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Guided discharge in water with the aid of NaCl crystals

V. A. Panov*, A. S. Saveliev and Yu. M. Kulikov

Joint Institute for High Temperatures of Russian Academy of Sciences, Moscow 125412 Russia

* E-mail: panovvladislav@gmail.com

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For the first time, the possibility of controlling the direction of propagation of an electric discharge channel in water by creating local zones of increased conductivity that arise in the "trace" of a table salt crystal moving in water has been demonstrated. A directed discharge was obtained in water with an electrical conductivity of $350\ \mu\text{S}/\text{cm}$ under the action of a millisecond-duration pulse voltage with an amplitude of 7 kV in an 8 mm interelectrode gap. The effect consists in the discharge channel changing its direction of propagation when it encounters the "trace" of a sinking crystal, i.e. normal horizontal (relative to the direction of gravity) propagation from the anode to the cathode is replaced by directed vertical propagation along the "trace" with increased conductivity due to the gradual dissolution of the crystal.

Keywords: guided discharge; breakdown; water; electrolyte; salt; NaCl; crystal.

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Introduction

A directed electrical discharge occurs in cases where the medium through which it propagates features a spatial non-uniformity of electrical strength associated with local additional charge carriers. Such non-uniformities can exist in the medium in a stationary state or be created for a certain period immediately before the electrical discharge channel propagates.

An example of such stationary non-uniformity in electrical conductivity can be vertical stratification of soil composition, which determines the mode and efficiency of grounding system operation [1], amplitudes of electric and magnetic fields generated by a lightning discharge [2], as well as transient voltage [3] and current characteristics [4].

Either quasi-stationary or short-term non-uniformities (of density, conductivity) can occur in gases due to strong diffusion compared to solids. Examples of such non-uniformities include shock waves and rarefaction waves, where changes in density act as a kind of "gas-

dynamic diode" for streamers [5]. For some types of discharges, a time-constant spatial distribution of density can be obtained using acoustic pressure fields [6], which leads to the possibility of stationary control over the position and shape of the discharge channel. However, the authors of paper [6] note that the channel's path cannot be influenced for other types of discharges due to the effects caused by temperature (density) gradients prevailing over acoustic pressure. An example of a short-term impact is laser pulsed heating of the gas in the interelectrode gap along the beam path, along which an electrical discharge propagates after that [7]. The guiding action in this case is associated with decrease in density and increase in the mean free path in the gas after laser heating. If the energy density exceeds a certain value, optical breakdown is possible in the form of individual plasma initiation sites along the radiation path [8]. Active lightning protection systems based on these phenomena are being developed [9].

Directed electrical discharge in water plays a significant role in electrohydraulic technology

for processing various materials through pulsed high-pressure impact and electrochemical effects [10]. Its essence lies in conversion of electrical energy into mechanical energy via rapid energy release in a thin discharge channel, followed by fluid motion and formation of shock waves. The efficiency of this conversion depends on many parameters – current pulse amplitude, distance between electrodes, duration and steepness of pulse fronts, shock capacitance magnitude, and others. However, the primary and most significant factor is the need to obtain long (and ultra-long) discharge channels, which is quite difficult due to the ionic conductivity of water. To solve this problem, the author [10] proposed a method of electrical (thermal) explosion of a conductor, typically a wire, which was initially connected to the electrodes and determined the direction of the future discharge channel when a high-density current was passed through it. The same author proposed an alternative method of directed radiative (including laser) exposure, where the current propagates along a channel with lower density, which occurred as a result of radiation propagating through the fluid.

As a new method for creating a region of preferential discharge channel development in water in the form of a local zone of increased conductivity, the motion of a salt crystal within the interelectrode gap is considered. The method essentially consists in gradual dissolution of the crystal as it moves and a trail is formed behind it with a locally increased concentration of salt ions (i.e., with increased electrical conductivity). This approach, on one hand, does not require mechanical repositioning of a wire, as in the case of its electrical explosion, and on the other hand, does not require additional equipment, as in the case of breakdown guided by laser radiation. Using salt also prevents contamination of electrodes, which occurs when parts of the exploded metal conductor are welded onto them. An additional advantage is the relatively long lifetime of the trail as compared to the discharge duration, which makes it easier to synchronize introduction of the crystal into the discharge gap and apply the voltage pulse.

The aim of this paper is to obtain a directed discharge in conductive water under the influence of a millisecond-duration pulsed voltage using common salt crystals.

Experimental Setup and Methods

The study uses the setup described in paper [11] and modified according to the purpose of the study. Distilled water was poured into a transparent acrylic container (1 in Fig. 1). Below the water level, electrodes were placed – a pointed high-voltage electrode (2) and a cylindrical electrode (3) made of a tungsten rod, which were positioned 8 mm apart from each other. The lateral surfaces of the electrodes were insulated from the water, except for the working ends. The water level in the container was such that it completely covered the electrodes, while the distance from the water surface to the surface of the high-voltage electrode was about 1 cm. This relatively small distance allows common salt crystals to reach the interelectrode gap at a constant speed, as their diameter changes insignificantly during dissolution. As the visualization results suggest, this ensures the formation of a trail of practically constant diameter. The crystal falling through the water leaves a thin trail in the form of an extended region of increased conductivity due to the partial dissolution of the salt (see Fig. 1) as a dashed line near electrode 2.

To visualize the process of high-conductivity trail formation, an optical scheme based on the shadowgraph method is used, which is sensitive to local changes in fluid density due to the partial dissolution of the crystal. Luminescent LED 4 and converging lens 5 create a parallel light beam illuminating the area near the high-voltage electrode. High-speed digital video camera 6 equipped with long-focus lens 7 continuously records the shadow pattern near the tip of electrode 2 with a spatial resolution of 95 $\mu\text{m}/\text{pixel}$. The video camera records the process into memory and, when started, sends a synchronization pulse to the trigger inputs of pulse generator 8 (“TRIG”) and oscilloscope (“Ext/10”). After that generator 8 produces a trigger pulse for high-voltage switch 10, with a duration of about 1 ms. Switch 10, without delay (rise time $\sim 0.1 \mu\text{s}$), switches the high voltage from battery C charged through ballast resistor R_b (1 M Ω) by high-voltage source 11 up to 7 kV, via limiting resistor R_l (5 k Ω) to the high-voltage electrode.

To correlate the frame number of the cinegram with the moment of high-voltage

application, the F_SYNC signal from the video camera corresponding to the start of exposure for each frame is sent to channel 1 of oscilloscope 9, and the signal from generator 8 is sent to channel 2. Additionally, the signal from high-voltage divider 12 (1:1000) connected to high-voltage electrode 2, is sent to channel 3 of the oscilloscope, and the voltage from current shunt R_s for measuring the circuit current is sent to channel 4.

Results and Discussion

Figure 2 shows photographs of the discharge gap at various moments after applying the voltage from capacitor C charged to 12 kV. The charging voltage was chosen so that, the gap would not short-circuit to plasma channel during discharge in the absence of salt trails. The state of the gap at the moment of voltage application is shown in frame #0. Trajectories of a group of moving crystals can be seen near the anode tip as bright filaments with dark edges, along with two crystals found closer to the cathode and appearing as dark dots with a diameter of about 0.4 mm, which remain practically stationary during the 1 ms pulse duration. The discharge development begins at the anode tip, where within the first 80 μs , water is heated, and a vapour-gas region stretching toward the cathode is formed (90 μs , #2). As soon as it reaches the nearest trail, the plasma of the discharge channel begins to glow more intensely, and its shape becomes T-shaped. From this moment on, the channel changes its direction of propagation and moves vertically along the crystal's trajectory, simultaneously upward and downward. The symmetry of the channel's propagation is indicative of medium's similar parameters, including conductivity within the trail, both along and against the crystal's motion direction. The channel growth rate was calculated between frames #3 and #4 and equaled to at least 7 m/s, which is characteristic of the thermal breakdown mechanism in conductive water [12]. Further development of the vapour-gas region, where channel (#5–#7) is located, occurs due to increase of its diameter with only minor elongation. Its structure maintains symmetry relative to the horizontal plane passing through the electrode axis. Simultaneously, the initial vapour-gas region, whose shape is close to

spherical, develops. A characteristic feature of the structure is the conical shape of the channel vertices with an angle of about 60° . At later stages of breakdown development, a second plasma region is initiated from the cathode. It is associated solely with thermal processes near the surface without salt crystals being involved. By the end of the voltage pulse, the vapour-gas region and the discharge channel at the anode lose their initial structure and exist as a unified region.

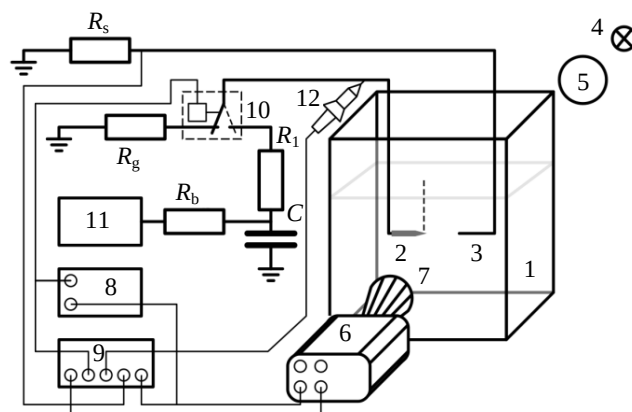


Fig. 1. Experimental setup diagram

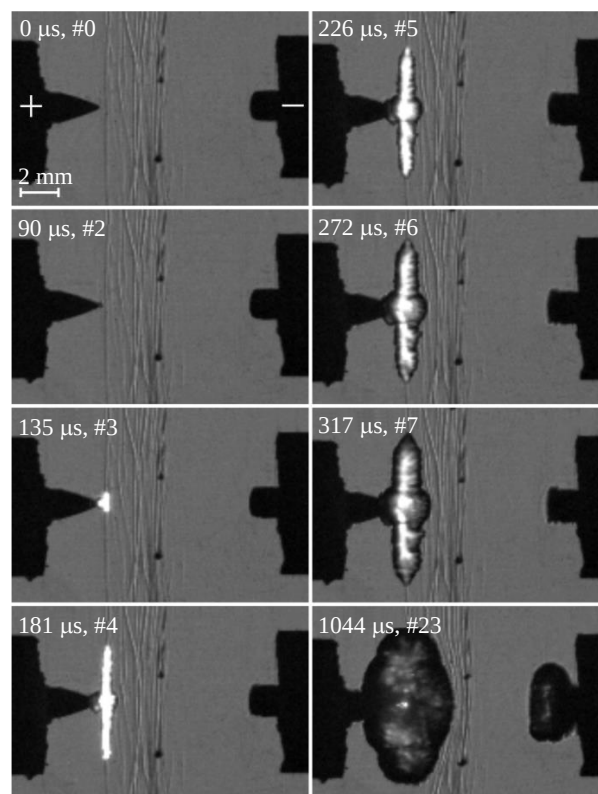


Fig. 2. Photos of the discharge gap during development of electric discharge in water guided by the trace from the sinking sodium chloride crystal. Exposure time 0.9 μs

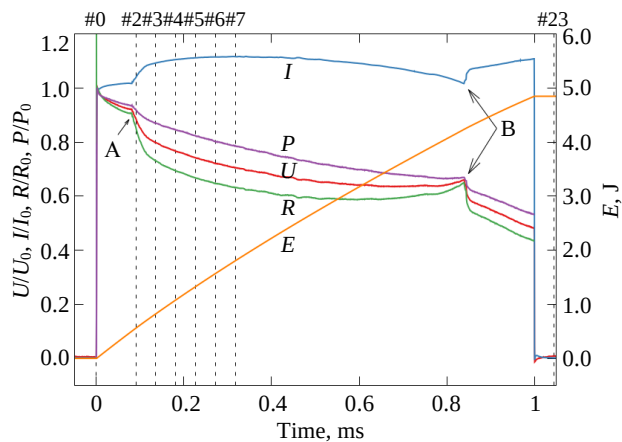


Fig. 3. Oscillograms of values normalized to their initial values ($t = 0$): voltage (U), current (I), resistance (R), power (P), and absolute value of dissipated energy (E) across the discharge gap during propagation of the directed discharge in water. $[U_0, I_0, R_0, P_0] = [5.1 \text{ kV}, 1.3 \text{ A}, 3.9 \text{ k}\Omega, 6.6 \text{ kW}]$. Dashed lines indicate the exposure moments of frames with corresponding numbers shown above the lines. Point A ($80 \mu\text{s}$) is the beginning of plasma formation at the anode tip; Point B ($840 \mu\text{s}$) is the beginning of plasma formation at the cathode.

The oscillograms of voltage, current, resistance, and dissipated power exhibit characteristic segments reflecting the phenomena observed in the photos. In the segment from $0 \mu\text{s}$ to point A (Fig. 3), $80 \mu\text{s}$, water is heated near the anode tip and a vapour-gas region is formed. At point A, plasma formation begins within the formed vapour-gas region. This is accompanied by current increase due to the growing conductivity within this region and overall contact area with the surrounding liquid. The main current growth and decrease in the overall gap resistance occur at the stage of channel propagation along the crystal's trajectory: additional 20% drop of resistance from the initial value takes place between 90 and $135 \mu\text{s}$. After the discharge ignites at point A, the power required to sustain it decreases, and the overall gap resistance continues to fall. However, this trend reverses into resistance increase as it approaches point B ($840 \mu\text{s}$). This is most likely associated with the growth of the vapour-gas

bubble near the cathode, which reduces the effective contact area of the cathode with water and impedes current flow until plasma occurs. After breakdown occurs within this bubble, the gap resistance drops sharply within a few microseconds and continues to decrease until the voltage application ends. The dissipated energy was increasing almost linearly during pulse duration. The total energy amounted to approximately 5 J .

Conclusions

The possibility of controlling the propagation direction of the electrical discharge channel in water has been demonstrated for the first time by creating local zones of increased conductivity that form in the trail of a common salt crystal moving in water. A directed discharge was obtained in water with the electrical conductivity of $350 \mu\text{S/cm}$ under the influence of a millisecond-duration pulsed voltage with the amplitude of 7 kV across the 8 mm interelectrode gap. The effect is expressed by the discharge channel changing its propagation direction upon encountering the trail of a sinking crystal, that is, the normal horizontal propagation from the anode to the cathode is changed by directed vertical propagation along the trajectory with increased conductivity resulting from gradual dissolution of the crystal. In this case, the discharge develops via a thermal mechanism characteristic of conductive water under relatively low voltages and long pulse durations. Analysis of the current and voltage oscillograms indicates a significant reduction in resistance between the electrodes at the moment when the discharge channel begins to propagate along the trail. The power dissipated in the discharge gap and the voltage drop across it also decrease at this moment, while the discharge current, conversely, increases. The time-dependence of the energy dissipated in the water grows linearly.

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About authors

Panov Vladislav Aleksandrovich, Candidate of Physical and Mathematical Sciences, senior research scientist, Joint Institute for High Temperatures of Russian Academy of Sciences (125412, Russia, Moscow, 13, Izhorskaya st., bldg. 2). E-mail: panovvladislav@gmail.com SPIN code: 5821-2776, AuthorID: 755538

Saveliev Andrey Sergeevich, Candidate of Physical and Mathematical Sciences, senior research scientist, Joint Institute for High Temperatures of Russian Academy of Sciences (125412, Russia, Moscow, 13, Izhorskaya st., bldg. 2). E-mail: fisteh@mail.ru SPIN code: 6888-7369, AuthorID: 866343

Kulikov Yuri Matveevich, Candidate of Physical and Mathematical Sciences, senior research scientist Joint Institute for High Temperatures of Russian Academy of Sciences (125412, Russia, Moscow, 13, Izhorskaya st., bldg. 2). E-mail: kulikov-yurii@yandex.ru SPIN code: 7719-8459, AuthorID: 1130937