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SHORT COMMUNICATIONS

Estimations of the Electric Field Strength of Nonelectrode Streamers in Water

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Abstract—The electric field strength of a nonelectrode streamer in water has been estimated using data of electro-optical measurements. The microscopic field strength on the tips of the anode-directed and cathode-directed streamers is approximately 10 MV/cm, while the macroscopic field strength of cathode-directed and anode-directed streamers near the streamer zone is approximately 300 kV/cm and 2 MV/cm, respectively.

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INTRODUCTION

It was shown in [1] using the electro-optical measurements that the modified electrodes make it possible to increase the local field strength in the center of the gap with a factor of two–three in comparison with the average field strength and decrease it near the electrode surface. This made it possible for the first time to detect the cathode- and anode-directed streamers initiated by the microparticles in the bulk of the gap [1, 2].

Determination of the field strength near the developing streamers is an important problem necessary for understanding the mechanism of electric breakdown.

The goal of this work is study of the field strength near the nonelectrode streamer according to the experimental data [1–5] and also to the authors' data not published earlier.

EXPERIMENTAL RESULTS

In [1–3] experiments were performed using voltage pulses with a characteristic rise time of 0.6 μs, duration of 1.5–2 μs, and amplitude U of up to 200 kV. Hemispherical electrodes with a diameter of 35–50 mm and a gap between them of d = 3–5 mm were used. Water with the conductivity $\sigma \approx 10^{-7}$ $(\Omega\ \text{cm})^{-1}$ entered the cell from the closed purification contour. Optical detection (the shadow method and the Kerr method) was implemented by a semiconductor laser ($\lambda = 0.61$ μm) with the pulse duration at a half-height of 3 ns and a spatial resolution of ≈10 μm.

Figure 1 shows the shadow photo of the nonelectrode streamer in the case of a modified anode creating increased electric conduction near the anode. The point of the initiation of a characteristic single streamer propagating simultaneously to the anode and cathode in the form of "half-streamers" is seen at the distance $\delta_A \approx 1$ mm from its surface. The "half-streamer" propagating towards the cathode has the form of a cone with a radius of 250 μm and the angle $\approx\pi/2$. It should be noted that the vertex angle of the cone is not a characteristic of streamers. For some streamers it was less than 45° [2]. The half-streamer propagating towards the anode has a bushlike shape with a length of 140 μm. Many such formations are observed on the surface of the cathode. The maximum height of the bushes is ≈1.4 mm. Optical density disturbances are detected at a distance of ≈0.1 mm from their tips. The structure of the cathode bush is branches with a thickness of 70 μm and a length of approximately 100 μm.

The generation of such a number of bushes is connected with the high field strength on the cathode ($E_k \approx U/(d - \delta_A) \approx 700$ kV/cm) and with the subsonic speed of their propagation.

The results of Kerr effect measurements of the nonelectrode streamer at the initial and later stages of the development are given in Fig. 2.

It can be seen in Figs. 1 and 2 that the initial streamer has the same shape in the shadow photo and the kerrogram. When the streamer touches the cathode (Fig. 2b), the field strength increases near the

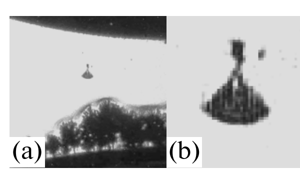

Fig. 1. Shadow photo (a): top, modified anode; bottom, metallic cathode; U = 142 kV, d = 3 mm, t = 2.05 μs; dark points are microparticles; (b) enlarged part of the interelectrode gap with the nonelectrode streamer.

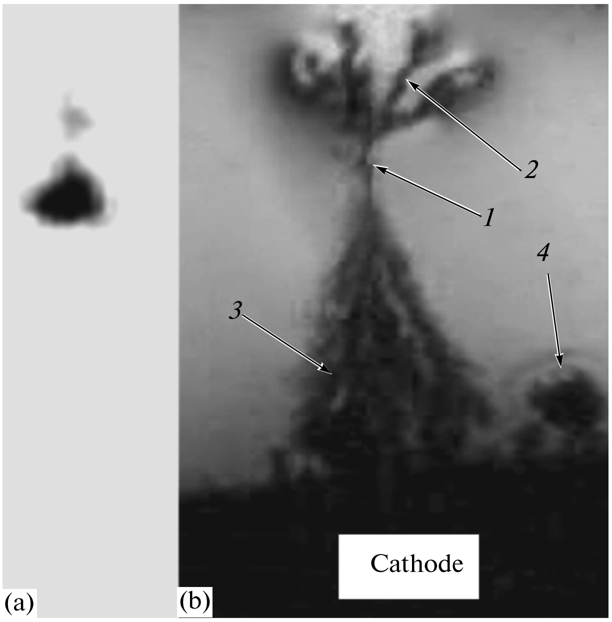

Fig. 2. Fragments of kerrograms with nonelectrode streamers: (a) total streamer length is 300 μm [1], (b) total streamer length is 2.9 mm [2]. Arrows show the point of the generation of streamers (*1*), cathode bushlike structure (*2*), anode streamer (*3*), and conventional cathode streamer (*4*).

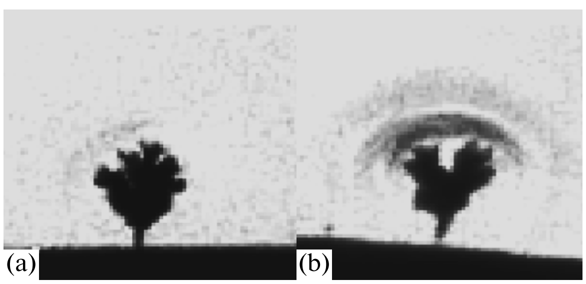

Fig. 3. Shadow photo (a) and kerrogram (b) of near-cathode streamers [3] on metallic electrodes, $U = 160$ kV, $d = 4$ mm, the frame size is 1×1 mm.

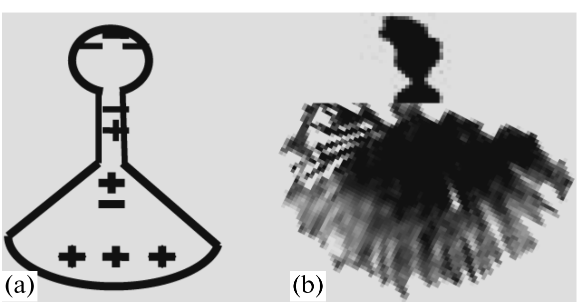

Fig. 4. Principle scheme of the nonelectrode streamer (a) and superposition of fragments of the cathode and anode streamers (b) [4] at $E \approx 800$ kV/cm, $t = 1.0$ μs.

anode-directed streamer. However, it is difficult to estimate the field strength in this photo, since it is not clear whether the field managed to be redistributed after the streamer touched the cathode.

Direct measurements of the field strength close to the tip of the cathode streamer were performed on metallic electrodes [3] (Fig. 3). The estimations of the average field strength near the streamer boundary gave the value of 2 MV/cm [4].

DISCUSSION

Nonelectrode streamers are not galvanically connected with electrodes. This unambiguously indicates the electric neutrality of the formation as a whole. To understand the physical picture of the processes, the nonelectrode streamer can be presented in the form of an electric dipole with the charge $+q$ and $-q$ located on the streamer boundary.

Figure 4 shows a schematic image of such a streamer, and also shadow microphotos of conventional streamers initiated by microbubbles from the anode and cathode [4]; moreover, the position and sizes of streamers are selected to obtain a picture similar to a nonelectrode streamer.

The experimental streamer shape is asymmetric. The anode-directed streamer with the characteristic size R_a has a smaller surface than the cathode-directed streamer with the size R_c. The increase in the macroscopic electric field strength near the surface can be estimated as $E_m \approx q/S\varepsilon\varepsilon_0$, where S is the area of the charged surface of the streamer. For the anode-directed streamer $S_a \approx 2\pi R_a^2$ (hemisphere), for the cathode-directed streamer $S_c \approx (\pi/2)R_c^2$ (the cone with the angle $\approx\pi/2$). At $R_a \approx 50$ μm and $R_c \approx 250$ μm [1] the macroscopic field strength of the anode-directed streamer E_{ma} is six times higher than that in front of the fan of the cathode-directed streamers E_{mc}.

It was shown in [4] that the initial streamer initiated by a bubble on the anode can consist of $n \approx 10^2$ branches with the thickness $2r_b \approx 50$ μm filling the hemisphere with the radius of 600 μm with the distance between their tips of 40–60 μm (Fig. 4b). Since the cathode-directed streamer initiated by the microparticle in the volume has the shape of a cone with the vertex angle of $\approx\pi/2$, it is possible to assume that the number of branches is proportional to the angle and is $n \approx 10^2 \times (\pi/2)/2\pi \approx 25$. Later [6], approximately 20 thin channels with a radius of $(3–6) \times 10^{-6}$ m dispersed in the space nearly at a direct angle were also detected in the transformer oil.

The microscopic field strength on the branch tip can be estimated as the field strength created by the charge concentrated on the branch tips: $E_b \approx (q/25)/(4\pi r_b^2\varepsilon\varepsilon_0) \approx (E_{mc}/200)(R_c/r_b)^2$. For $R_c \approx 250$ μm and $r_b \approx 2.5–5$ μm, we have $E_b \approx (12–48)E_{mc}$.

Thus, the main relations of the field strength of the nonelectrode streamer parts were obtained taking into account the electroneutrality of the nonelectrode streamer and its geometric sizes. It is necessary to determine the charge q for the quantitative estimations. According to data of [3] (see Fig. 3), $E_{ma} \approx$ 2 MV/cm in front of the cathode streamer, consequently, the charge $q \approx E_{ma} 2\pi R_a^2 \varepsilon\varepsilon_0 \approx 2.2 \times 10^{-9}$ K ($R_a = 50$ μm).

Then the macroscopic field strength of the cathode-directed streamer $E_{mc} \approx 300$ kV/cm, and the microscopic field strength $E_b \approx (12–48)E_{mc} \approx 3.6–14.4$ MV/cm, which is enough for auto-ionization of liquids.

The minimal field strength between the dipole charges $\sim 2q/4\pi(l/2)^2\varepsilon\varepsilon_0$. For $l = R_a + R_c \approx 300$ μm, we have 200 kV/cm. This value is less than the average field $E_0 = 620$ kV/cm, which does not contradict the experimental data.

The electro-optical diagnostics used in [1] did not make it possible to detect such fields reliably against the background of the homogeneous field due to the smallness of the phase incursion on micron sizes. The use of the tip anode in the nonbreakdown mode [5] made it possible to detect experimentally the macroscopic field strength near the cathode-directed streamer of 320 kV/cm, which confirms the above estimations $E_{mc} \approx 300$ kV/cm.

CONCLUSIONS

Thus, the microscopic electric field strength in front of the branches of the cathode and anode streamers is ≈10 MV/cm; however, the macroscopic field strength near the cathode-directed streamer is much less than that near the anode-directed streamer. It is clear that the structure of streamers and the mechanism of their propagation differ strongly.

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