ON SOME FEATURES OF PLASMA DISCHARGE ABOVE WATER SURFACE

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We have created an experimental installation which allows one to produce autonomous spherical plasma formations. The processes that occur at the initial discharge stage have been studied, and two possible scenarios of their development have been described. The current-voltage and spectral characteristics of plasmoids, as well as photos of the discharge development in time, are presented.

Plasma discharges above the water surface attract a certain attention, in particular, owing to their possible applications for the disinfection of products, objects, and premises. However, a number of experimentally observed facts had no convincing physical interpretations. First of all, the values obtained for the breakdown voltage across the contact gap before a discharge started were much lower than those described in the literature. The observed glow intensities weakly correlated with discharge conditions. "Hydrated ions", the concept of which was used for the explanation of effects obtained, reminded, by the mechanism of their formation, gas–water–salt nuclei which were observed in aqueous solutions subjected to the pulse acoustic treatment. Therefore, a complex study of such objects could shed an additional light on the phenomena concerned.

In works [1–3], experiments on the creation of independent plasma formations, plasmoids, which simulate spherical lightnings, were reported, as well as theoretical data connected with the possible role of hydrated ions. However, some issues concerning the initial stage of a discharge were not covered in work [1].

Our experimental system (Fig. 1) was a duplicate of that described in work [1]. Additionally, it was supplemented with a shunt for current measurements. The videorecords of discharges were carried out from above and from the side at a rate of 1000 frames per second (fps). Photodiodes were used to measure the glow of plasma formations. In the majority of experiments, the discharge voltage was kept at a level of 3–4 kV. The central electrode was made of iron in a porcelain insulator. Its schematic view is exhibited in Fig. 2. The diameter of a dielectric discharge chamber was changed from 10 to 50 cm, the depth from 4 to 30 cm. However, no substantial influence of the vessel dimensions on the discharge parameters was revealed.

In Fig. 3, a photo of the stationary discharge phase – a current flow over the insulator surface – is depicted

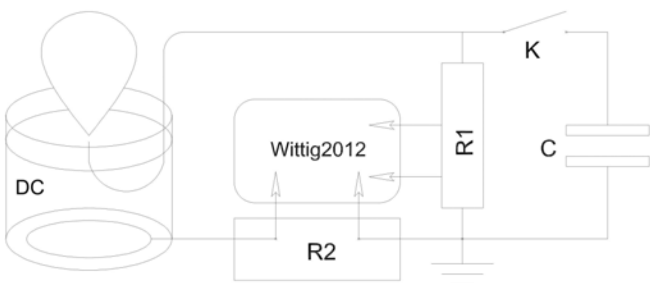

Fig. 1. Schematic of the experiment. Capacitor battery $C = 1200\ \mu$F; K is a circuit breaker, $R1$ is a voltage meter; $R2$ is a shunt for current measurements; DC is a dielectric discharge chamber (a vessel with two electrodes, an grounded ring one and a central one under a negative potential, with the electrically insulated current feedthroughs

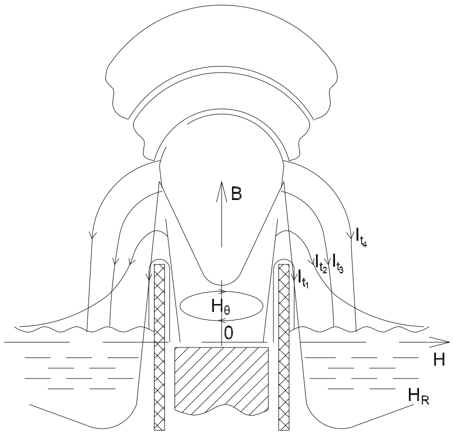

Fig. 2. Central electrode. An iron current feedthrough in a porcelain insulator. The insulator juts out by 1 to 5 mm from the electrode and the water level. The current-carrying plasma column and current channels are functions of time. Separated plasmoids, the dependence of the radial magnetic field, and magnetic field lines in the insulator are shown

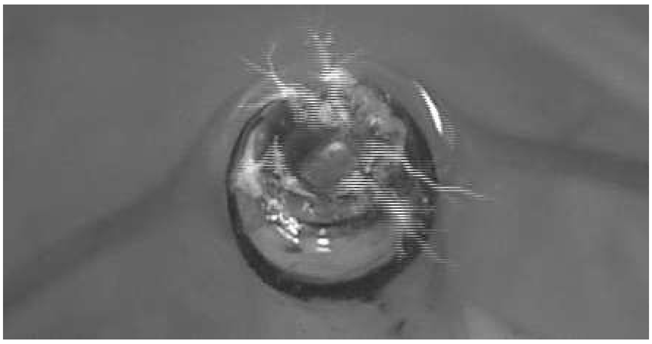

Fig. 3. Stationary discharge phase

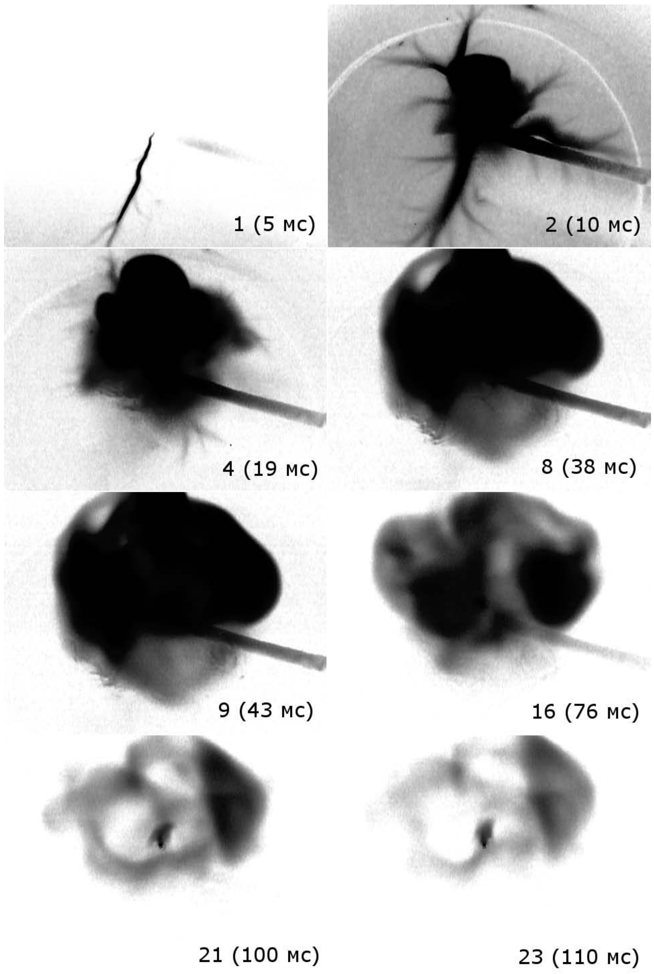

Fig. 4. Discharge dynamics (top view). 210 frames per second

(the voltage is 1 kV and the current is about 0.1 A). An increase of the discharge current up to 0.2 A results in an increase of the number of parallel plasma channels. It is probable that, if the current grows up to 100 A and above, the discharge on the insulator can become almost continuous.

In Figs. 4 and 5, the development of a discharge in time recorded at a rate of 210 and 420 fps, respectively, is demonstrated. Figure 4 exhibits the view from above, at an angle of 45°. In frame 1, one can see a plasma channel that goes from the electrode and reaches the insulating wall of the vessel–the discharge chamber. This channel arises in the place of a primary streamer, the latter being not visible in every frame, which is explained by the magnitude of the time interval between frames at the given frame rate. In addition, the channel brightness is low against that of the liquid surface; nevertheless, one can distinguish a glow on the central electrode's insulator and a light spot on the wall of the dielectric discharge chamber. In frame 2, which was made in 5 ms, the system of plasma discharge channels is already visible. It reaches the insulating wall and is short-circuited to the water surface. At the center, over the electrode, there has already arisen a plasma column. A straight segment, which glows in the right part of the frame and goes from the center, is an insulated input lead. It is immersed into the liquid and is visible in every frame. In frame 4, made in 20 ms, the channels of the discharge current are badly seen against the background of the main discharge; some of them came under the plasma torch which expands more and more radially. Those channels, the glowing sky-blue cords, are current pathways; they start from be-

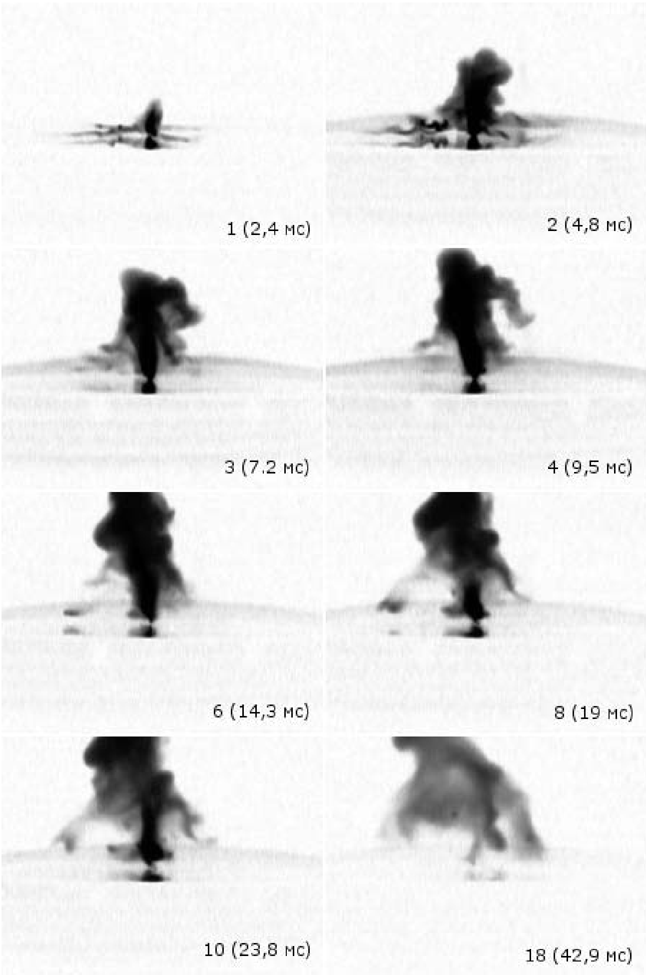

Fig. 5. Discharge dynamics (side view). 420 frames per second

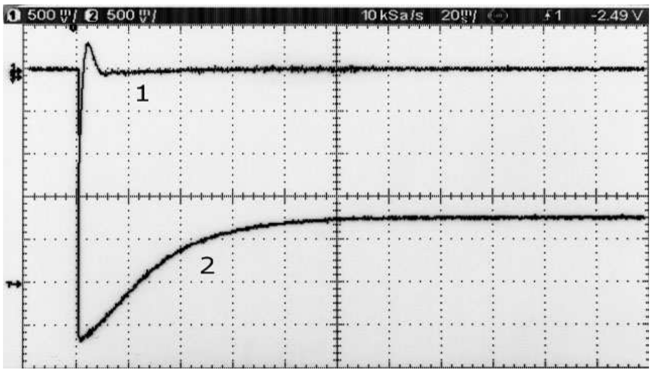

Fig. 6. Current-voltage characteristic (20 ms per div) *1* – current characteristic ; *2* – time dependence of the voltage

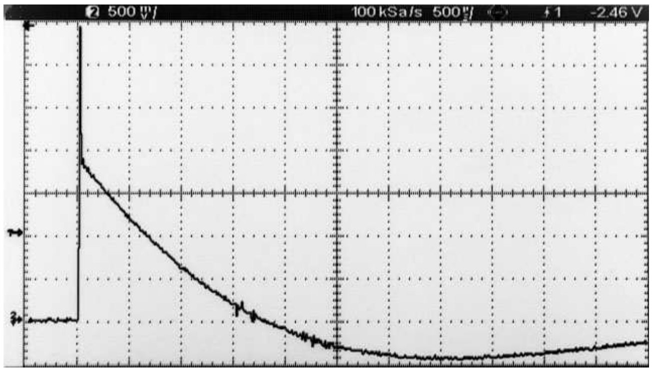

Fig. 7. Time dependence of discharge current (500 μs per div)

neath the top of a plasma torch, approximately 5–10 cm over the electrode. Probably, the effect of the magnetic insulation of a plasma column takes place here, which manifests itself as the fact that plasma current feedthroughs begin to propagate radially only starting from this height.

Further, the photos demonstrate that not only the glow brightness changes. The shape of a plasma formation approaches the spherical one, which, however, is followed by the appearance of regions with a lower glowing. At the center, one can see the region like a candle. It is a plasma column which appears from the central electrode, whose glow brightness diminishes. Further, the discharge degenerates; there appear two dark regions surrounded by glowing balls, which are some kind of current channels with a closed form. The magnitudes of discharge currents are small at this time; respectively, also small are the magnetic fields that surround them. However, they form and hold a low-temperature plasma which consists, in our opinion, of hydrated ions that are susceptible to the action of weak magnetic fields at a level of 0.2 Oe (see frames 21 and 23).

Figure 5 demonstrates a vertical picture of the discharge development. (One should pay attention to specular reflections of the discharge by the water surface.) One can see the current channels that go above the liquid surface. The height of the plasma column is about 2.5 cm on the first frame and 12 cm on the second one (at the initial moment, it reaches the height up to 5 cm in various experimental series). Further, its height achieves 15 cm (on frame 3) and then grows slowly.

Till 25 ms, one can see a rather bright plasma column-channel which appears from the central electrode. Till 45 ms, the plasma channel is not observable, but three current-carrying channels, which reach water and walls, do exist.

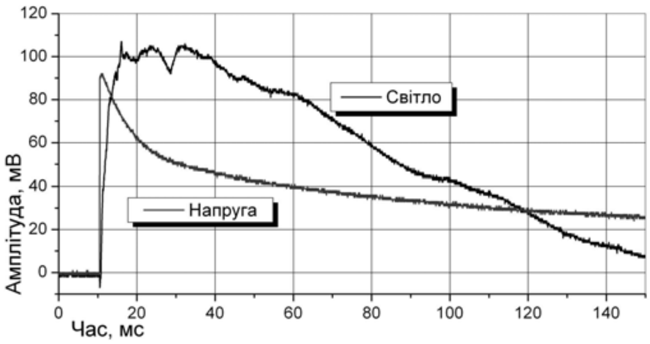

Fig. 8. Time dependences of the glow intensity (upper curve) and the battery voltage (lower curve)

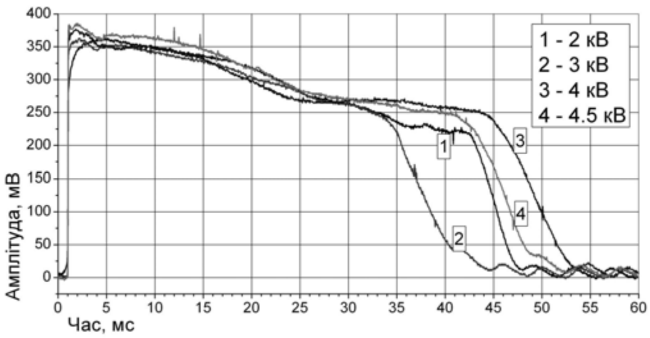

Fig. 9. Time dependences of the total glow intensity at various battery voltages

In oscillograms 6 and 7, the current-voltage characteristics of the discharge development are depicted. In Fig. 6, curve 2 is the time dependence of the voltage. The maximal amplitude of the charging voltage across a battery was 4 kV. Curve 1 is the current characteristic. In Fig. 7, the current characteristic is presented scaled up, which allows the initial stage of a discharge, which lasts for nanoseconds, to be observed. Additionally, it makes possible the pulse voltage increase across gaps that cannot be broken down by the initial voltage to be calculated. As is seen in both frames, the current signal has high enough characteristics only within the first 10 ms. A short splash of about 1 kA at the first moment and a subsequent decay followed by the sign change are observed. Here, the current is lower; the maximal amplitude reaches 270 A; afterwards, there begins a prolong decay. The estimation of the discharge current made from the voltage curve in Fig. 6 brings about the following current values: 36 A within the interval 0–20 ms, 28 A within the period 20–40 ms, 17 A within 40–60 ms, 7 A within 60–80 ms, and so on. As is seen, the time interval of a relatively high current discharge takes at most 1/10 of the total discharge time, and the existence of an independent plasmoid is accompanied by small discharge currents.

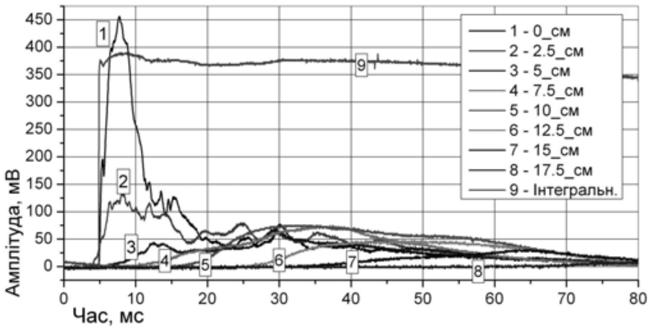

Fig. 10. Time dependences of the integral luminosity of a plasma formation (upper curve) and intensities of a plasma jet glow at various heights (lower curves)

The glow intensities of a plasma formation are presented in Fig. 8: the lower curve is the time dependence of the voltage across the discharge, the upper one describes the plasma glow which was obtained from a photodiode that accepts, due its wide aperture, the integral radiation emission produced by the discharge. It is evident that the integral intensity of the glow weakly depends on the battery loading voltage and, respectively, on the initial discharge currents, although it increases a little with increase in the charging voltage. In addition, the glow intensity is no longer related to high discharge currents. In Fig. 10, the characteristics of two types are shown. The upper curve is the integral luminosity of a plasma formation. The family of lower curves are the time dependences of the glow intensity of a plasma jet-column at its various heights (the curves were measured at the strong collimation of a photodiode). Since the plasma jet flows out from the central electrode, its brightness is governed by discharges on the insulator and discharge currents. The latter run along current channels on the insulator which do not remain stable, but move in time and space. All that is responsible for the brightness of a plasma column. The torch brightness, in general, correlates with the current characteristic, but only near the electrode. A prolonged afterglow reveals itself already at a distance of 3 to 4 cm. One can see that everything testifies to a long lifetime of excited states of molecules or their clusters which are localized in the peripheral regions of a discharge, where the temperature is lower.

Figure 11 demonstrates an optical spectrum measured at a distance of 3–5 mm above the central electrode. Farther from the electrode, as in Fig. 10, the brightness of lines falls down, and their number decreases. Lines H_β and H_α disappear, which evidences the plasma cooling, as well as calcium lines, but sodium lines persist to distances of 30 cm.

Experiments with salty water (the salt content was up to 10 g/l) were also carried out. The discharge was very bright, and it was accompanied by an intensive clap.

Two scenarios of the initial stage of discharge development are possible.

1. At the initial discharge stage, the short-term high discharge currents are observed. They are associated with the charging of the water capacitance formed by electrodes in the discharge chamber from the main battery. To check the hypothesis on charging the water capacitance, we mounted an equivalent circuit, where the discharge chamber was imitated by a capacitance C and a resistance R. At $C = 10$ pF and $R = 3$ Ohm, the initial section of the current curve turned out similar to that obtained at the experimental installation.

When the water capacitance discharges, there emerges a substantial potential difference $U = L \cdot di/dt$ across the gap between the electrodes which exceeds the charging voltage for a capacitor bank. (It is this voltage that results in the breakdown of wide air gaps.) This gap equals 20 cm for the ring system presented in Fig. 1 and 50 cm for the linear system. At such lengths, the magnitude of breakdown voltage should reach 50 to 60 kV. There appears a streamer followed by a plasma channel. Simultaneously, a breakdown over the insulator surface develops. Such currents and the magnitude of potential difference across the central electrode make an explosive emission possible, which results in the emergence of an electron beam that is slowed down in the atmosphere. The height of the plasma torch column in frame 1 in Fig. 3 is approximately 2.5–5 cm, which corresponds to the braking length of an electron beam with an energy of about 60 kV in air at the ambient pressure. During the beam deceleration, which is accompanied by the processes of ionization and excitation of molecules in air, there occurs an "ultra-violet illumination" in the whole space around the central electrode. The beam lifetime corresponds to the duration of the water capacitance discharge; then, a gas discharge above the water surface is ignited.

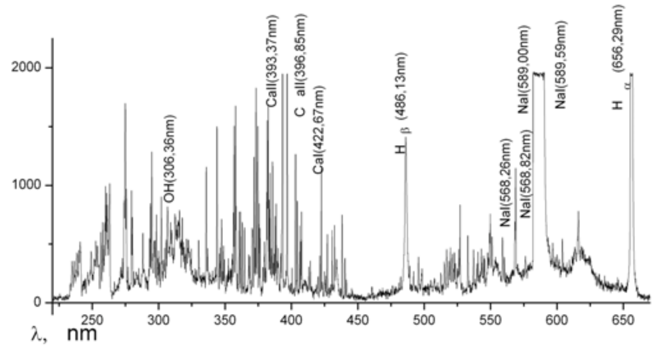

Fig. 11. Spectral characteristics of a discharge

2. The breakdown of the central electrode insulator invokes high current flows, so that current channels fill almost the whole insulator volume. Every current channel on the insulator is equivalent to a plasma source of the known "railotron" type, where the plasma junction between two oppositely directed currents is accelerated. In our case, the plasma junction is located on the upper end face of the insulator. The direct and inverse currents are mutually divided from the very beginning: first, by the insulator, and afterwards, as the plasma junction moves upwards, by the magnetic field H_θ formed around the current-carrying plasma column that goes upwards. Reverse plasma current pathways start from the plasma column at a height of about 10 cm. They are short-circuited to water and the insulating wall which is glowing. Plasma that propagates upwards is cooled down owing to its deceleration in the atmospheric air; it expands and forms plenty of hydrated ions, slow and long-term, in this region. The subsequent propagation of a discharge above the water surface is governed by the ratio between the air plasma and water resistances. In the case of salty water, its resistance is small. Therefore, the corresponding discharges are more likely localized near the water and central electrode surfaces which do not allow the discharge to expand strongly and to leave into an independent flight, because the higher temperature in those discharges "burns out" hydrated ions and cancels the excitation more quickly.

The concept of "hydrated ions" is rather wide; it includes complex ions composed of water molecules and its components H^+ and OH^-. In addition, sodium, iron, and chlorine ions, as well as other ions that are available in tap water, are included. The energy reserve of hydrated ions is relatively low. The internal energy of hydrated ions can range within the limits from the energy of chemical reactions down to the level of binding energies in complex ions, i.e. $q \approx 0.01 - 5$ eV. To understand the capabilities of hydrated ions, one has to know the actual size of those formations, their structure, binding energies, and the total energy. On the macroscopic scale, the mass distribution and the concentration are needed to be known. It should be noted that hydrated ions are not involved in high-pressure gas discharges. In work [4], water-gas-salt complexes were observed which included 3×10^6 molecules; their concentration was 10^{11} cm^{-3}, and the lifetime equaled tens of seconds.

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ПРО ДЕЯКІ ОСОБЛИВОСТІ ПЛАЗМОВИХ РОЗРЯДІВ НАД ПОВЕРХНЕЮ ВОДИ

В.Б. Юферов, Є.В. Муфель, В.І. Ткачов, С.В. Шарий, А.М. Шаповал

Р е з ю м е

Створено експериментальну установку, що дозволяє створювати автономні сферичні плазмові утворення. Досліджено процеси, які відбуваються в початковій стадії розряду. Описано два можливі сценарії їх розвитку. Наведено вольт-амперні і спектральні характеристики плазмоїдів, а також фотографії розвитку розряду в часі.