by the quivering of motes with one end adhering to the electrode and oriented along the field, and also by the phenomenon of "electric wind" (in a liquid!) arising in the neighborhood of the ends of some motes. Sometimes these motes undergo an amusing boring motion of an astonishingly large velocity (many tens of revolutions per second).

These effects were also observed in certain other liquids, not subjected to any special purification.

Benzene has a very large specific resistance (therefore the conduction current is extremely small). It is set into intensive motion at small voltages. This motion is readily observed with a hot as well as with a cold electrode.

An enormous current, 3 ma at 600 v, flows through nitrobenzene (in contrast with benzene). With a hot electrode, electrical convection develops mainly around the electrode, and is very intensive. With a cold electrode it spreads through the entire thickness of the liquid. With a cold electrode, the general direction of flow coincides with the direction of purely thermal convection (and not the reverse as with turpentine and benzene). Thanks to the large number of motes not adhering to the electrodes, the hydrodynamic motion in the space between the electrodes is readily traced,--it calls to mind the Benar cell. Through the motion of motes, which skip between the electrodes, one may readily observe how the motes that become charged by contact with one electrode tear away from it, not getting as far as the other electrode, giving up their charge to the liquid, and in time coming to a standstill.

In aviation benzine, the same effects are noted as in benzine or turpentine, but especially clearly seen is the rotary motion of the adhering motes. In transformer oil, in consequence of its large viscosity, the hydrodynamic effects are slowed down considerably, and the thermal effects are somewhat accelerated. In ethyl alcohol, in view of its comparatively large electro-conductivity, the hydrodynamic effects are different, and merit separate investigation.

It is evident from the above-mentioned photographs that in many places the dark stripes are cut by narrow light lines, and conversely. This indicates that the phenomenon of optical diffraction is taking place. Through this effect we can estimate the sensitivity of the method, used with photography. Let us assume that in some region of the photographed model, its optical thickness varies according to the law

$$nS = a_0 + a_1y + a_2y^2. \quad (1)$$

where y denotes a vertical coordinate on the model. Then the region around $y=0$ is projected on the zeroth rod of the grating, the region around $y=y_1$ is projected on the first rod of the grating, the region around $y=y_2$ —on the second, and so on. The zeroth of these regions will be distinguished in that for it, $(d(nS)/dy)_0 \approx 0$, the first in that for it,

$$\begin{aligned} y_0 &= 0; \\ (d(nS)/dy)_1 &= a_1 + 2a_2y_1 = d/p; & y_1 &= (d/p - a_1)/2a_2; \\ (d(nS)/dy)_2 &= a_1 + 2a_2y_2 = 2d/p; & y_2 &= (2d/p - a_1)/2a_2. \end{aligned}$$

Hence the distance between stripes is

$$y_1 - y_0 = (d/p - a_1)/2a_2; \quad y_2 - y_1 = d/2pa_2.$$

The stripes will be equi-distant if $a_1=0$. Then taking account of Eq. (2), $\Delta y \equiv y_2 - y_1 = y_1 - y_0 = d/2a_2p = \lambda p/d$. Hence $a_2 = \lambda/2(\Delta y)$.² Setting this in Eq. (1), we find for the first stripe

$$(nS)_1 - (nS)_0 = a_2y_1^2 = \lambda/2. \quad (3)$$

For the second stripe

$$(nS)_2 - (nS)_0 = a_2y_2^2 = 2\lambda$$

and so forth. Hence it is evident that in our case, when the sharpness of the stripes already suffers from diffraction, the first dark stripe after the initial zeroth darkening corresponds to a path difference through the model of less than half a wavelength.

According to the Lorentz-Lorenz formula for the square of the index of refraction, we find for small changes of the temperature around $t=0$.

$$\frac{n^2 - 1}{n^2 + 2} = A\rho_0(1 - \alpha t); \quad (4)$$

$$\frac{dn}{dt} = - \frac{(n^2 + 2)(n^2 - 1)}{6n} \alpha.$$

$(d(nS)/dy)_1 \approx d/p$, the second in that $(d(nS)/dy)_2 \approx 2d/p$, and so forth.

Each of these regions will be registered on the picture by dark stripes with light spaces between them. The smallest angular distance between neighboring stripes, still providing sharpness of the stripes, is obtained thus:³

$$\begin{aligned} (y_2 - y_1)/p & \\ &= (y_1 - y_0)/p = x/f = \lambda/d. \end{aligned} \quad (2)$$

where p is the distance from the model to the grating, f is the focal distance of the camera, x is the distance between the rods of the grating, and λ is the wavelength of light in the cavity of the camera. Writing explicitly the three relations presupposed by Eq. (1), we find,

For the first stripe according to Eq. (3), and taking into account that $n_1 < n_0$,

$$(n_1 - n_0)S = -\Delta nS = -(dn/dt)S\Delta t = \lambda/2.$$

or, according to Eq. (4),

$$\Delta t = - \frac{\lambda}{2S(dn/dt)} = \frac{3\lambda n}{S(n^2 + 2)(n^2 - 1)\alpha}.$$

The geometrical length of the path of a beam of light between the electrodes can be estimated by the diameter of the electrode, $S=5$ cm. For turpentine,⁴ the index of refraction is $n=1.47$ and the thermal coefficient of expansion is $\alpha = 0.94 \times 10^{-3}$ deg.⁻¹ Hence the first dark stripe corresponds to a mean temperature rise of $\Delta t = 0.98 \times 10^{-2}$ degree along the ray. This estimate illustrates the sensitivity of the applied optical method. It forces us to believe that the intense hydrodynamic process observed could not be due to such a small temperature gradient. This is not that process in strongly non-uniform fields which was studied earlier in gases and is now investigated in liquids.⁵ It should be expected that this process is conditioned not only by some inhomogeneity of the field, but also by peculiarities of the electric field in mobile

⁴D. Kei and T. Lebi, *Handbook of Experimental Physics*, III, Moscow, 1949.

⁵H. Senftleben and E. Bultmann, *Physik Z.* 1 36, 389 (1953).

(fluid) imperfect (conducting) dielectrics.

In this connection it should be expected that the molecular nature and chemical composition of the liquid does not play a decisive role here. This process must take place not only in pure liquids, but also in mixtures and solutions. The only requirement is that there be no evident phase division (a solution must not be turbid or opalescent). By this token, this investigation should be demarcated from the investigation of the passage of current through pure liquids where all of the effects can be accounted for by the molecular composition and degree of purity of the given chemical sub-

stance.^{6,7} On the other hand, the investigated effect is demarcated also from those specific effects where a many-phase liquid plays the essential role, for example, cataphoresis or electromagnetophoretic effects.⁸

⁶A. Nikuradse, Z. Physik 34, 97 (1933).

⁷E. Schmidt u. W. Leidenfrost, Forsch. Geb. Ing. 19, 65 (1953).

⁸A. Kolin, J. Appl. Phys. 25, 1065, (1954).

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52