

Analysis of main regularities of periodic discharge passing in fluid stream

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Abstract. This paper describes the basic processes in the gas discharge plasma accompanying the jet of liquid flowing between the high-voltage electrode in the form of a tubular tip and the plane grounded electrode. The process is quasi-periodic due to a jet break caused by the "core" discharge on the surface of the jet and the arising shock wave. The main discharge is accompanied by one or more pinch discharges. At the bottom of a pinch in the metal there occurs a zone with $\sim (100 \div 300)$ micron size and with ultra-high energy release, where the metal is hardened. The paper analyzes the cause of formation of pinches and of formation of channels in the matter of the anode which are similar to channels generated in gas during the passage of intense beams. The paper concludes that there is a self-focusing mechanism not previously studied.

1. Introduction

A periodic discharge in a flow of liquid (PDFL) was first implemented in NRNU MEPhI in 1995 [1] and since then has found application in a number of technological processes used in aircraft industry [2, 3], heavy engineering [4, 5], in the manufacture of endoprostheses [3], tools, in the manufacture of rails [6], and others. In the study of PDFL its potential has not been fully identified. One of the constraints in this area is the difficulty in interpreting the physical processes that determine its flow. It is easiest to examine the PDFL mechanism, starting with the operation of a processing system in the original version.

2. Description of a processing system

The physical nature of a high-voltage discharge in a flow of liquid is illustrated by the given principal diagram of a system (Figure 1). The processed material (3) is placed on the stage (5) which is movable both automatically and manually. Above the specimen there is a hollow metal tip (1) attached to a reservoir of liquid (7) by a dielectric flow line (8). On the tip (1) a constant high potential (generally negative, with the declining current-voltage characteristic of around 7 kV) is supplied from the power unit (9). The specimen (3) with the stage (5) is located in the dielectric chamber (6). The excess of liquid is drained through the drain system (4). In case of a gap 3 ... 15 mm, a periodic discharge (2) with a repetition frequency $f \approx 50 \dots 300$ Hz appears between the specimen and the tip. The arc discharge with duration of a few tens of nanoseconds (a crater diameter of 5 ... 20 mm) has "point" effect on the treated surface. The displacement speed of the stage typically varied from 0.25 to 2.0 mm/sec.

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A jet of liquid flowing out of the container on a flat surface does not retain its cylindrical shape. It is known [8], herewith there appears a system of capillary waves fixed with respect to this obstacle. As the electric current passes through a jet from the constant rechargeable high-capacity capacitor, the normal instability in the form of wavy distortion of the smooth cylindrical jet [9] is significantly worsened by electrical charges [10] accumulated on its raised surface. Due to the presence of charges in a liquid jet the expansion pressure of Faraday-Maxwell will arise [11].

3. Photometric measurements of a discharge

The process of discharge leads to the disintegration of the continuity of a liquid mass and the emergence of shock waves accompanied by a powerful crash and emissions of some parts of a substance on the remote distance in relation to the scale of the experiment (up to tens of cm) (Figure 2).

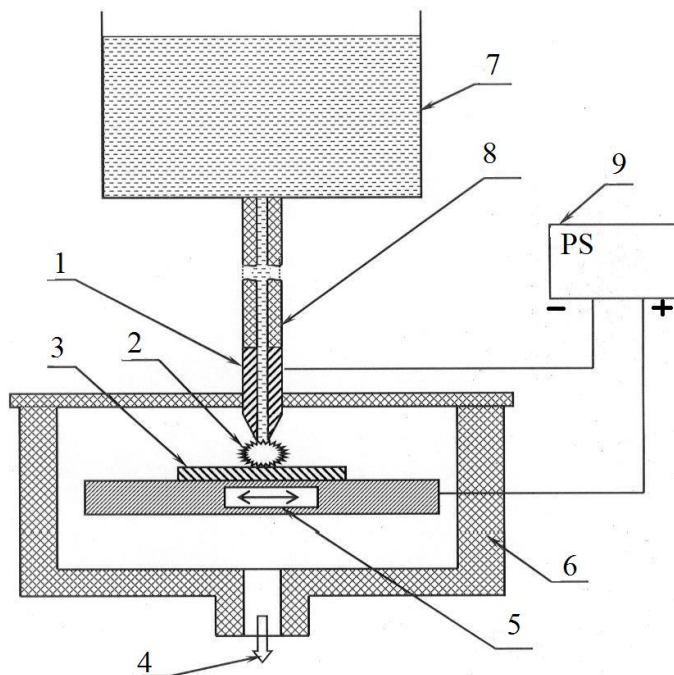


Figure 1. The diagram of a system for processing the specimens in the PDFL: 1 - the tip; 2 - the area of a discharge; 3 - the specimen; 4 - the drain system; 5 - the stage; 6 - the dielectric chamber; 7 - a reservoir of liquid; 8 a dielectric flow line; 9 - the power unit

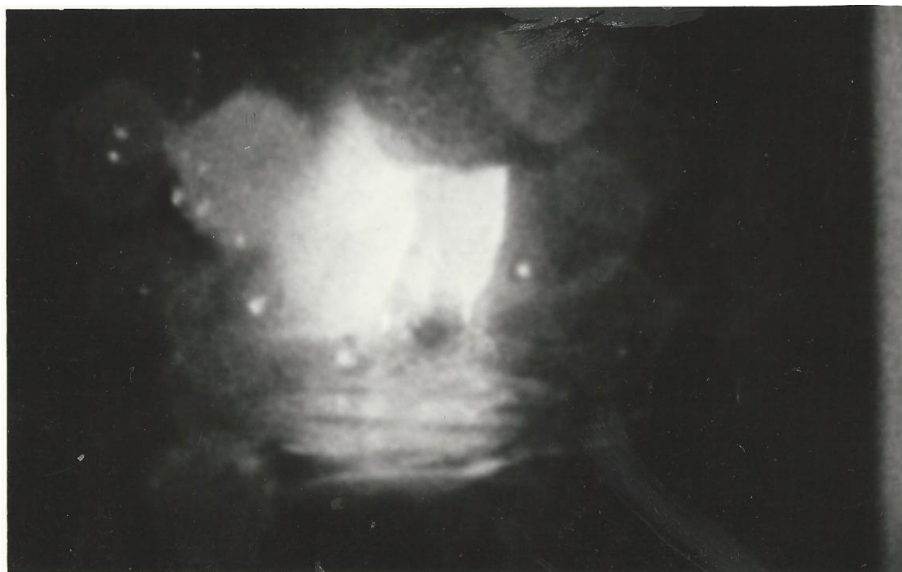


Figure 2. A jet break by a discharge and formation of clusters in the form of spheres.

In close proximity to a jet of liquid clearly distinguishable objects are formed taking the shape of spheres or polyhedrons, and having a "granular" structure like a peeled pomegranate, according to the authors, the most likely explanation for the appearance of these objects, in case of long-lived (up to several seconds), could be the formation, which is known from physical electronics and physics of a gas discharge, of hydrated ions of oxonium, whose structure at the molecular level is shown in Figure 3. It has the character of a dodecahedron.

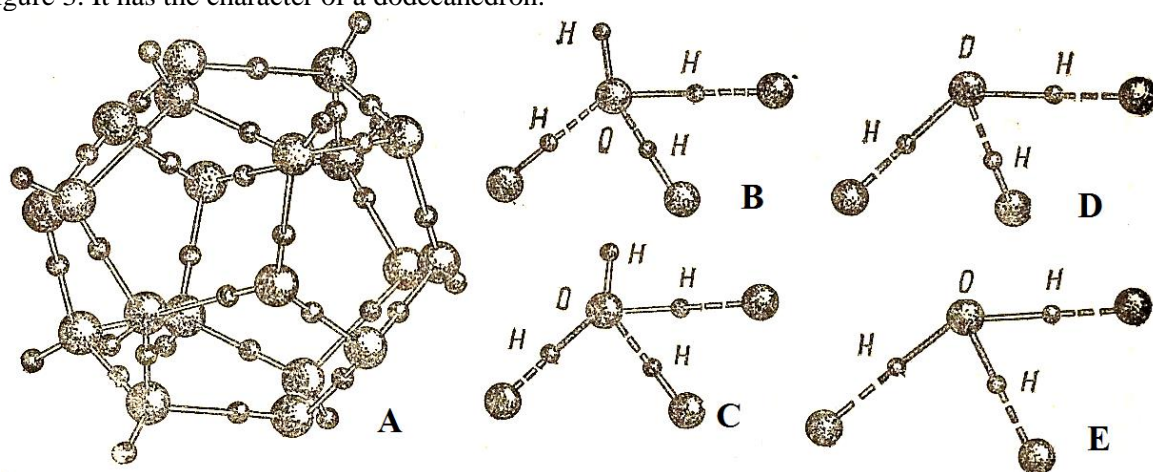


Figure 3. Ion $H^+ (H_2O)_{21}$:

a – the structure of ion; b, c – the top of the first type, where a molecule of water and oxonium ion is located respectively; d, e – the top of the second type with a molecule of water and oxonium ion; solid lines – valence bonds; a dashed line – a hydrogen bond.

This hypothesis is one of the key hypotheses explaining the nature of ball lightning [12]. This structure has a high capacitance and a lifetime.

The presence of such clusters on the basis of hydrated ions causes the appearance of the discharges of completely different type, in particular, the pinch discharges, in the localization area of the main discharge in a liquid jet (Figure 4).

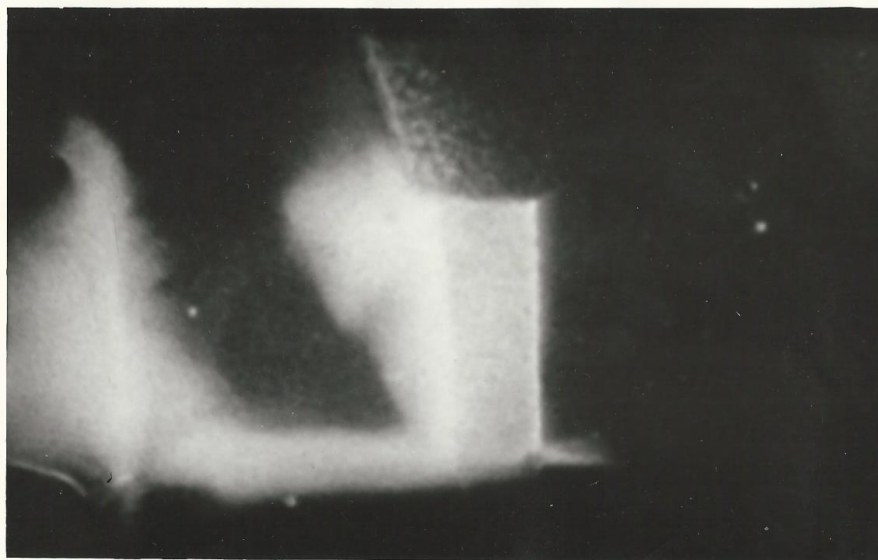


Figure 4. A pinch discharge (at the left) accompanying the appearance of the main one (at the center).

From the analysis of photo and filmed materials it is possible to make an unambiguous conclusion about the cluster origin of the pinch discharges. It is clearly seen that there may be several clusters and pinches on one "main" discharge along the jet (Figure 5). Clusters have substantially the same size and, consequently, the same capacitance and charge. This accounts for almost the same size of traces on the anode which remained at the bottom of the pinch discharges. Noteworthy is the fact that all types have in the bottom the typical structure which is characteristic of the so-called θ - pinch, when the flow of electrons moves on a narrowing spiral, like a tornado.



Figure 5. A few pinches simultaneously and a black object on their background.

4. The physical model of the process

Along a jet of liquid (water and etc.) on its surface there is a pinch discharge contributing to the formation of a hydrodynamic wave which breaks a jet. The process is periodic with a frequency of up to several tens of Hz. In the area of the jet localization (Figure 6), a region of enhanced ionization and low pressure caused by the flows of counter ions and electrons (e_0 and i^+) appears as in any electric discharge pump (the power unit of a processing unit - standard, intended for supplying magnetic discharge pumps such as NORD-100). In the presence of the emitting surface in the discharge area (E), or simply a charged region (as in a thundercloud) and conditions arise for the pinch discharges, especially if preionization and lowering of the gas (air) density have occurred. Electrons moving initially in parallel (vertically) form a pinching flow, since their space charge has been neutralized by the positive ions, and "parallel currents" are known to be attracted. A well-known «Z» -pinch is formed. But the process does not end here. The «Z» - pinch when approaching the anode becomes the « θ » - pinch, as indicated by the results of the analysis of photo and filmed materials. The author of [13] managed to find out the cause of this phenomenon. Its essence lies in the fact that only one of the directions of electrons rotation corresponds to the stable motion of electrons, namely, that coincides with the direction of magnetic induction vector of the azimuthal magnetic field \vec{B}_ϕ formed by the current of 'primary' electrons and ions in a flow. This practically means a "twisting" of the particle flux (electrons) in this direction when approaching the anode. The process is self-supporting, a so-called "collapse" is formed, and at the bottom of a pinch the current density may reach several tens of kiloAmperes per square millimeter (up to 5 kA at the pinch bottom not more than 30 microns in diameter).

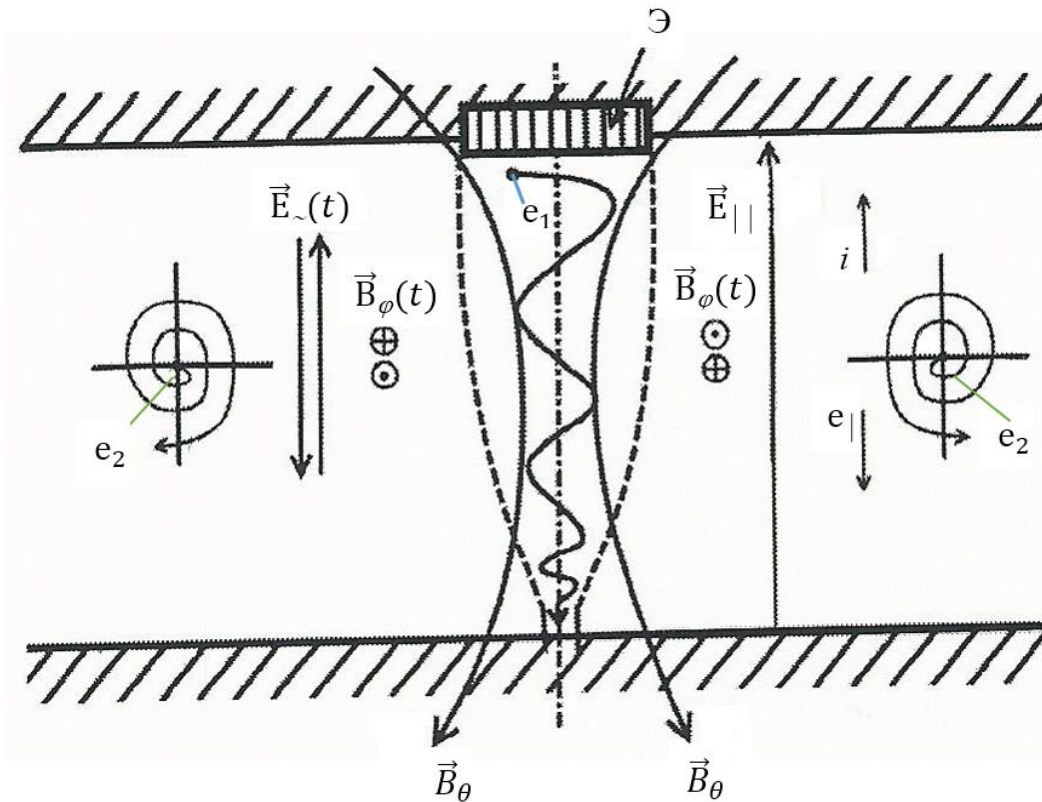


Figure 6. The diagram explaining the emergence of electric and magnetic fields and particle dynamics in the process of PDFL.

The azimuthal component of the electrons velocity generates the magnetic field B , which is essentially the field of a magnetic dipole. It can have an impact on the dynamics of particles in the surrounding area, but mostly - by collapsing a jet. Near a pinch the field \vec{B}_ϕ can accelerate ionization electrons in the betatron mode, stimulating the formation of plasmoids of ball and cylinder type, similar to the super high frequency (SHF) systems type - injectors based on the cyclotron resonance. Strengthening of the formation effect of plasmoids may be due to the presence of SHF - fields generated by the pinch discharges. The presence of a powerful SHF radiation has been detected by the authors, including in the frequency range corresponding to the electron cyclotron resonance, which corresponds to values of magnetic induction $|\vec{B}_\phi|$ in close proximity to the pinch discharges with currents up to 5 kA.

The presence of such plasmoids also was detected using photo and filmed materials.

Special attention is paid to the presence of absolutely black (non-transparent for radiating a discharge or laser light) spherical objects with the size of about 0.5 - 1 mm, sometimes with a central spherical part having presumably its own glow. The experimenters [14] encountered the objects on the facilities for the detection of an air spray glow. It has been suggested that the internal environment is formed by the radiation of the excited components of air and water ionized by particles (protons) with a short path. The outer sphere is separated from the inner sphere of black color where the light emission is suppressed. In the direction of the potential gradient in the outer sphere has been a modest glow trail.

During the unsteady evolution of a cold plasma experiencing the accelerating effect of Coulomb forces and the wave capture of light particles (electrons, protons) at the initial stage of its inception, there is a process of free charges pairing, which results in both the emitting plasma states and the

states of self-absorption of electromagnetic energy that are characteristic of relaxation phases of the Josephson generation [16].

Taken into account the fact that the source of the gas-kinetic and plasma excitation in the collapse of a particle is the point source, in the nature of the spatial distribution of localization areas of the particles energy the extrema of density are observed. The emergence of such spatially localized extrema of density (detected by light emission of excited components of air) owes its origin to the effect of a "virtual" electrode [15].

We cannot disregard the appearance of glowing regions in the form of hemispheres on the "grounded" electrode surface (in this case - the anode) (Figure 7) both in the discharge process and in its absence. According to the authors, this mysterious effect can be explained as follows.

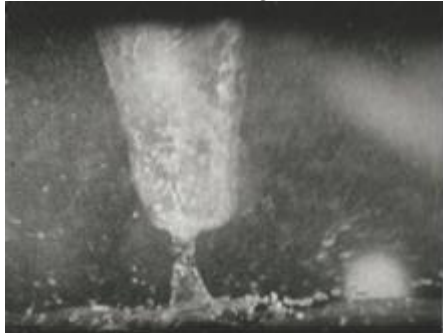


Figure 7. A glowing region in the form of a hemisphere on the anode surface after the end of discharge.

Similarly to the "step potential" known to specialists in electrical engineering and related in particular to the presence of leakage currents on the insulators of high voltage lines, in this case, the leakage current on a liquid jet, which in the immediate area generates the voltage other than zero, may be responsible for a glow. So, if the voltage on the power unit with an incomplete discharge capacity is an order of magnitude smaller, for example, 1 kW, on the surface of the water droplet with a diameter of 1 mm, which lies on the anode, it may be the electric field intensity ~ 20 kV/cm sufficient to the emergence of the so-called corona discharge in the humid air. This hypothesis is supported by the fact that such glows are displaced radially from the axis of a jet of water, most likely under the influence of a shock wave in the air.

Studies of the pinch discharges are of interest not only for solving technological applications mentioned in the paper introduction, but also for the problems of a fundamental nature. As the calculations and materials research of electrodes exposed to the pinch effects have shown, in the area of the bottom of pinches at the surface layer the zones up to 0.3 mm deep and with a diameter of about 0.7 mm are formed, in which a substance becomes amorphous instead of crystalline. Properties of a metal subjected to such an impact indicate that it has stayed in the stage of ultra-high pressure (up to $\sim 10^7$ kg/cm²) and temperature of about several thousand degrees. From the theory of shock waves is known that at pressures in the range of $10^4 \dots 10^5$ kg/cm² significant deviations from the linear law of compressibility are already observed and polymorphic phase transitions are found which are associated with changes in the atomic structure. At pressures of $10^6 \dots 10^7$ kg/cm² electron transitions occur; the destruction of electron shells and partial loss of the individual properties by atoms are also possible. A further pressure increase up to $10^8 \dots 10^9$ kg/cm² leads to the complete destruction of electron shells and the degeneration of the properties: the substance is converted into electron-nuclear gas. High pressures are accompanied by high temperatures. The relationship between pressure p , density ρ (specific volume V) and temperature T in the substance is expressed by the equation of state.

As a result of the materials research of the substance subjected to the PDFL, it was found that there are specific features associated, according to the authors, with the ultra-high densities of current and low pulse width with the pinch discharges. As can be seen from Figures 8 and 9, in the cross-section there are channels (up to a few cm) with the cross sectional dimensions of about (0.5 ÷ 1) mm, inside which the metal has an amorphous structure and color characteristic of the superheated metal and rotating around its own axis. This behavior of the charged particles flow is characteristic of the gas medium, when the beam is "self-focused" by its own magnetic field, in particular, when electrons

passing through the plasma. Herewith, the repulsive effect of the electrons space charge is compensated or overcompensated by the space charge of positive ions.



Figure 8. Pictures of channels in the substance, $\times 350$.

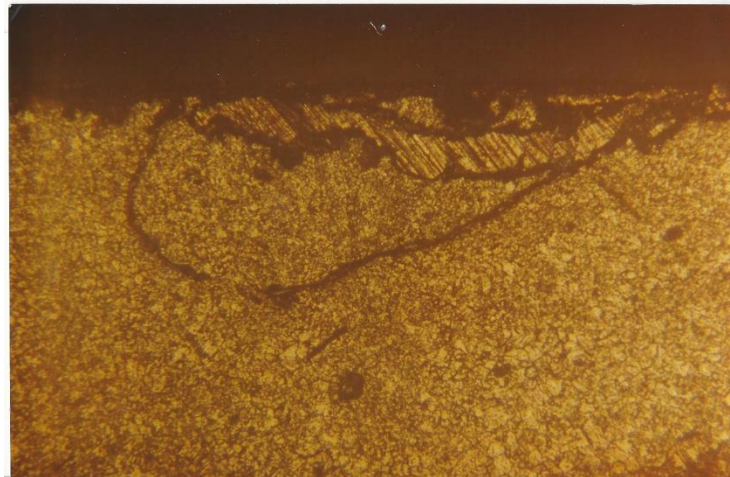


Figure 9. Pictures of channels in the substance, $\times 350$.

When electrons passing through the anode (metal or semiconductor) in the localization area of the conduction electrons flow (near the bottom of a pinch or the main discharge), a considerable number of "holes" is formed, the mobility of which is significantly lower than that of the conduction electrons. In particular, in Ge it is more than 2 times lower and in InSb and InAs it is about 70 times lower. This gives reason to believe that at some point, "the accumulated holes" are like a fixed background that compensates or overcompensates the charge of the electron flow focused by its own azimuthal magnetic field. The cross section shows that the trace of the flow narrows and then widens again. Most likely, there is a situation similar to the Hall effect in metals and semiconductors, particularly since we do not exclude the effect of the cross sectional magnetic field from "neighboring" currents, for example, the main discharge on the pinch discharge (in the space above the surface we can see the curvature of pinch axes being close to the main discharge - Figure 4).

The rotation of the current channel around its own axis can be attributed to reasons similar instabilities such as "snakes" or "sausages"-type during the passage of the particles flow in the gas.

5. Conclusions.

Results of the study of this process may be of practical importance for electrical engineering, in particular for the proper design of high-current pulse mode facilities to which the future of high-power electronics is ascribed.

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