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Electrical discharge in condensed matter at phase transitions

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The discharge process in I-40A oil during its crystallization was investigated. The solidification of the liquid with the electrical discharge inside it did not lead to the termination of the discharge. At the same time, the breakdown of a single frozen drop does not occur even at voltages an order of magnitude higher than the breakdown voltage in a liquid. Spectroscopy of the electrical discharge in a single drop demonstrates its identity with the discharge in a bulk of liquid.

Keywords: liquid dielectrics, electrical breakdown, crystallization, melting, light emission spectrum.

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Electrical discharge in liquids has been studied in much less detail than gas discharge. Specifically, it still remains debatable what comes first in the process of electrical breakdown of liquids: the formation of a vapor phase or the electrical discharge itself [1]. In view of this, it seems logical to examine the electrical discharge in liquid during phase transitions in it. The results of examination of a discharge in liquid with varying thermodynamic parameters of SF_6 were presented in monograph [2]: sharp changes in breakdown electric field strength were detected neither in the transition from a single-phase system to a two-phase one (during boiling) nor at supercritical parameters. The author of [2] concludes that the „importance of the phase transition in this case is incommensurate with the attention paid to it in studies of the breakdown mechanism of liquids."

The present study is focused on the influence of the liquid–solid phase transition on electrical breakdown of the medium.

Experiments with the setup discussed in [3] were carried out first: a discharge in oil I-40A between two electrodes immersed to a depth of ~ 10 mm was investigated. Electrodes were made of copper with a ZnCl coating; their diameter was 1 mm, and the interelectrode distance was 2 mm. The current in the circuit was measured using a Fluke 17B multimeter. The error was $1.5\,\% + 3$ within the entire measurement range. The voltage level was determined based on the generator readings.

When voltage was applied between the electrodes, an electrical discharge was initiated (see [3] for details). The studied liquid was then frozen: liquid nitrogen was poured from the top, forming an ice crust that covered completely the discharge region (both the liquid surface and the electrodes). According to the thermocouple sensor readings, the ice temperature dropped below $-20\,^\circ$C, which is consistent with the data on the I-40A oil crystallization temperature: $-15\,^\circ$C (GOST 20799−88).

At the start of the experiment in the configuration described above, a room-temperature discharge in liquid was observed at voltage $U = 2.5$ kV and current $I = 37\,\mu$A in the circuit (Fig. 1). When liquid nitrogen was introduced (the procedure took about 2 min), the current in the circuit decreased briefly to $2.8\,\mu$A at a voltage of 10.9 kV; i.e. the discharge became significantly weaker, but was not disrupted completely. The error corresponding to the specified current value was $0.3\,\mu$A; no glow was observed at this moment. Following the formation of ice, the voltage fluctuated from 2.6 to 4.0 kV for ~ 7 min at a current of $38-62\,\mu$A; no glow was observed, which may be attributed, among other possible factors, to the opacity of ice. As ice thawed noticeably, individual flashes appeared, and the current in the circuit rose briefly to $98\,\mu$A; the voltage at this point was 4.4 kV. After that, the discharge parameters returned to their earlier levels: $U = 2.5-5$ kV and $I = 39-60\,\mu$A. Flashes continued for ~ 2 min, during which time the discharge region became completely free of ice and almost transparent. The flashes then stopped, and the discharge regime changed dramatically within ~ 1 s: no glow was observed ($U = 1.8-2.3$ kV and $I = 238-295\,\mu$A). This regime change was noted in multiple experiments.

It may be concluded that the crystallization of liquid failed to disrupt the electrical discharge in it: although no glow was observed, the current in the circuit was maintained at all times. Moreover, the electrical parameters of the discharge in ice are approximately the same as those corresponding to the discharge in liquid. With the exception of the last phase of the process, the points of the current–voltage curve fit well into a single dependence, which may be approximated roughly by a power function (Fig. 1). It should also be noted that the formation of a vapor phase in the discharge region was not observed in the examined process (even after thawing of ice).

The method of forming the solid phase was then changed. Further experiments were carried out with a single drop of oil I-40A hanging (due to surface tension forces) between two electrodes mounted in air at a distance of ~ 1 mm from each other. The drop was frozen by vapor of liquid nitrogen positioned in a reservoir under the working area, but remained as transparent as in the liquid state. Following freezing, a voltage up to 14 kV was applied to the working area; breakdown and glow were not observed. When the reservoir with liquid nitrogen was removed, the drop melted (this was made obvious by a change in its shape), and a stationary electric discharge was observed in it at a voltage of ∼ 1.4−1.6 kV.

The spectrum of glow observed in the liquid drop recorded with an AvaSpec-2048 spectrometer (with a resolution of 2.4 nm) is shown in Fig. 2. It is rather noisy, since the discharge region is small and the glow is fairly weak. In general, this spectrum is similar to the one reported in [3], where the discharge between two electrodes immersed completely in liquid was investigated, and is observed both in the case of an electric discharge in oil I-40A and in various kinds of its luminescence. The electric discharge spectrum recorded in a single drop differs from the one studied in [3] in that it lacks the H_α line and features a fairly bright A peak.

Spectral peak A (Fig. 2) was not observed in some experiments. Apparently, it corresponds to two overlapping emission lines (435.13 and 435.15 nm) of oxygen ions transitioning from the $2s^22p^2(^1D)3p$ level. The third line (with a wavelength of 576.1 nm) in the considered range corresponding to the transition from this level was not observed due to a much lower transition probability [4]. Although the origin of this line is beyond the scope of the present study, it should be noted that a similar peak was found in [5] in experiments with other hydrocarbon liquids.

Thus, a breakdown of the liquid phase was observed for a single drop and was accompanied by its glow at a voltage of ∼ 1.5 kV, while a breakdown of the solid phase did not occur, even at a voltage as high as 14 kV. Such a significant difference in voltage may imply that mechanisms infeasible in a solid body are essential for the electrical breakdown of liquid. The formation of a vapor phase inside a liquid one could be a mechanism of this kind: although the emergence of bubbles in a drop was naturally not observed, it is possible that a stationary gas cavity, which is hard to detect given its small size, did form in it.

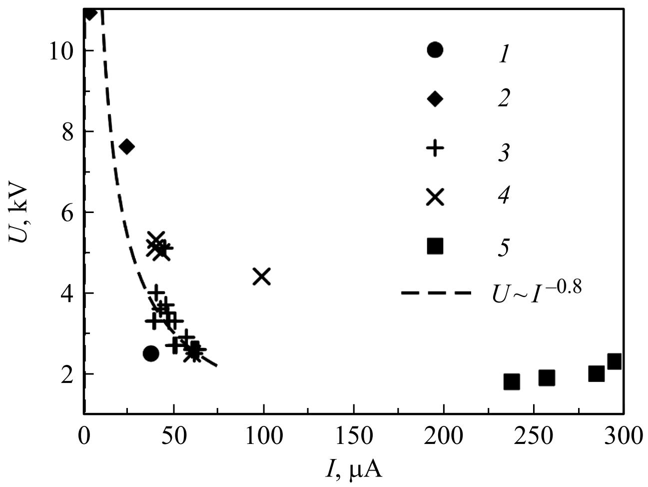

Figure 1. Current–voltage curve of a discharge in oil I-40A during a phase transition. *1* — Liquid, *2* — solidification, *3* — ice, *4* — melting, and *5* — liquid after melting of ice.

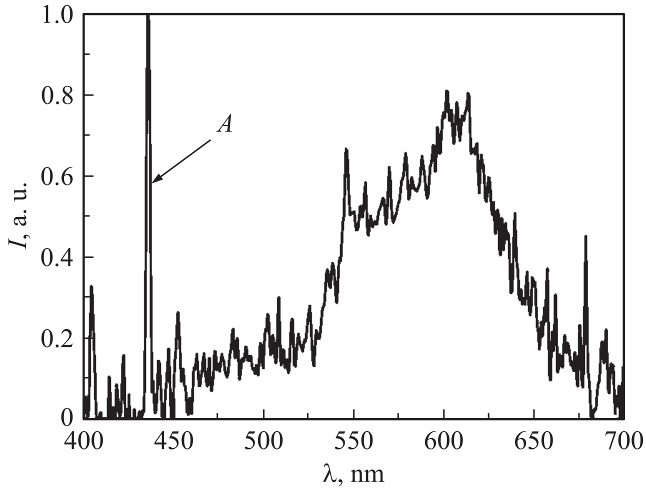

Figure 2. Emission spectrum of a discharge in a single drop of oil I-40A.

Thus, the results of experiments with a single frozen drop may be interpreted as evidence that a gas phase needs to form inside the examined liquid prior to its electrical breakdown. However, the observation of continuous discharge current during phase transitions inside a large volume of liquid warrants further study and explanation. It may also be concluded at the current stage of research that certain regimes of current flow in liquid are not accompanied by light emission.

Conflict of interest

The authors declare that they have no conflict of interest.

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