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The influence of crystal diameter on the directed electric discharge in water along a thin trace with NaCl salt ions

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A recent study demonstrated that it is possible to control the trajectory of an electrical discharge in water using a thin trail of increased electrical conductivity formed by the movement of a sodium chloride (NaCl) crystal in water. An unusual structure of the discharge channel was also noted, namely the formation of separate, unconnected plasma regions that subsequently merge into a single discharge channel. An explanation for this phenomenon was provided based on shadowgraph images depicting the distribution of dissolved salt around the crystal and the results of numerical simulations of concentration. These revealed the influence of a vortex forming behind the crystal on the distribution of salt, conductivity, and ultimately, energy release in the region immediately following the crystal, the maximum of which was found to be significantly displaced from the surface. In the present work, the investigation was conducted using a crystal of smaller diameter (195 μm vs. 518 μm), and a comparison of the results is presented. The reduction in diameter led to a vortex-free flow regime and a more monotonic distribution of salt concentration within the trail. This, in turn, altered the discharge development, which became sequential – propagating from the electrode to the crystal and then continuously further into the trail. Numerical simulations, implemented in a new, refined three-dimensional formulation, revealed a pattern of heat release distribution distinct from the case of the 518 μm crystal and consistent with the results of the present experiment.

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

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Introduction

Controlling the trajectory and dynamics of a pulsed electric discharge in condensed media is a fundamental scientific and engineering task. This problem is most acute in liquids, in particular in water, where high heat capacity and the presence of ionic conductivity create obstacles to the formation of extended discharge channels. Classical approaches to solving this problem,

originating from the work of L. A. Yutkin on the electrohydraulic effect [1], include the use of exploded wires (metal wire) or the use of laser radiation to create an area of reduced density or optical breakdown along the discharge path [2, 3]. However, both methods have a number of features and limitations. The wire method requires mechanical reinstallation of the electrode after each pulse and leads to contamination of the working medium and electrodes with erosion

products [1]. Laser control, although contactless, involves the use of more complex and expensive equipment [4, 5]. Therefore, the search for alternative, simpler, and more cost-effective methods of creating guiding channels with enhanced conductivity in water is currently relevant.

A new approach proposed in [6] is the use of a crystal of table salt (NaCl) moving in the interelectrode gap. As the crystal dissolves, it leaves a trace with a locally increased concentration of ions, which determines the preferred trajectory for the development of the discharge [6]. The paper not only confirmed the fundamental possibility of such control, but also revealed the unusual nature of the discharge process: the formation of two separate, unrelated plasma regions – at the electrode and in the wake of the crystal, which subsequently combined into a single channel. It was hypothesized that this phenomenon is related to the hydrodynamic regime of crystal flow. When using a crystal with a diameter of 518 microns, a trailing-vortex wake formed behind it, leading to a nonmonotonic distribution of salt concentration (and therefore conductivity) and, as a result, to the localization of energy release at some distance from the crystal surface. The obtained results suggest a broader formulation of the question: how do the geometric parameters of the initiating element (crystal) influence the hydrodynamics of the flow, the spatial distribution of conductivity in the wake, and ultimately – the dynamics of discharge channel formation?

The purpose of this paper is an experimental and numerical study of the effect of the diameter of a NaCl crystal on its flow regimes and the features of the development of a pulsed electric discharge in water. In this paper, the results obtained for a crystal with a diameter of 195 microns are compared with previously published data for a crystal with a diameter of 518 microns [6]. Reducing the diameter made it possible to implement a vortex-free flow around regime, which led to a more monotonous distribution of salt concentration inside the wake and a fundamentally different sequential breakdown dynamics. A refined three-dimensional numerical model has been developed to interpret experimental data and imaging the heat release distribution.

Experimental setup

The task in the experimental part of the study is set as follows. The study focuses on the discharge channel development path in weakly conducting water, where regions of high electric field intensity (near the pointed electrode) and sodium chloride crystal moving in water are simultaneously present in close proximity. The crystal leaves behind a thin brine wake of relatively high conductivity due to partial dissolution.

An experimental setup described in detail in [6, 7] was used to study the behavior of the discharge channel in the presence of the wake behind a falling salt crystal. Here we will give only a brief description of it, with an emphasis on its main parts and properties. The breakdown was carried out in a needle-plane electrode system, where "needle" refers to a pointed tungsten electrode (a cone ~0.1 mm rounded tip radius) to which a high-voltage pulse was applied, and "plane" refers to a grounded round plate made of stainless steel. This configuration of the electrodes was chosen in order to ensure the maximum electric-field intensity near the high-voltage electrode, where the salt crystal fell and high-speed imaging of the process was conducted. The electrodes were placed in a ~0.5 L cell with transparent walls filled with distilled water so that the entire surface of the electrodes was under water, the axis of the pointed electrode was perpendicular to the plane of the grounded electrode and parallel to the surface of the water. The distance from the pointed electrode top to the surface of the grounded one was 8 mm, and to the surface of the water – 1 cm.

To ensure that the crystal falls, a tube with an inner surface in the form of a cone is used, so that when the crystal falls through it into the water, its path is well controlled. By adjusting the position of the tube, we achieved the crystal transmission in the immediate vicinity of the crystal edge. The optical scheme described in [6, 7] was used to control the crystal path. Here we briefly note that a shadow imaging method was used, which allows observing not only the crystal and the electrode, but also the thin wake with increased salt concentration. The spatial resolution of the system was approximately 3 microns/pixel, and the frames exposure was 10 microseconds. It should be noted that the

ability to control the location of the crystal drop made it possible to use a high-speed video camera as a trigger for the rest equipment used in the experiment: a high-voltage switch, an oscilloscope [6, 7].

The high-voltage supply to the pointed electrode was realized using a high-voltage switch of the "half-bridge" type, which, with a rise time of ~ 100 ns and a fall time of ~ 100 ns, applied voltage to the electrode and removed it, respectively. The voltage was applied from a high-voltage capacitor through a current shunt and a current-limiting resistor, triggered by a high-speed video camera signal—i.e., at the moment the crystal reached the region near the pointed end of the high-voltage electrode. During the experiment the following was recorded: voltage waveforms on the pointed electrode, the current between the electrodes, as well as high-speed shadow film of frame strips of the development of an electric discharge between them. The study used salt crystals of two diameters: 195 and 518 microns.

Mathematical modeling methods

The electrical breakdown modeling of a salt crystal moving in water is divided into two stages. On the first stage, the flow around the crystal from the surface of which the salt dissolves is calculated. The crystal size (the ball radius) is considered unchanged when flowing around. For particle motion in the gravity field, the velocity distribution and salt concentration are calculated based on the Navier–Stokes equations solution, impurity transfer, and ODE (ordinary differential equations). The model uses a non-inertial moving cylindrical coordinate system associated with a particle. The viscous friction force acting on a particle from a continuous medium is calculated by integrating the normal component of the stress tensor over the particle surface. Due to the axial symmetry of the problem, only the force component along the z axis differs from zero. On the particle surface, an adhesion condition is set as a boundary one. At the inflow boundary, the velocity of the liquid is equal to the crystal falling velocity. On the region outer boundary (the normal velocity and tangential stress are zero) a symmetry condition is set. At the initial moment of time, the crystal is

considered stationary. The impurity transfer equation is solved in mass fraction variables, and the diffusion model is based on Fick's law. The solution density is determined based on the mass fractions of the mixture. A Dirichlet type condition is set on the surface of the sphere, i.e. the maximum mass fraction of salt is set based on the solubility limit. In addition, the conditions of axial symmetry, zero flow, as well as the condition for the free flow of passive impurities are set. The diameter is a characteristic parameter for the size of the computational region, as well as the size of the grid cells. In dimensionless coordinates, taking into account the axial symmetry setting, the ball center is 3 calibers away from the lower boundary. The trailing edge is located at a distance of 12 calibers from the center of the ball. The lateral (vertical) boundary of the computational region is located 4 calibers from the axis. The region dimensions were chosen in such a way that, in the local coordinate system of the falling body, the velocity field disturbances introduced by it into the flow are small at the boundaries. At start time, there is no admixture of salt in the solution. The solution conductivity is determined based on the obtained asymptotic distribution of the salt concentration based on experimental data from other authors [8].

At the second stage, the obtained distribution is used for a stationary tasks in a three-dimensional formulation based on Maxwell's equations and relations for material parameters. On the electrode left surface (modeling a high-voltage pointed electrode), a constant potential is set with an amplitude corresponding to the experimental value ($V = 8$ kV), the right (grounded) electrode of the same shape is grounded ($V = 0$ C), the remaining boundaries are provided with zero charge condition. At a distance from the crystal, the liquid parameters (permittivity, conductivity) are assumed to be equal to the values of distilled water. The results of the second modeling stage include the distributions of electric potential, current, and heat source density.

Results and discussion. Experimental results

Earlier, the authors showed [7] that the development of an electric discharge in the wake

of a moving crystal has a feature: in the early stages of development, the discharge channel is not continuous, but consists of separate sections – the first is located between the electrode and the crystal, and the second is inside the wake at a distance from the crystal of the order of its diameter. The explanation of this effect was given based on the results of numerical modeling of the crystal flow around, taking into account its dissolution and the salt concentration distribution, which provides increased electrical conductivity of individual regions. The formation of a toroidal vortex immediately behind the crystal led to the formation of a large region with increased conductivity and, thus, with a current density insufficient for boiling. At the same time, within the thin part of the wake behind the crystal, the current density becomes higher, and the heat generation is sufficient to form a vapor, and subsequently a plasma region.

The crystal size plays an important role in terms of the formation of plasma regions and the formation of a discharge channel. It affects the motion rate, which in turn affects the absolute amount of dissolved salt, the increase in the diameter of the wake due to diffusion, the Reynolds number and the crystal flow around. The above factors ultimately determine the distribution pattern of electrical conductivity, heat generation, and the structure of the discharge channel.

Figure 1 presents the film of frame strips of discharge development for crystals with diameters of 195 microns (upper row) and 518 microns (lower row). In both cases, the discharge takes place between the electrode surface and the crystal surface facing it. Initiation takes place almost simultaneously with a correction for a larger distance for a crystal with a diameter of 195 microns. A distinctive feature in the case of a crystal with a diameter of 518 microns is additional boiling (followed by plasma formation) in the wake of the crystal at some distance. Starting from frame #3 (31 microseconds), the channel for a 195 micron diameter crystal develops in one direction – from the electrode towards the far end of the wake, and for a diameter of 518 microns – in three directions at once: from the electrode to the crystal, from the wake to the crystal, and from the wake towards its far end. With further

development (frame #5, bottom row), a part of the channel is clearly visible, which formed later than the others and connecting the upper pole of the crystal with the rest portion of the wake, the diameter of which is several times smaller compared to the more distant part of the discharge channel.

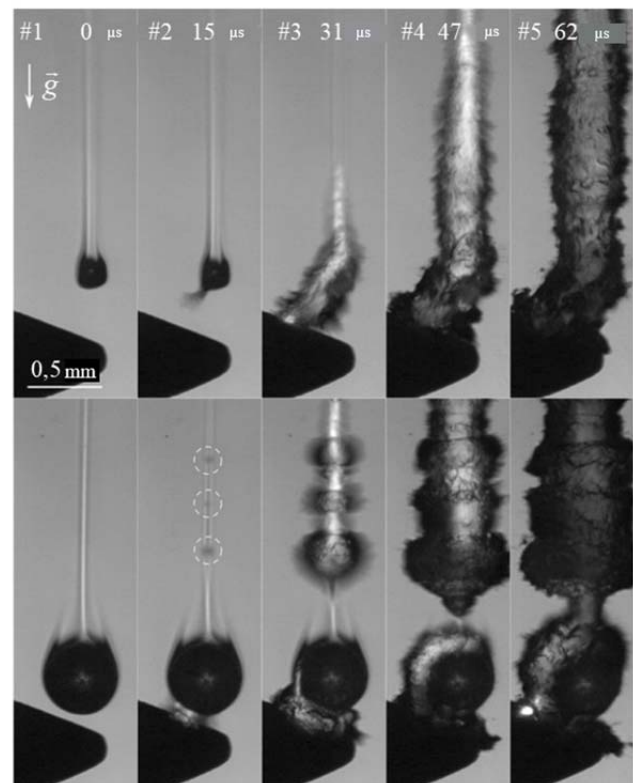


Fig. 1. Film of frame strips of the development of an electric discharge in water, guided by a trace of a moving salt crystal of different diameters: the upper row is 195 microns, the lower one is 518 microns. Exposure time of 10 microseconds, 64,000 fps

The detected difference in the nature of the discharge development can also be traced on the oscillograph record of voltage, current and gap resistance (Fig. 2). When comparing the course of the oscillograph record (solid lines for 195 microns, dotted lines for 518 microns), it can be seen that the current rise and resistance decrease for 195 microns take place monotonously and correspond to the development pattern of the discharge channel, and the only jump is associated with ionization and plasma formation in a single channel. For a crystal with a diameter of 518 microns, on the contrary, the rise and fall of the current between frames #2 and #3 coincide with the phases of heating and vaporization in the far part of the wake, which

briefly hinders the flow of current, which then increases abruptly after ionization in this region.

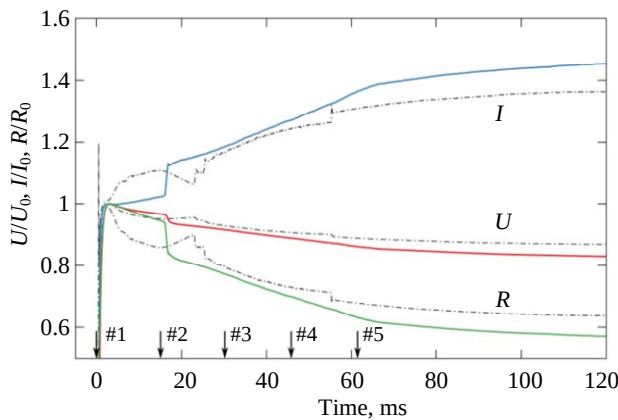


Fig. 2. The waveforms of voltage (U), current (I), and resistance (R) at the discharge gap, corresponding to the film of frame strips in Fig. 1, are normalized to their values immediately after the voltage is applied. The frame numbers are marked at the bottom. Solid lines are for a crystal with a diameter of 195 microns, dotted lines are for a diameter of 518 microns.

The observed difference in the behavior of the discharge channel is well interpreted by the results of the numerical modeling. Figure 3 presents the distribution of concentration (left) and velocity (right) for both crystals. In addition to the obvious difference in the characteristic dimension of the conductive region with a high salt concentration, the difference in its distribution in the region between the crystal surface and the thin part of the wake is clearly visible: due to the larger dimension of the crystal with a diameter of 518 microns, a vortex forms when it flows around the upper pole, which leads to a non-monotonic concentration distribution across the wake and an increase in the region transverse dimension of increased concentration. For a 195 μm crystal, on the contrary, the distribution across the wake is monotonic with a maximum near the wake axis. This distribution of concentration leads to the fact that the distribution of heat release along the wake axis has a maximum closer to the crystal surface for a diameter of 195 microns compared with the case for a diameter of 518 microns (Fig. 4, curves 1 and 2, respectively). At the same time, in the range from 0 to about 0.8 mm, the energy release for a crystal with a diameter of 195 microns significantly exceeds its value for a crystal with a diameter of 518 microns (curves 3 and 4, respectively), which corresponds to the results of optical detection (see Fig. 1).

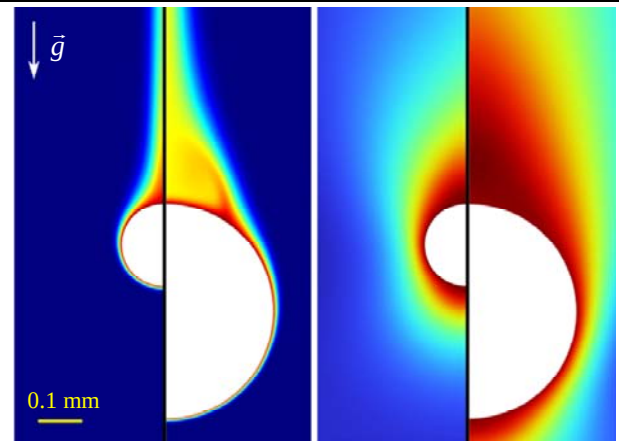


Fig. 3. Modeling results of the crystals flow around with diameters of 195 and 518 microns for the concentration of dissolved salt (left) and the medium velocity (right)

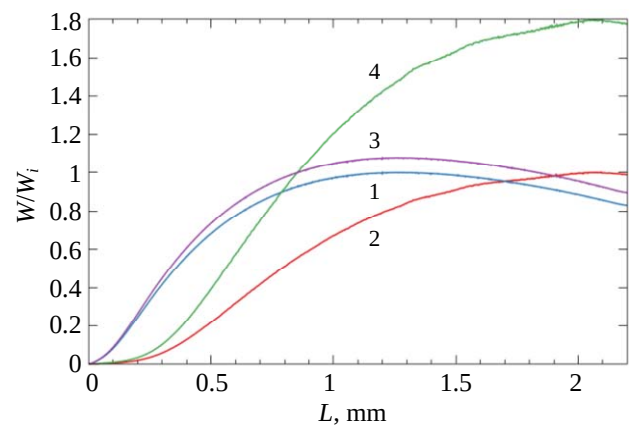


Fig. 4. The distribution of the normalized energy release along the wake axis, the distance L is calculated from the upper pole of the crystal. Curves 1 (195 microns) and 2 (518 microns) are normalized to their global maxima along the entire length of the wake. Curves 3 (195 microns) and 4 (518 microns) are normalized to the value at their intersection point at $L \approx 0.85$ mm

Findings

The development of an electric discharge in water, guided by a conductive wake from a moving NaCl salt crystal, has a number of features related to the distribution of the concentration of dissolved salt in the wake.

When a small crystal (195 microns in diameter) moves, the breakdown takes place sequentially from the high-voltage electrode along the surface of the crystal and further into the wake – without ruptures of the plasma channel, which is explained by the vortex-free regime of its flow around.

When a larger crystal (518 microns in diameter) moves, a discharge channel is initiated

at a high-voltage electrode, moves along the surface of the crystal, but then becomes a part of the wake far from it, leaving a non-ionized area located immediately behind the crystal in its bottom part.

This effect is explained by the difference in the distribution of the dissolved salt concentration (and, accordingly, the resulting conductivity) in the region immediately behind the crystal: the

flow around of a smaller crystal takes place without the formation of a vortex in the bottom area and leads to a fairly monotonous distribution of conductivity; the flow around of a large crystal leads to the appearance of a vortex in the bottom area, increasing the size of the area with increased and heterogeneous conductivity, which results in a lower current density and heat generation, insufficient for steam and plasma formation.

REFERENCES

1. Yutkin L. A. Elektrogidravlicheskiy effekt i ego primeneniye v promyshlennosti. Leningrad: Mashinostroeniye, 1986 [in Russian].
2. Aihara Y., Shindo T., Miki M., and Suzuki T., Electrical Engineering in Japan **113** (4), 66–77 (1993).
3. Woodworth J. R., Zamoski N. D., Johnson D. L., Sarkisov G. S., Blickem J. R., Valde D. M. V. D., Starbird R. L., and Wilkins F. L. Laser Triggering of Water Switches in Terrawatt-Class Pulse Power Accelerators. Sandia National Laboratories, 2005.
4. Vasilyak L., Kostyuchenko S., Kudryavtsev N., and Filyugin I., Uspekhi Fizicheskikh Nauk **164** (3), 263 (1994).
5. Ball L. M., Applied Optics **13** (10), 2292 (1974).
6. Panov V. A., Saveliev A. S., and Kulikov Yu. M., Applied Physics, No. 6, 30–34 (2025).
7. Panov V. A., Saveliev A. S., Kulikov Yu. M., Applied Physics, No. 5, 48–53 (2025).
8. Rao S. M. and Thyagaraj T., Appl. Clay Sci. **38** (1–2), 113–129 (2007).

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