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NEW DATA ON THE ELECTRIC PUNCTURE OF ALUMINUM SUSPENSIONS IN DIELECTRICS

(Presented by Academician P. A. Rehbinder on 25 XII 1964)

As is known ([1,2]), when a constant electric field is applied to suspensions of powdered aluminum in liquid dielectrics, for example in benzine, these suspensions undergo structuring, which at E_{cr}, equal for the powder studied to ~ 4000 V/cm, ends in their puncture. The abrupt transformation of suspensions from dielectrics into conductors is due to the formation, within the structures that have arisen, of a bridge of aluminum particles short-circuiting the circuit. The type of puncture described is of interest not only as a distinctive physical phenomenon whose mechanism is still far from entirely clear, but also because it is to some extent typical of the behavior of many other analogous disperse systems and, finally, models the puncture of liquid dielectrics, which in practice are rarely completely pure and homogeneous ([3,4]). Combining the properties of a dielectric (with allowance for the surface oxidized layer) and of a highly conducting metal, aluminum in the process of structuring of its suspensions makes it possible to reveal effects that cannot be detected in suspensions of other metals.

For a more precise phenomenological description of the process we decided to carry out motion-picture recording of its most important stages. The high-voltage setup for producing puncture was in principle analogous to the previous one ([1]). The glass cuvette with stainless-steel electrodes was also similar to that used earlier; the distance between the electrodes was 2 mm. Filming was carried out continuously, in transmitted light, by means of a stationary microfilm apparatus MKU-1, at a speed of 0.25 frames/sec. The size of the aluminum powder particles varied from fractions of a micron to several microns, with the maximum of the size-distribution curve falling on particles of size 1 μ. Aviation benzine B-70 served as the dispersion medium.

The most characteristic of the frames obtained, illustrating the development of the structuring process and its finale—the puncture—are presented in Fig. 1.

Fig. 1. Film frames recording various stages of structuring

Figure 1: Fig. 1. Film frames recording various stages of structuring

Frame I captured the moment preceding puncture. The interelectrode space is filled with aggregates of aluminum particles oriented along the field lines, which, however, does not prevent the system from remaining a dielectric. Frames II and III record the moment of the just-completed puncture, which brought about a drop in the field strength and the shedding from the interelectrode space of aluminum aggregates that did not take part in forming the bridge. Frame IV shows the bridge in a field of strength 1 V/cm immediately after puncture. Removal of the field has no effect on the external appearance of the bridge. Frames V and VI show the effect of "overturning" of the bridge, when, under the influence of a gradual increase in voltage, it first straightens slightly and then "overturns," i.e., turns with the arrow of curvature upward, in which position it can remain until the field is removed. Incidentally, the "overturning" effect manifests itself differently depending on the strength of the current passed through the bridge.

At a current of the order of 10–100 μA, the effect described earlier (^{2}) is observed; at a current of the order of 10–100 mA, the one described here.

Finally, frames VII–IX show a bridge that underwent rupture and was restored again under the action of an already comparatively weak field. It is characteristic that the rupture that occurred at one point did not entail complete disaggregation of the bridge. This testifies to the strength of the bonds between its links.

The cinematographic picture presented here agrees very closely with that drawn earlier (^{1,2,8}).

Fig. 1. Film frames recording various stages of structuring

Next we again returned to the fundamental questions concerning the structure of the bridge being formed, and the nature of the forces to which it owes its genesis and existence. For this purpose, oscillograms of the current and voltage of the bridges were taken. An MPO-2 loop oscillograph with an additional continuously adjustable voltage source was connected into the circuit of the high-voltage setup. During oscillography, the cuvette with the dispersion system under study was disconnected from the high-voltage source and connected into the oscillograph circuit. In parallel with the cuvette, a definite standard resistance (100 ohms) was connected, and simultaneous recording was made of the currents through this resistance and through the aluminum bridge; this made it possible to construct the current–voltage characteristic of the bridge (Fig. 2).

In addition to suspensions of aluminum in gasoline, aluminum powders impregnated with gasoline were also studied; their structuring was caused by the immersion of electrodes into them.

Fig. 2. Current-voltage characteristics of bridges without a loop (a) and with a hysteresis loop (b)

Figure 2: Fig. 2. Current-voltage characteristics of bridges without a loop (a) and with a hysteresis loop (b)

The curves $i = f(V)$ (Fig. 2), up to the strongest currents sustained by the bridge, have a monotonic character. The initial portions of these curves are in all cases practically rectilinear (Ohm’ s law is obeyed); then their angle of inclination begins to decrease (the resistance increases).

Fig. 2. Current-voltage characteristics of bridges without a loop (*a*) and with a hysteresis loop (*b*)

In the region of nonlinearity the bridges become considerably less stable: the slightest push is sufficient for them to be destroyed. This destruction may be either irreversible or reversible, when conditions exist for welding the rupture points.

On the oscillograms these reversible destructions— “rearrangements” —find their expression in a fall and the subsequent rise of the current in the bridge circuit and in “spikes” of current in the circuit of the known resistance; on the current-voltage characteristic, the “rearrangements” of the bridge appear as breaks in the curve (in Fig. 2b this rearrangement is marked by arrows).

The branches of the current-voltage characteristics obtained when the voltage is increased and when it is decreased coincide with one another in some cases (Fig. 2a), while in others (Fig. 2b) they do not coincide, forming a peculiar hysteresis loop. This loop is formed only when the above-described “spike” is observed on the oscillogram. It follows from this that the hysteresis loop arises as a result of a rearrangement of the bridge.

The observed deviations from Ohm’ s law are evidently due to the release of Joule heat. The mean temperature T of the bridge (along its length) can be found approximately from the expression

$$R = R_0[1 + \alpha(T - T_0)], \tag{1}$$

where R is the resistance at temperature T; R_0 is the resistance of the same

bridge at zero current (at ambient temperature T_0); α is the temperature coefficient of the electrical resistivity of aluminum.

Taking into account heat release ($\sim iV$) and heat removal from the bridge ($\sim (T - T_0)$), it is easy to obtain the following relation between the electrical parameters of the bridge (under steady-state conditions):

$$R/R_0 - 1 = kiV, \tag{2}$$

where k is a coefficient depending on the thermophysical characteristics:

$$k \sim \alpha/\gamma \tag{3}$$

(γ is the coefficient of heat transfer to the surrounding medium, composed of thermal conductivity and convection). The coefficient k determines the nonlinearity of the current-voltage characteristic of the bridge.

Owing to the low thermal conductivity of gasoline, heat removal from the bridge in the case of a suspension is apparently effected mainly by convection of the liquid; in the case of a powder impregnated with gasoline, by heat transfer to neighboring particles. If it were possible sharply to weaken the heat removal, then the bridges should have more nonlinear characteristics (a larger value of the coefficient k). This was achieved by obtaining bridges in an air medium.

Needle electrodes under voltage were immersed in aluminum powder and, after the appearance of current in the circuit (breakdown), were raised again; they turned out to be short-circuited by an ordinary bridge made of aluminum particles. Comparative data on the values of k for bridges in different media are given in Table 1.

Processing of the experimental data by equation (2) showed that, indeed, an increase in nonlinearity takes place as heat removal becomes worse.

Table 1

Nonlinearity of the current-voltage characteristics of bridges as a function of heat-removal conditions

Medium	Number of bridges tested	k_{av}
Aluminum powder impregnated with gasoline	25	0.43
Gasoline	35	1.23
Air	25	2.08

The value of E_{cr}, as has now been established, depends not only on the size of the aluminum particles (^{1,2}), but also on other factors: it was observed that even with light blows on the wall of the cuvette, breakdown occurred at a considerably lower value of E than in the case when the cuvette was at rest. Thus, there exists a "push effect," which lowers the value of E_{cr}, sometimes by a factor of two.

At the same time, the higher E is, the more effectively the push acts (see Table 2). This effect is consistent with Auerbach' s observations on the behavior of coherers (^{5}).

Table 2

Decrease of E_{cr} under the influence of shaking
(n—number of breakdown events out of 10 tests)

E, V/cm	1600	1800	2000
n	0	8	10

The facts presented serve as confirmation of the earlier suggestion that the connection between the individual links of the bridge is a metallic connection, and that during breakdown "welding" of the aluminum particles occurs. At the same time, the character of the oscillograms obtained indicates that, while the bridge is under current, the forces of the electric field also play a large role, permanently restoring the disrupted contact between the links of the bridge and imparting to it a certain stability.

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Note: Figure translations are in progress. See original paper for figures.