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The influence of local conductivity inhomogeneities on the shape of a discharge channel in water

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The paper experimentally demonstrates the effect of formation of counter discharge channels during breakdown initiation in weakly conducting water along a trace with increased conductivity from a moving crystal of table salt. The first channel is initiated in the gap between the high-voltage electrode and the salt crystal, due to which the current begins to flow mainly along the trace with increased conductivity as a result of the crystal dissolution. The second channel is initiated inside the trace at some distance from the crystal and has no direct contact with the grounded electrode, which is located at a distance of 8 mm. The counter motion of the discharge channels leads to their unification and final formation of a single channel. This effect is explained based on numerical modeling, which consists in the presence of vortex structures in the trace directly behind the moving crystal, which form a wider, compared to the main part of the trace, region with lower salt concentration and conductivity. As a result, the current density in this region is lower than in the main part of the trace, which leads to later boiling of the liquid and the appearance of a plasma channel.

Keywords: guided discharge; breakdown; water; electrolyte; salt; NaCl; crystal; non-uniform conductivity field.

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Introduction

The electrical discharge direction can be controlled by various methods depending on the medium where it is to propagate. In a gas, this can be achieved either through common thermal effects (heating in the radiation propagation region [1]) or via optical breakdown, which results in a long laser spark [2].

One of the methods to control the discharge direction is breakdown along the media interface [3–5].

As for discharges propagating freely under water, the interelectrode gap is filled with water. Consequently, pre-breakdown phenomena depend on the water conductivity [6], electrode topology, and parameters of high-voltage pulses, which are determined by the pulse excitation circuit. The initial phase of a free underwater discharge may

involve the formation of a gas cavity due to Joule heating which is followed by development of a gas discharge within this cavity (the gas bubble theory [7]).

The discharge direction in liquids can be also controlled using laser radiation. Specifically, the paper [8] studies the ability of laser pulses to control water switches designed for powerful accelerators. The authors used three harmonics of pulsed Nd:YAG laser (1064, 532, and 355 nm). Threshold radiation density values were established – 110 J/cm² (14 GW/cm²) for 532 nm.

However, the discharge direction in a liquid can be controlled by a simpler and more economical method. In particular, in the paper [9] a thin metal wire was used to stabilize the breakdown process and to create longer spark plasma channels between electrodes. In such cases, pre-breakdown processes involve rapid

pulsed heating and melting of the wire, followed by breakdown of the channel filled with gas (vapor) and liquid metal droplets. Such breakdowns initiated by the wire typically result in significantly shorter initiation times and lower energy losses as compared to discharges freely propagating in water. This approach has been extensively studied in the paper [10].

The experimental part of study [9] focused on studying pressure pulses generated by freely propagating discharges and discharges initiated with wire in terms of the energy available in the discharge, its losses prior to breakdown, and the energy delivered to the spark channel.

The paper [11] studies the influence of solution conductivity on the pulsed electrical discharge in liquid by means of optical emission spectroscopy in the reactor with electrodes of pin-plane geometry. The emission intensity of hydroxyl radicals (OH⁻), hydrogen radicals (H⁺), and oxygen radicals (O⁻) was measured using the intensity calibration method.

The paper [12] studies the parameters of the pulsed plasma discharge in water for the pin-to-pin electrode configuration. The influence of two parameters was examined: water conductivity (from 50 to 500 $\mu\text{S/cm}$) and applied voltage (from 6 to 16 kV). Two additional diagnostic procedures based on the refractive index (with time resolution) were used, along with electrical measurements, to study discharge propagation and breakdown in water. For low conductivity (from 50 to 100 $\mu\text{S/cm}$), the results confirmed the existence of two discharge modes (cathodic and anodic), while an increase of the applied voltage at first promotes the development of the anodic mode. For the conductivity of 500 $\mu\text{S/cm}$, the cathodic mode primarily develops at a low voltage applied, while a mixed mode (anodic and cathodic) develops at a high voltage applied.

The papers [13, 14] study the phenomenon of discharge on the water surface and under water when lightning strikes a liquid surface. Laboratory experiments were conducted using a point-plane electrode system in a medium simulating seawater. Tap water and salt solutions with varying conductivity were used, and a lightning strike was simulated by a pulsed discharge on the water surface. The curves of the average current value and the electric current density at the anode and cathode vs. the interelectrode distance and electrical conductivity of a medium were derived.

Analysis of the literature references shows that researchers focus on gas-liquid discharges (discharge with a liquid electrode) propagating along and perpendicular to the interface, as well as on discharge development in media with varying electrical conductivity but which is homogeneous over the volume. Thus, currently there are no results on the study of discharge in liquids with conductivity stratification due to spatial inhomogeneity of the equilibrium charge carrier (impurity ion) density.

It was shown earlier [15] that the trace left by a salt crystal moving in weakly conductive water has a guiding effect on discharge development in the water, and the voltage was applied at the moment when the crystal had moved away from the high-voltage electrode, and the discharge propagated along the homogeneous trace as a single (unbroken) plasma channel.

The aim of this paper is the experimental and numerical study of the effect of two separate discharge channels forming at the electrode and in the trace and separated by the crystal.

Experimental Setup and Methods

The experimental part of the work consists of two stages. The first stage involves recording the electrical discharge guided along the trace left by a moving salt crystal. The second stage consists in determining the conductivity of the liquid inside the trace.

The first stage was conducted using the setup described in detail earlier in [15] where the method of uncontrolled seeding of a group of crystals into the discharge gap was replaced by a method of introducing a single crystal into a controlled point within the discharge gap. This was achieved using a thin glass tube with a diameter of 3 mm and a length of about 10 cm. Its tapered end ($\varnothing 1$ mm) touched the water surface at a point above the tip of the high-voltage electrode. When a crystal was introduced into the open end of the tube, the vector of the decreasing velocity was nearly vertical, which improved positioning accuracy and experimental repeatability. The salt crystals were pre-screened by size using vibrational sieves.

At the second stage, the liquid conductivity inside the trace was measured. For this purpose, the setup was modified by changing its optical

and electrical parts. The method for measuring the conductivity in the trace involves measuring the resistance between two electrodes, separated by a known distance and contacting the trace of the identical length and of diameter measured optically.

An optical (shadow) visualization method was used to measure the trace diameter as it allows detecting liquid regions with non-zero salt concentration. Since the accuracy of the trace diameter measurement has the greatest impact on measuring accuracy, a high-speed camera was equipped with a microscope, which allowed to increase the spatial resolution by more than 40 times (to 2 $\mu\text{m}/\text{pixel}$). The remaining parts of the optical system remained unchanged. The optical system was also used to monitor the trace length. For this purpose, the high-speed video camera operated in the mode of start in response to image. The partially sharpened electrode could be seen in the lower part of the field of view, and the video camera was configured to start recording when the salt crystal approached its surface. This same starting method was used at the first (discharge) stage of the experiments. Since camera's output signals were fed to an oscilloscope, it was started at the same moment, which ensured monitoring the length of the trace through which the current flowed. To generate the current, a potential difference was applied to both sides of the trace by supplying a voltage (5 V) to the sharpened electrode and to a 0.2 mm diameter nickel alloy wire, which was positioned inside the glass tube so that its end was flush with the glass tube's opening.

The oscillograms show that when the crystal touches the electrode, its noticeable and relatively rapid increase occurs, and the resistance between the electrodes decreases significantly. The trace resistance between the electrodes was calculated as the ratio of the applied voltage to the difference in current magnitudes measured before and after the salt crystal touched the electrode. Due to the significant difference between the conductivity of the brine in the trace and that of its surrounding water, current flow through the lateral boundaries of the trace can be neglected. Subsequently, the conductivity in the trace was calculated for the DC current conductor of circular cross-section with its known length and diameter. This was possible due to the significant difference between the characteristic

time of salt diffusion in water and trace formation time (crystal fall time).

Findings and Discussion

Experimental Results. Figure 1 shows the record depicting the discharge development near the anode tip. The crystal moves along the gravity vector $\vec{g}$ at a speed of approximately 5 cm/s. The automatic voltage pulse is triggered when the distance between the electrode and the crystal is about 50 μm . Within the first 15 μs , the first plasma channel is initiated in the gap between the high-voltage electrode and salt crystal as well as heating and vaporization in the trace behind the crystal which are expressed in the form of darkening of its central part and three separate spots of more intense boiling. These are marked by a dashed line and are likely caused by detachment of macroscopic particles from the crystal. The total resistance of the gap (Fig. 2) between the anode and cathode at first decreases due to occurrence of the first plasma channel, then briefly increases for about 20 μs , which is most likely due to the liquid in the trace changing into the gaseous phase. Ionization then occurs within it, leading to the formation of a second plasma channel, while the gap resistance drops rapidly. A significant non-ionized gap of approximately ~ 0.5 mm remains between the first and second plasma channels (frame at 31 μs). During the next 30 μs they move towards each other: the first channel goes around the crystal along its surface, while the second advances along the conductive trace towards the first. The channels close up at 55 μs . After this the gap resistance, voltage, and current reach steady-state values.

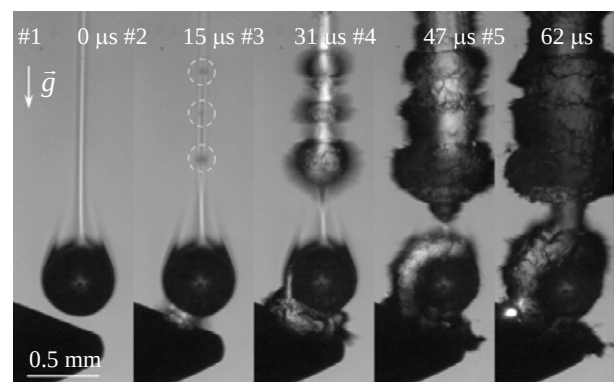


Fig. 1. Photos of the discharge gap during development of electric discharge in water guided by the trace from the sinking sodium chloride crystal. Exposure time 10 μs , 64,000 frames per second

The formation of two counter-propagating channels may be caused by the specific distribution of salt concentration (and conductivity) in the area behind the crystal. The trace contours that can be seen near the crystal surface are an indirect sign thereof – besides the cylindrical vertical part of the trace, which starts at the crystal's upper pole and extends upwards beyond the visible area, lateral traces can also be seen, and these lateral traces originate closer to the equator and are directed towards the cylindrical part at a certain angle.

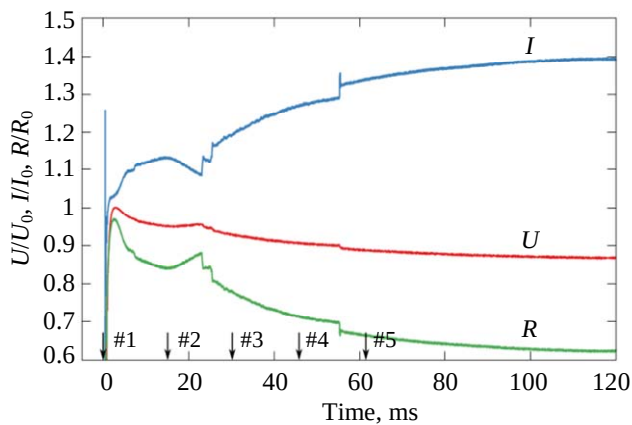


Fig. 2. Oscillograms of voltage (U), current (I), and resistance (R) across the discharge gap that corresponding to the record in Fig. 1. Frame numbers are shown above

Mathematic Simulation. To verify this assumption, two-dimensional (planar) numerical simulation was conducted. It concluded two parts: 1) simulation of the crystal flow-around regime with sodium chloride diffusing from the crystal surface to obtain the salt concentration distribution in the trace; 2) simulation of current flow in water, considering the conductivity heterogeneity.

The results of the flow simulation are presented in Figure 3 for the velocity field (left) and conductivity (right). The crystal flow-around regime is laminar, with a pair of vortices formed on the trace side. Their shape and position determine the distribution of the medium's conductivity (and salt concentration). Its structure matches the one observed during the experiment: the presence of a central part and lateral envelopes originating near the crystal's equator and terminating on the central part of the trace at a distance of about 0.5 mm from the crystal

surface. The more elongated shape of the wide part of the simulated trace may be due to the influence of gravity, which is not accounted for in the present calculation but can shorten the length of the wide part of the trace, and also due to the limited sensitivity of the shadow method to density gradients.

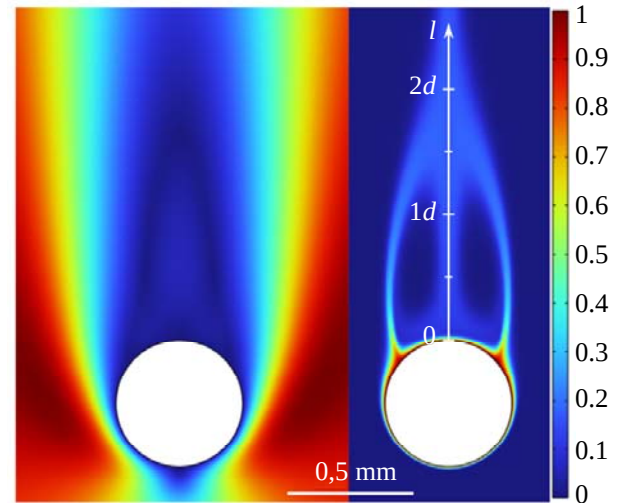


Fig. 3. Simulation results of the crystal flow-around for velocity (left, m/s) and medium conductivity (right, mS/cm)

The results of simulating the electric current flow are shown in Figure 4.

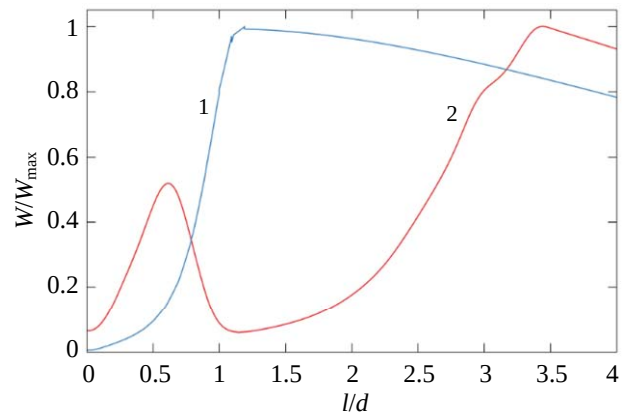


Fig. 4. Simulation results of the heat generation distribution W [W/m³]/ $W_{\max}$ [W/m³] along the trace axis. Distance l is measured from the crystal surface (see Figure 3, right). Curve 1 – the calculation variant with constant conductivity in the trace; curve 2 – the calculation with variable conductivity accounting for vortices

The volumetric heat generation distribution (W/cm³) is given along the trace axis, with the origin at the crystal surface, in normalized form for two cases: 1) The medium is divided into two regions: the surrounding fluid with a conductivity

of 50 $\mu\text{S}/\text{cm}$, and the trace contour (matching the experimental one) with a constant internal conductivity calculated from the experiment and equal to 50 mS/cm . 2) Differs from the first case by the trace contour and conductivity distribution, which are taken from the calculation. Despite the simplifications assumed in the first case, the heat generation plot (curve 1) agrees well with the boiling pattern observed – the maximum value is reached at a distance of 0.5 mm, where darkening of the trace and subsequent boiling are experimentally observed. In the second case (curve 2), the formation of vortices with reduced conductivity inside them leads to current flowing predominantly in the near-axis zone, thus explaining the local maximum developing near coordinate $x = 0.3$ mm. The amplitude of this maximum is significantly influenced by the calculation time because of the low diffusion of NaCl ions. The graph shown has been selected for the time moment approaching the time of crystal's moving from the water surface to the high-voltage electrode surface. While moving away from the crystal, both graphs show a decrease in heat generation which is caused by the reduced electric field strength due to the increasing distance from both electrodes (high-voltage and grounded). This is consistent with the limited propagation of the discharge channel in the trace previously documented in [15].

Conclusions

The development of the electric discharge in water, which direction is controlled by the

conductive trace from the moving NaCl salt crystal, exhibits several features related to the distribution of dissolved salt concentration in the trace, these features having an ultimate influence on the structure of the discharge channel formed. Laminar flow-around of the crystal results in formation of vortices adjoining the crystal on the trace side and contributing to the trace expansion in this part and non-uniform distribution of the dissolved salt. Experimental results and simulation indicate non-uniform heat generation within the trace, which leads to the initiation of two separate discharge channels separated by a volume of non-ionized liquid. The first channel originates at the electrode surface and terminates at the crystal surface, while the second channel both originates and terminates within the trace, that is it has only indirect contact with electrodes via the surrounding low-conductivity liquid and the trace segment near the crystal (and does not have direct "plasma-metal" contact).

This feature was not observed previously, when the high-voltage electrode remained behind the crystal by the voltage transfer, and the discharge initiated within the homogeneous cylindrical part of the trace. The crystal and the adjacent wide part of the trace found in the path of the discharge channel add a delay of tens of microseconds (under the conditions of this experiment) in the formation of a unified plasma channel. This delay shall be considered for the purpose of any potential practical application of this method for guided breakdown initiation.

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