Features of a gas discharge with a liquid electrolyte cathode in an extended discharge gap

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Abstract. A gas discharge in an extended gap between a liquid electrolyte cathode and a copper anode was studied experimentally. The discharge was obtained in an open air atmosphere at a distance of 2-18 cm between the electrodes. It was revealed that there are combustion modes with a homogeneous and inhomogeneous plasma column. The electrical properties of the discharge in these two combustion modes were studied. The electric field strength in the plasma column was determined by varying the length of the discharge gap.

1. Introduction
Gas discharges with a liquid electrolyte cathode make it possible to obtain volumetric plasma at atmospheric pressure [1]. This plasma is promising for use in various plasma-chemical processes [2-6]. For practical applications, a gas discharge ignited in extended discharge gaps is of particular interest. Since this option facilitates the conditions for the introduction of reagents into the plasma. In works [7-14], gas discharges with plasma column of tens of centimeters in length were obtained and investigated. However, the results obtained are fragmentary, the mechanisms of the formation of plasma column above the electrolyte cathode have not been fully disclosed. In this regard, the purpose of this work was to obtain gas discharge with liquid electrolyte cathode in an extended discharge gap and a more detailed study of its properties.

2. Experiment
Experimental studies were carried out in the range of currents 2-5 A. As an electrolyte, solutions of sodium chloride in distilled water were used. The specific electrical conductivity \( \sigma \) of the solutions was in the range of 7-16 mS/cm. The electrolyte circulated through the gas discharge device, which is schematically shown in figure 1.

![Figure 1. Gas discharge device. 1 – output channel of cathode assembly, 2 – current lead, 3 – electrolyte, 4 – anode.](image-url)

Two power sources were used in the experiments: 1) three-phase two-half-period rectifier with a capacitive-inductive filter; 2) inverter blocks of "GORN" type. High-frequency converters of inverter units create significant interference in the operation of electronic measuring devices. On the other
hand, such sources allow maintaining a given current value with great accuracy. During video filming and oscillographic studies, electric power was supplied from a rectifier. The study of the properties of discharge at fixed current values was carried out using the "GORN" inverter units.

Snapshot images of discharge were obtained using a high-speed video camera VIDEOSKAN-401, which makes it possible to shoot frames with an exposure of 1 μs. An M2016 and M2015 pointer instruments of accuracy class 0.2 were used as an ammeter and voltmeter. Current and voltage were recorded by a two-beam memory oscilloscope AKIP-15/1 with a bandwidth of 25 MHz.

The discharge was ignited at small interelectrode distances. Then, during the burning of discharge, the cathode assembly was moved. In each position of the cathode assembly the voltage at the terminals of the gas-discharge device was recorded and the current was corrected. The current was kept constant. Thus, the regularities of voltage variation with increasing interelectrode distance in different current modes \( I = \text{const} \) were determined. A series of experiments were carried out using aqueous solutions with different concentrations, respectively, with different values of \( \sigma \). The results obtained were used to find the electric field strength \( E \). It was determined by the angle of inclination of the tangents to the graphs of experimental data. The numerical values were calculated as the ratio of the voltage increment \( \Delta U \) to the elongation of the interelectrode distance \( \Delta l \).

3. Results of experiments

One of the features of gas discharge was recorded during high-speed video shooting. In the video frames, the states of the plasma column with homogeneous (figure 2a) and inhomogeneous (figure 2b) luminescence were recorded. In a discharge with an inhomogeneous plasma column, two regions were clearly distinguished. A diffuse volumetric plasma was formed near the cathode, and a bright filament clearly stood out against the background of a weak glow near the anode (figure 2b). Moreover, in the video frames, a sharply outlined border between the two regions was observed. The position of this border was constantly changing in a random manner. The area near the anode is similar in appearance to a low-current electric arc [15-16]. It is obvious that the mechanisms of current flow in homogeneous and inhomogeneous region are different. The yellow color of plasma column near cathode indicates the removal of sodium from their aqueous solution into the interelectrode gap. Sodium ions are carried out in composition of small droplets of an aqueous solution. Therefore, ionic conductivity is possible in this homogeneous region. And the electrical conductivity near the anode, in the area with the bright cord, is probably electronic.

![Figure 2. Instant photos of discharge. (a) - l = 16 cm; (b) – 17 cm. \( \sigma = 10 \text{ mS/cm} \). Exposure 0.2 ms](image_url)

Figure 3 shows the oscillograms corresponding to different combustion modes. Current and voltage ripples are detected in both modes. As can be seen, a violation of homogeneity of plasma column is accompanied by an increase in these pulsations (figure 3b).
When the voltage increases, the current decreases, which indicates a deterioration in the current flow conditions. At these moments, the number of current carriers in the discharge gap decreases. In all probability, ions are decreasing. This conclusion is confirmed by the results of video shooting. In plasma column, a homogeneous area with a yellow glow, where sodium ions are present, is reduced (figure 2b).

Figure 4 shows the results of measuring the voltage at the terminals of discharge device. Here one more feature of extended gas discharge is revealed. As the interelectrode distance $l$ increases, voltage $U$ increases nonlinearly. The nonlinearity increases at large interelectrode distances. This effect is clearly seen from comparing the steepness of the tangent lines $m$ and $n$.

An increase in the steepness of the tangent lines indicates an increase in the electric field strength $E$ in plasma column. The calculated values of $E$ are shown in table 1. The following patterns of changes in electric field strength in plasma column are revealed. It decreases as current increases. Its reduction also occurs when using aqueous solutions with a higher specific electrical conductivity (respectively, concentration). In all probability, these patterns are due to changes in the concentration of sodium ions in discharge gap. It is obvious that both with an increase in current and with the use of more concentrated solutions, the intensity of the substance entering to plasma from the liquid cathode increases. The concentration of ions increases and, accordingly, to maintain the current at a fixed level, an electric field with a lower intensity is required.

**Table 1. Electric field intensity.**

| Line | $E$, V/cm |
|------|-----------|

Figure 4. The voltage at the terminals of discharge device: (a) $\sigma = 16$ mS/cm, $I = 2$ A, $2 - 5$ A; (b) $I = 3$ A, $3 - \sigma = 7.5$ mS/cm, $4 - 16$. 

Figure 3. The oscillograms of current and voltage in two different modes of discharge: with homogeneous (a) and inhomogeneous plasma column (b).
4. Conclusion

A gas discharge with a liquid electrolyte cathode in current range of 2-5 A at distances of 2-18 cm between the electrodes was obtained and studied. The combustion modes with formation of homogeneous and inhomogeneous plasma column are revealed. It is established that the voltage increases nonlinearly with increasing interelectrode distance. Experimental data are used to calculate the electric field strength in plasma column. It was found that it decreases with increasing current, as well as when using more concentrated aqueous solutions of sodium chloride as an electrolyte. It is assumed that the revealed regularities are due to changes in the total amount and concentration of sodium ions in the discharge gap.

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