RESULTS OF MEASUREMENT OF THE ELECTRICAL CONDUCTIVITY OF INSULATING LIQUIDS

G. A. OSTROUMOV

Leningrad State University

A hydrodynamical explanation is proposed for the deviation from "Ohm's law" encountered in measurements of the specific electric conductivity of some liquids. The explanation is confirmed by the experimental data reported in the literature.

IN studying the electric conductivity of liquids, experimenters frequently encounter "deviations from Ohm's law": the voltage is found to be proportional to neither the current nor the distance between electrodes. Explanations for this circumstance are sought on the basis of gas electronics with the possible motion of the liquid medium neglected.

For example, Goodwin and Macfadyen [1] (see also [2], p. 340) report measurements of the resistance of highly purified n-hexane between flat electrodes (no dimensions indicated) spaced 550 to 420 μ apart. The plotted results (Fig. 6 of [1] or Fig. 230 of [2]) show that the current increases strongly with increasing voltage. An explanation, which is not too rigorously confirmed by experiment (the bending of the lines in Fig. 7) is sought in the "simplest theory of impact ionization": the liquid is considered to be as a whole a stationary medium, through which the ions move and are sometimes recombined.

Yet the possible role of hydrodynamic phenomena in the process involved in the passage of current through liquids (and gases) has been mentioned earlier on several occasions, for example in [3,4]. In particular, even primitive dimensionality considerations, say the very listing of the possible cases, make it possible to establish (neglecting the inhomogeneity of the dielectric constant and electrostriction) that a real liquid capable of electrolysis cannot be immobile in a strong electric field between stationary electrodes. The spontaneous motion of the liquid under these conditions was noted many times (see, for example,[5], Fig. 5). In the case of laminar spontaneous motion of the liquid, the electric current flowing is proportional to the cube of the field intensity [[4], formula (19)], so that "Ohm's first law" is not satisfied.

If we replot Fig. 6 of [1] in new coordinates (the cube root of the flowing current i vs. the potential difference between the electrodes El = U) we obtain the plot shown in Fig. 1. It is seen from this
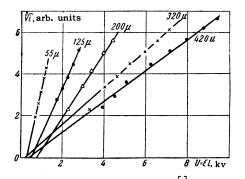

FIG. 1. Results of replotting Fig. 6 of [1] for n-hexane. The numbers on the curves denote the interelectrode distance in microns. The liquid was in spontaneous laminar motion.

plot that the experimental points (with several isolated exceptions) fit well straight lines with abscissa intercepts whose average is approximately 500 volts. This shows that the applied voltage produces essentially in the liquid an electric field, the cube of which is proportional to the mean density of the electric current in the spontaneously moving liquid. The remaining small part of the voltage is needed to overcome the surface resistance on the boundary of the electrodes (and perhaps also to remove the electrons from the metal of the electrodes), and to produce a current of sufficient strength (see Fig. 49 in the book by Levich,[6] Sec. 46, p. 252).

If we now relate the slope of the resultant lines with the interelectrode distance, we obtain from Fig. 1 the plot shown in Fig. 2, from which it is seen that for a specified current the voltage applied to the liquid (i.e., after subtracting the voltage drops at the electrodes) is proportional to the distance between electrodes: "Ohm's second
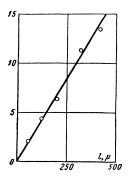
FIG. 2. Reciprocal of the slopes of the lines of Fig. 1, in arbitrary scale, as a function of the distance between electrodes. The "effective resistance" is proportional to the distance between electrodes.

law" holds. This means that we indeed deal here with a relation between the current density and the field intensity within the layer of moving medium (averaged values), and not with an edge or wall effect.

If these considerations are true, then we must recall (see [4]) that the coefficient of proportionality between the current and the cube of the field intensity is not at all connected with the specific electric conductivity of the liquid, but is obtained essentially by dividing the square of the dielectric constant of the liquid by its dynamic coefficient of viscosity. To measure the intrinsic conductivity of an electric insulating liquid it is necessary to use a low electric field intensity (see [4], table on p. 1918, with benzene as an example).

G. A. Skanavi ([2], p. 270, Fig. 156) gives the measured values of the electric conductivity of transformer oil. These show once more that the current is not proportional to the voltage, and that certain differences in the five cited curves can be attributed to the shapes and finishes of the electrodes. Figure 3 shows curves 1, 2, 3, and 5 replotted as in Fig. 1, but for different electrode shapes. It is seen that the lines drawn through the points pass either through the origin or very close to it. We can therefore conclude that here, too, the liquid was in spontaneous laminar motion during the measurements.

Curve 4 corresponds to a particular set of carefully cleaned flat copper electrodes, has a different form and is therefore not included in the foregoing group of replotted curves. In the text this curve is pointed out as being one example of particularly precise results. Yet, as shown in [4] (formula 22), if the liquid is in turbulent spontaneous motion the current density is proportional to the square of the field intensity, the coefficient of proportionality being essentially determined by the dielectric constant and by the density of the liquid and also by the linear dimensions of the instrument, and is not at all connected with the electric conductivity.
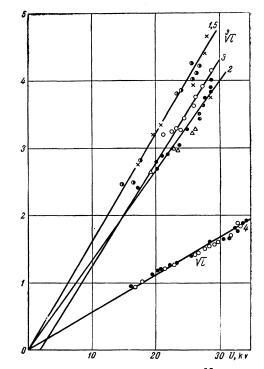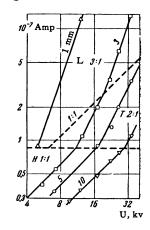

FIG. 3. Result of replotting Fig. 156 of[2] for transformer oil. Curve 4 is for liquid in spontaneous turbulent motion, while the remaining curves are plotted for laminar flow.

Curve 4 of Fig. 3 is the mate of curve 4 in Fig. 156 of[2], having the same values of the voltage (abscissa), but the ordinates are now the square roots of the current (arbitrary scale). It is seen that the points all fit quite well a straight line passing through the origin. This means that the liquid was in spontaneous turbulent motion during the measurements. The conciseness of the original text does not enable us to advance any hypothesis to explain the change of the laminar motion of curves 1, 2, 3, and 5 into the turbulent motion of curve 4.

Some light is cast on this question by Fig. 10 of the paper of Toriyama [7] on the electric conductivity of transformer oil. In Fig. 4 we show in

FIG. 4. Result of replotting Fig. 10 of[7] for transformer oil. The figures on the curves are the distances between flat electrodes, in millimeters. In the regions S, L, and T the liquid was stationary, laminar, and turbulent, respectively.

logarithmic coordinates the dependence of the current on the applied voltage, obtained from the aforementioned diagram. The entire diagram consists evidently of regions demarcated by the dashed lines and marked S, L, and T. In the region corresponding to low current densities (less than 8.5×10^{-8} amp/cm^2), the current is approximately proportional to the voltage and inversely proportional to the distance between the plane electrodes (diameter 25 mm), so that both "Ohm's laws" are obeyed satisfactorily. It must be assumed that the liquid was stationary during the measurements (region S). The specific resistivity, calculated from the data for this region, is found to be 2.1×10^{12} ohm-cm $\pm$ 13 percent.

The region corresponding to large currents but small distances between the electrodes, i.e., to small applied voltages, shows a cubic dependence of the current on voltage (the slope of the lines is 3 : 1) and therefore indicates that the spontaneous motion of the liquid is laminar (region L).

At large distances between the electrodes, and accordingly at large applied voltages, the two foregoing regions become separated by a third one, characterized by a quadratic dependence of current on the voltage (slope of curves 2 : 1). It must be assumed that this is a region where the liquid is in turbulent spontaneous motion (region T).

It is possible to see on this diagram that as the distance between electrodes is increased and if the applied voltage is high (for example, 16 kv), the liquid between electrodes is first stationary (region S), and the current is low and obeys "Ohm's law." After a certain sufficient field intensity is reached (about 40 kv/cm) the liquid goes into spontaneous turbulent motion and the current increases as the square of the field intensity; the effective resistance is then inversely proportional to the field intensity. As the electrodes come closer together, the motion of the liquid begins to be slowed down by the viscous boundary layer adhering to the electrodes and becomes laminar in spite of the continuing increase in field intensity; the effective resistance decreases as the inverse square of the field intensity. No region of turbulent motion was observed at low voltages.

The small number of points on the last diagram and their relative spread did not enable us to establish with sufficient reliability the limits of the indicated regions. More detailed experimental investigations are therefore necessary, as well as attempts at a theoretical solution of the nonlinear problem of electric convection, following, Benard and Rayleigh,* for example.

A. Shteĭnberg and R. Shatrova participated in the reduction of the curves.

---

*We note that an error has crept into[4], namely that in Sec. IV of the article the letter μ denotes (unlike the remaining sections of the article) not the dynamic but the kinematic viscosity of the liquid. This error occurred also in the numerical values for air, listed in the table on p. 1918. The error was corrected in[8].

---

[1] D. W. Goodwin and K. A. Macfadyen. Proc. Phys. Soc. **B66**, 85 (1953).

[2] G. A. Skanavi, Fizika dielektrikov (Physics of Dielectrics) Fizmatgiz, (1958).

[3] A. Nikuradze, Zhidkie dielektriki (Liquid Dielectrics), Gostekhizdat, (1936), p. 65.

[4] G. A. Ostroumov, J. Tech. Phys. (U.S.S.R.) **24**, 1915 (1954).

[5] G. A. Ostroumov, JETP **30**, 282 (1956), Soviet Phys. JETP **3**, 259 (1956).

[6] V. G. Levich, Fiziko-khimicheskaya gidrodinamika (Physico-Chemical Hydrodynamics), Fizmatgiz, (1959).

[7] Y. Toriyama. Arch. Elektrotechnik **19**, 31 (1927).

[8] G. A. Ostroumov, J. Tech. Phys. (U.S.S.R.) **25**, 366 (1955).

Translated by J. G. Adashko
82