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PHYSICS

Electrooptical Measurements of the Electric Field Strength in Water with Near-Electrode Conductive Layers

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The problem of increasing the pulsed electrical strength of water is topical for the development of capacitive energy storage systems [1]. Increased values of the breakdown strength of water were previously attained by a decrease in the electric field intensity near the electrodes [2]. This was realized by different ways, namely, via injection of the charges by electrode materials, via introduction of bipolar ions of amino acids, by the formation of near-electrode layers via passing the current, and by the formation of diffusion ion layers near the electrode surface. However, until now, no production variant that could be used in actual storage systems has been suggested.

Modifying the electrodes with the purpose of inducing an increased electrical conductivity near the surface seems to be promising for use in the high-voltage technique. The goal of this work is to evaluate the efficiency of increasing the field strength in the spacing with modified electrodes.

The experiments were performed for voltage pulses with a duration of 1.5–2 μs with a characteristic time of increasing $\tau_f \approx 0.6$ μs, of the decay ~0.1 μs, and amplitude U up to 200 kV. We used a cell made of stainless steel with hemispherical electrodes 35–50 mm in diameter and with spacing between them $d = 3$–5 mm. Deionized water with specific conductivity $\sigma \approx 10^{-7}$ $(\Omega\,\text{cm})^{-1}$ was supplied to a cell from the closed purification contour of water.

Spatial kerrograms were obtained using a semiconductor laser with wavelength $\lambda = 0.61$ μm and pulse duration 3 ns. To record the electric field strength in the center of the spacing, a He–Ne laser (0.63 μm) was used. Its beam ~0.3 mm in diameter passed through the cell center at an angle of 45° with respect to the beam of the pulsed laser. The phase incursion was recorded using a photomultiplier.

In the scheme of the crossed polarizer used, the intensity ratio I/I_0 at the output from the cell is recorded in the form

$$\frac{I}{I_0} = \sin^2\varphi = \sin^2\left(\pi B_K \int_\ell E_z^2(x)dx\right), \qquad (1)$$

where B_K is the Kerr constant, $E_z(x)$ is the component of the electric field perpendicular to the laser beam, and x is the direction of the probing beam. The results of calibration for this system of recording on metal electrodes of the same size are presented in [3]. The phase incursion $\varphi = \pi/2$ was detected at an average field strength $E = 360$ kV/cm.

Figure 1 shows the fragments of spatial kerrograms in the maximum of voltage for metallic and modified electrodes.

A series of closed dark bands in the spacing with diffusion electrodes indicates a sufficient enhancement in the electric field strength in the medium part of the spacing.

By the dynamics of the phase incursion up to 0.3 μs, the values of the average and local field strength are close. In the maximum of the strength ($t = 1.5$ μs), the local field strength E_l in the center increased reaching more than ~880 kV/cm.

The electric field strength near the surface $E_e(t)$ can be evaluated from the expression obtained for the diffusion electrodes [4]:

$$E_e(t) \approx \frac{U}{d}\left(\frac{\tau}{\tau_{fd}} - 1\right)^{-1}\left[\exp\left(-\frac{t}{\tau}\right) - \exp\left(-\frac{t}{\tau_{fd}}\right)\right], \qquad (2)$$

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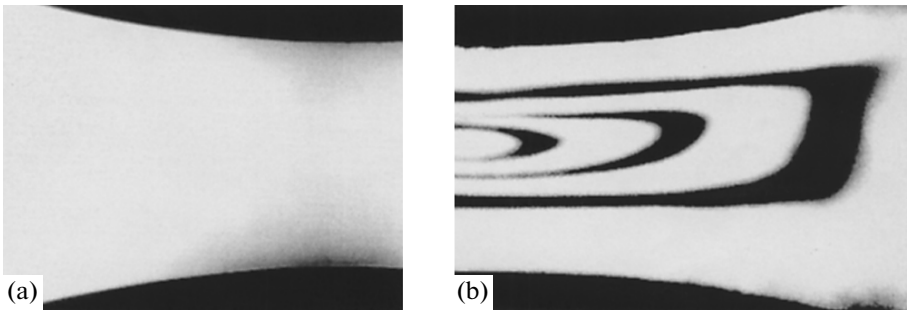

Fig. 1. Fragments of typical kerrograms in the maximum of the strength ($E \approx U/d \approx 420$ kV/cm): (a) metal electrodes and (b) modified electrodes. Phase incursion π corresponds to the local strength $E_l \approx 510$ kV/cm, 2π corresponds to 720 kV/cm, and 3π corresponds to 880 kV/cm.

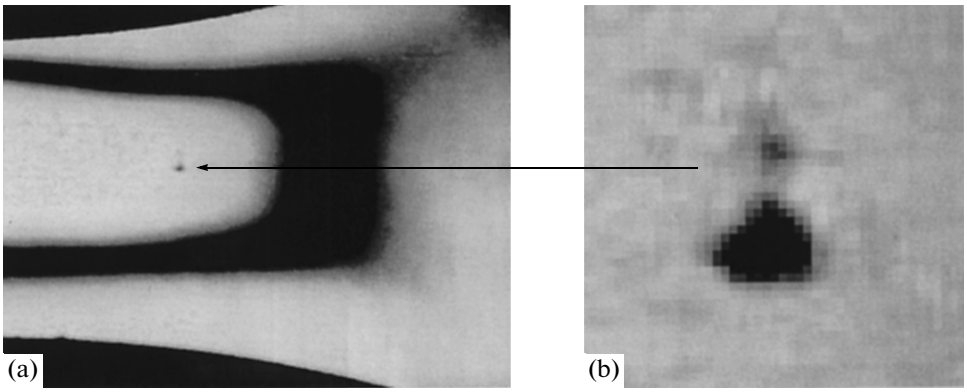

Fig. 2. Panoramic kerrogram of the initial ionization processes in the spacing bulk ($E = U/d \approx 440$ kV/cm): (a) general view and (b) increased fragment. The anode is at the top.

where τ is the characteristic time of increasing the voltage and $\tau_{fd} \approx \varepsilon\varepsilon_0/\sigma$ is the characteristic time of field decay for the layer with conductivity σ. We can show that, according to (2), the near-electrode strength for the used voltage pulse initially increases almost proportionally to the voltage to $E_e \approx 200$ kV/cm and then drops to $E_e \approx 20$ kV/cm.

In some cases, the increased electric field strength in the central part of the spacing and the weakened one on the electrode surface are favorable for the development of initial ionization processes in the bulk [4]. These processes can be initiated by the particles situated in the interelectrode spacing.

Figure 2 shows the photography obtained for several tens of nanoseconds before the cut of the voltage pulse. The characteristic optical nonuniformity indicates the nucleation of initial ionization processes. The evaluation by the phase incursion gives the value of the electric field strength in the central part E_l= 620 kV/cm. The diameter of the neck of optical nonuniformity does not exceed 20 μm. The characteristic length of nonuniformity from the neck along the direction to the cathode is 220–240 μm, while that to the anode is 100–120 μm. In our opinion, the structure of the development of ionization processes in the spacing bulk is detected here for the first time.

Thus, using the electrooptical method, the spatiotemporal distribution of the electric field strength of modified electrodes in water is measured. The diffusion electrodes, which cause an increase in the electric field strength in the bulk of the interelectrode spacing, can be used for investigation of physical processes of initiating the discharge without electrodes.

The obtained physical results give grounds for applying the modified electrodes in pulsed energy storage systems, which will provide an increase in the density of stored energy and limiting power of the storage systems.

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