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THERMAL AND ELECTRIC BREAKDOWN OF WATER AT CROWN AND SPARK DISCHARGES

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Abstract- The present article related to thermal and electric breakdown of water at influence of strong electric fields is devoted. Thermal processes in water lead to its boiling up and formation of gas inclusions, in which the crown and spark discharges are developed. It is shown, that at electric breakdown of water, unlike the thermal one, the delay time and emitted energy depends not only from parameters of the high-voltage equipment and electrode system, but also on water conductivity. The crown and spark discharges in water cause the shock waves and dispersing liquid streams, thermo ionization, formation of atomic oxygen, ozone and UV-radiation in all interelectrode distance. The considered physical processes can be successfully used in pilot-industrial installations for conditioning of drinking water and to disinfecting of wastewater.

Keywords: Thermal Breakdown, Crown Discharge, Spark Discharge, Delay Time, Emitted Energy, UV-Radiation, Ozone, Tension, Drinking Water, Wastewater, Gap, Pressure, Leader, Streamer, Channel, Gas Inclusions, High Voltage, Pin-Electrode, Polarity, Boiling Up, Conductivity, Electrode System.

I. INTRODUCTION

Last years the wide demand in development and application of hi-tech pulse technologies in various areas of a national economy is around the world observed. It is connected with exhaustion of mineral stocks, need of development of power effective and ecologically safe technologies for their further introduction in industry. This problem concerned as well the water sector, where still in many countries the chemical reagents are used for disinfecting of drinking and wastewater.

It is well known, that after such processing, there are conditions for formation of the complexes, harmful to human health and, as a whole, for all environment. In this regard, in many countries researches on development of enough innovative barriers for minimization of such toxic complexes are directed [1]. UV-radiation is well entered in this concept due to absence of the secondary products and achievement of high disinfecting efficiency [2-4]. Over the last 10 years, more than 30 large stations of UV-radiation in drinking water preparation systems, superficial water sources in the world into operation were put.

The main reason for application of UV-radiation in preparation of drinking water and disinfection of wastewater connects with need of destruction of viruses and the simplest twists, resistant to chlorine. In this regard research of the thermal and electric physical processes in water at influence of high voltage pulses and. as a result, development of crown and spark discharges for achievement of the full inactivation of microorganisms in drinking water and wastewater causes the huge interest and importance [5].

II. EQUIPMENT AND MATERIALS

The present article to studying of thermal and electric processes in water by effect of high electric fields is devoted. Effects, which can take place at a high voltage in water, are considered. In Figure 1 an electric scheme of high voltage equipment for pulsed water treatment is shown. Here the condenser battery by capacity 1-10 mcF and voltage up to 100 kV, as a source of pulses, is used.

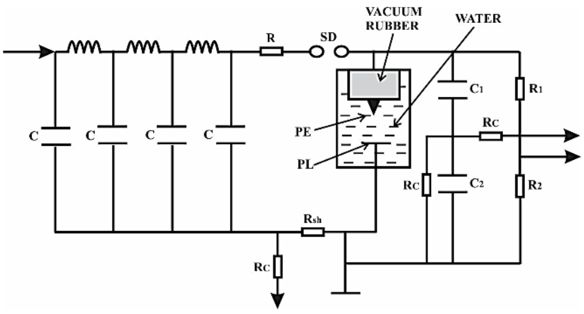

Figure 1. Electric scheme of high-voltage pulsed equipment and elements of the measuring devices:
C is capacitors, *R* is current-limiting resistance, *SD* is operated spherical discharger, *PE* is "pin" electrode, *PL* is plane electrode, R_1 and R_2 are ohmic tension divider, R_{sh} is shunt, C_1 and C_2 are capacitor tension divider, R_c is coordinating resistance, *PT* is pulse transformer [5]

At the scheme, the ohmic and capacitor voltage dividers are used. The ohmic voltage dividers are equal to the scheme low-voltage part resistance and are respectively equal to the wave resistance of the measuring cable. For registration of current during breakdown processes, the low inductive shunts by resistance 0.3-30 Ohm are used [5]. In researches (Figure 2) the "pin-plane" (PE-PL) electrode system, placed inside of vessel with explored water, is used [6].

For convenient supervision over breakdown processes, the water vessel from Plexiglas material and by size $140\times140\times140$ cm^3 was designed. For getting the strong non-uniform electric fields, the "pin" electrode is *PE* (radius of curvature ~ 0.1-0.8 cm) by vacuum rubber is insulated, but only its edge is connected with water. Experiments in tap water by conductivity $\sigma = (2.5\text{-}4)\times10^{-4}$ Om^{-1}cm^{-1} were done.

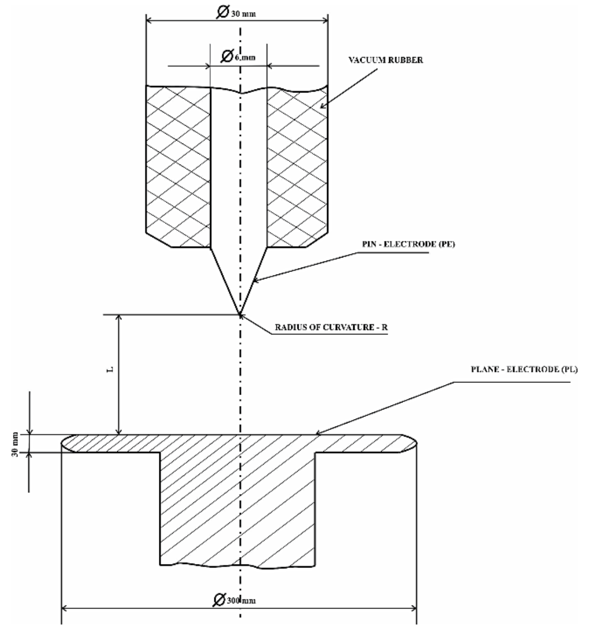

Figure 2. "Pin-plane" electrode system of discharge gap [5]

"Pin-plane" electrode system with the bared end creates the sharp heterogeneity of electric field, allowed to rapid development of physical and chemical processes in water, promoting formation of gas inclusions, the high-speed streamers and leaders inside of them [6]. The thermal and electric physical processes, such as, water boiling up, shock and photo ionizations, bringing to formation of atomic oxygen, ozone, UV-radiation, development of plasma channels in form of crown and spark discharges in all inter-electrode distance, emergence of the weak and strong waves, perniciously influence on bacteria and viruses [7]. Various polarity and amplitude of tension on "pin" electrode allows drawing a distinction between the beginning of thermal and electric breakdown of water and to reveal the electric and also design data of high voltage installation for minimization of power losses.

III. ANALYTICAL PART

For research of breakdown processes in water, the high-voltage pulsed generator with microsecond pulses in output was used. Will note, that one of the main parameters of breakdown process is a breakdown time, consisted from the following Equation (1): t_d is delay time, t_i is ionization time, t_l is leader's formation time, t_f is time of leader's final jump to opposite electrode and t_r is time of reverse discharge:

$$t_d + t_i + t_l + t_f + t_r \quad (1)$$

As t_f and t_r are less than other parameters in Equation (1), they can be neglected.

Considering, that at small tensions (U < 20 kV) near the "pin" electrode the thermal processes (liquid boiling up) and electrolysis are taken place, an electric field around it is strongly distorted [8]. At small interelectrode distances, t_l and t_i can be neglected and breakdown time only by t_d will be defined. By increase of tension amplitude (U > 20kV) in formed gas inclusions, owing to high internal temperature and pressure, the shock ionization, photo ionization and thermo ionization processes are observed and, as a result, the high-conductivity streamer and leader channels are appeared.

In this case, breakdown time from sum of three parameters t_d, t_i and t_l will be consisted. In long interelectode distances and at U > 50 kV delay time - t_d can be neglected and breakdown time of gap only by leader formation time - t_l will be defined. Necessary time for water boiling (from 0° to 100 °C) will depend from electric field intensity, specific electro conductivity and heat physical properties of water.

This time, taking into account, that water electro conductivity is a function of temperature as $\sigma = \sigma_0 (1 + \alpha T)$ (T is temperature at 0 °C, α is temperature factor, equal 0,011 1/degree, σ_0 is electro conductivity at 0 °C). The dissipated energy in unit of water volume at time -dt is expressed by formula $0.24E^2\sigma dt = c_1 m_1 dT$ (c_1 and m_1 are the specific heat and water density factors respectively) by following formula will be determined:

$$t = \frac{1}{0.24E^2\sigma_0}\int_{T_1}^{T_2}\frac{dT}{1+\alpha T} = \frac{\ln(1+\alpha T_2) - \ln(1+\alpha T_1)}{0.24E^2\sigma_0\alpha} \quad (2)$$

We will consider interdependence of parameters of electrode system and power source. As it was already noted, the high voltage pulsed generator on capacitor energy stores, as a power source, was used. It is known, that during impact of high electric fields, tension in water medium, is changed by law:

$$U = U_0 e^{-\frac{t}{RC}} \quad (3)$$

where, U_0 is tension on condenser, R is the active resistance. R depends from geometrical sizes of electrode system and conductivity of water. If we accept an electro conductivity of water σ independent from temperature and equal to average electro conductivity σ_{av} (for simplification of calculations), an Equation (2) will takes a form:

$$t = -\frac{RC}{2}\ln\left(1 - \frac{2\Delta T c_1 m_1}{0.24E_{0\max}^2\sigma_{av}RC}\right) \quad (4)$$

After some transformations, we can get Equations (5), (6) for determination of minimum tensions and field intensities, when the breakdown process in water is taken place:

$$E_{0\min} = \frac{25.8}{\sqrt{\sigma_{av}RC}} \quad (5)$$

$$U_{0\min} = \frac{25.8l}{k\sqrt{\sigma_{av}RC}} \quad (6)$$

Let us estimate the parameters R and k. It is possible for estimation R to use an electrostatic analogy method [9], where spreading resistance in the conductive area through capacity of electrode can be expressed. As mentioned above, the "pin" electrode in our experiments, is isolated by vacuum rubber, but only its edge by radius of curvature r and square S was directly connected with water. Capacity of uninsulated part is equal (in this case) to the capacity of the metal sphere with a stripping surface S. Besides, we use a simple expression for capacity of "sphere-plane" electrode system [10]:

$$R=\frac{1}{4\pi\sigma}\left(\frac{1}{\sqrt{\frac{S}{4\pi}}}-\frac{1}{2\left(l+\sqrt{\frac{S}{4\pi}}\right)}\right)=\frac{1}{\sigma}\left(\frac{1}{2\sqrt{\pi S}}-\frac{1}{8\pi l+4\sqrt{\pi S}}\right) \tag{7}$$

At assessment of heterogeneity coefficient k, we will consider, that the form of potential electrode in "pin-plane" electrode system represents the hyperboloid, which equation is:

$$\frac{x^2}{\lambda^2}-\frac{y^2}{b^2-\lambda^2}-\frac{z^2}{b^2-\lambda^2}=1 \tag{8}$$

where, λ is the big half shaft of a hyperbole, equaled to length of discharge gap, but $\sqrt{b^2-\lambda^2}$ is a small half shaft (λ = l, $\lambda < b$, $x > 0$). The maximum field intensity at the top of hyperboloid is defined from following expression:

$$E_{\max}=\frac{2U_0}{\sqrt{rl}}\times\frac{\sqrt{1+\frac{l}{r}}}{\ln\left(\sqrt{1+\frac{l}{r}}+\sqrt{\frac{l}{r}}\right)-\ln\left(\sqrt{1+\frac{l}{r}}-\sqrt{\frac{l}{r}}\right)} \tag{9}$$

By substitute of Equation (9) in a ratio for electric field's heterogeneity, and Equations (7) and (10) in (6), we will get a formula for k and $U_{0\min}$ for "pin-plane" electrode system:

$$k=2\sqrt{\frac{l}{r}}\times\frac{\sqrt{1+\frac{l}{r}}}{\ln\left(\sqrt{1+\frac{l}{r}}+\sqrt{\frac{l}{r}}\right)-\ln\left(\sqrt{1+\frac{l}{r}}-\sqrt{\frac{l}{r}}\right)}\approx 2\frac{l}{r}\times\frac{1}{\ln 4\frac{l}{r}} \tag{10}$$

$$U_{0\min}=\frac{12.9\sqrt{rl}}{\sqrt{C}}\times\frac{\ln\left(\sqrt{1+\frac{l}{r}}+\sqrt{\frac{l}{r}}\right)-\ln\left(\sqrt{1+\frac{l}{r}}-\sqrt{\frac{l}{r}}\right)}{\sqrt{1+\frac{l}{r}}\times\sqrt{\frac{1}{2\sqrt{\pi S}}-\frac{1}{8\pi l+4\sqrt{\pi S}}}} \tag{11}$$

By transforming the Equation (11), it is possible to define the minimum reserved energy in condenser, necessary to thermal breakdown, and its dependence from parameters of explored electrode system:

$$\frac{CU_{0\min}^2}{2}=80rl\frac{\left[\ln\left(\sqrt{1+\frac{l}{2r}}+\sqrt{\frac{l}{r}}\right)-\ln\left(\sqrt{1+\frac{l}{r}}-\sqrt{\frac{l}{r}}\right)\right]^2}{\left(1+\frac{l}{r}\right)\left(\frac{1}{2\sqrt{\pi S}}-\frac{1}{8\pi l+4\sqrt{\pi S}}\right)} \tag{12}$$

It is visible, that the minimum tension and reserved energy depends from geometrical sizes of "pin" electrode and interelectrode distance l, r and S. It should be noted, that dependence from radius of curvature of "pin" electrode r is especially strong.

Let us consider the change of current and consumed energy in time, before and during thermal breakdown in water. At influence of the high voltage on water, before the discharge processes, the thermal ones are taken place. As result of growth of electro conductivity and temperature in gas inclusions the current in discharge channels is also increased. We will consider the change of this current during formation of thermal breakdown.

Let, there is the electrode system with the bared surface of "pin" electrode and non-uniform electric field. Considering the Equation (2) for time of water boiling up, Equation (7) for the active resistance and a ratio for electric field's heterogeneity, the change of current before the discharge can be presented as:

$$i_{(t)}=\frac{lE\sigma_0\left(1+\alpha T_1\right)}{k\left(\frac{1}{2\sqrt{\pi S}}-\frac{1}{8\pi l+4\sqrt{\pi S}}\right)}e^{0.24\sigma_0\alpha E^2 t} \tag{13}$$

At T = 100 °C Equation (13) takes a form:

$$i_{100^0C}=\frac{El\sigma_0\left(1+\alpha T_1\right)}{k\left(\frac{1}{2\sqrt{\pi S}}-\frac{1}{8\pi l+4\sqrt{\pi S}}\right)}\times\frac{1+100\alpha}{1+\alpha T_1}=i_0\left(\frac{1+100\alpha}{1+\alpha T_1}\right) \tag{14}$$

where, i_0 is a current at the time of tension turning on.

Before the thermal breakdown, independently neither of the stripping area of "pin" electrode, nor of water electro conductivity and distance between electrodes, the current is increased in $(1 + 100\alpha)/(1 + \alpha T_1)$ times. The energy, spent for water heating before the beginning of thermal breakdown, can be defined from following expression:

$$W=\int_0^t Uidt=\frac{\Delta Tl^2}{0.24k^2\left(\frac{1}{2\sqrt{\pi S}}-\frac{1}{8\pi l+4\sqrt{\pi S}}\right)} \tag{15}$$

In this formula by substitute the value k from Equation (10), we can get expression for consumed energy, identical to Equation (12). From the analysis of above-stated formulas, it is possible to conclude, that for starting of thermal breakdown in water, it is necessary to spend some energy, depending on water temperature and intensity of electric field. Beginning of thermal breakdown is connected with increase of current and reduction of water resistance.

By knowing the size of conductive ionization zone, it is possible to calculate the value of this current. If to assume, that thermal breakdown comes to the end in points with the smallest field intensity (nearly plane electrode) and to accept it a constant and equaled to average value, the consumed energy at thermal breakdown in water can be determined by the following formula:

$$W = \frac{\Delta T l^2}{0.24\left(\frac{1}{2\sqrt{\pi S}} - \frac{1}{8\pi l + 4\sqrt{\pi S}}\right)} \approx 14.8 \Delta T l^2 \sqrt{S} \quad (16)$$

Comparing Equations (15) and (16), it is visible, that during thermal breakdown process the consumed energy is in k^2 times more. Breakdown time is also increased in comparison with time of beginning of the water boiling up process around "pin" electrode:

$$t = \frac{l^2}{0.24 U^2 \sigma_0 \alpha} \ln \frac{1+100\alpha}{1+\alpha T_1} \quad (17)$$

By increase of initial field intensity (E > 45 kV/cm) the thermal processes are replaced by electric ones, accompanied by appearance of plasma channels streamers and leaders. Time, required for their formation, is called as "leader delay" time. During this time the current change, as well as at thermal breakdown process, happens similar to Equation (13). Value of the "leader delay" time is much less, than time of the beginning of thermal breakdown. Therefore, it is possible to consider, that water's electro conductivity is changed no more. Current during this time can be defined from the following expression:

$$i_0 = \frac{U}{R} = \frac{U\sigma}{\left(\frac{1}{2\sqrt{\pi S}} - \frac{1}{8\pi l + 4\sqrt{\pi S}}\right)} \quad (18)$$

It should be noted, that leaders have some parameters: r is radius of channel, $l = v \times t$ is length, proportional to leader formation time t and speed of leaders v. At $l > 10r$, resistance of the leaders can be expressed by following formula [11]:

$$R_l = \frac{1}{\pi \sigma v t} \ln \frac{v_l t}{r} \quad (19)$$

Current of the single leader can be defined as:

$$i_{1l} = \frac{\pi \sigma v U t}{\ln vt - \ln r} \quad (20)$$

If we have n leader channels, the total leader current will be defined by following expression:

$$i_{1l} = \frac{\pi \sigma v U t}{\ln vt - \ln r} \quad (21)$$

It is visible, that leader's current at big tensions and big distribution speeds in "pin-plane" electrode system is linearly increased in time. The consumed energy during the leader stage, in turn, can be calculated by formula:

$$W = \int_0^{t=\frac{l}{v}} U i dt = \frac{\sigma n \pi l^2 U^2}{2v\left(\ln v - \ln v_1\right)} \quad (22)$$

where, v_1 is an extension speed of leader channels.

The above-stated reasoning's allow by regulation of some parameters of power source and electrode system to calculate the optimum operating modes of high-voltage installations for solution of corresponding task.

IV. EXPERIMENTAL PART AND DISCUSSIONS

Researches of physical processes in water under effect of high voltage pulses for its disinfection were carried out on various tension amplitudes, interelectrode distances and tension polarities. It was defined, that an electric field intensity smaller than E~85 kV/cm, the time before formation of leaders from "pin" electrode with negative voltage polarity is a little less, than for positive one. When an electric field intensity is E~350 kV/cm, some other processes are observed [12].

At U = 13 kV "leader delay" time is ~700 µs, and speed of crown discharge is increased a little. Between the "pin" electrode and "vacuum rubber" the crown discharge is also observed and covered more area. By increase of tension amplitude (up to U = 19 kV) "leader delay" time is reduced up to 40-400 µs. Breakdown process in interelectrode distance by development of leaders from a crown zone is completed. Speed of the leaders reaches 2×10^6 cm/sec (supersonic speed in water).

In Figure 3, the integrated digital luminescence photos of crown and spark discharges in water at "pin-plane" (+ *PE* - *PL*) electrode system with positive polarity of "pin" electrode at U = 19 kV (tension amplitude) and L = 30 mm (distance between the electrodes) are given.

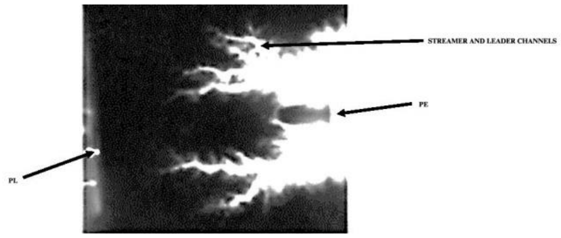

Figure 3. Digital luminescence photos, + *PE* - *PL*, L = 30 mm, U = 19 kV [4]

In Figure 4 the integrated digital luminescence photos of crown and spark discharges in water at "pin-plane" (- *PE* + *PL*) electrode system with negative polarity of "pin" electrode at U = 19 kV (tension amplitude) and L = 30 mm (distance between the electrodes) are given. We observe the more streamer and leader channels, developed in water with a subsonic speed ~1.5 mm/µs. By increase of electric field intensity, more leader channels are arisen. We can also observe an extension of the leader channels.

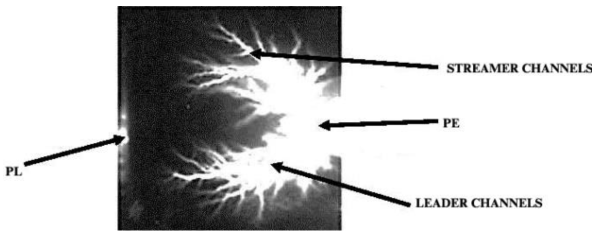

Figure 4. Digital luminescence photos, - *PE* + *PL*, L = 30 mm, U = 19 kV [4]

At U = 13 kV between the electrodes the wide dispersion of the luminescence is taken place. "Leader delay" time and breakdown time are ~ 220 - 900 μs and ~ 300 - 1000 μs respectively. At U = 19 kV through ~ 10 - 20 μs the crown discharge nearly "vacuum rubber", consisted from small streamer and leader channels and their further development towards an opposite electrode with a speed ~2×10^4 cm/sec in all interelectrode distance is observed. "Leader delay" time up to 50-100 μs is reduced. Leader channels usually start from rubber insulation.

With increase of tension, the number of leaders and their ramifications increases. At both tension polarities of "pin" electrode an electric breakdown process in water by crossing of leaders of all interelectrode distance is completed, i.e. by spark discharge. Temperature and pressure at the discharge channel can accordingly reach to $(3\text{-}4)\times10^4$ K and $(2\text{-}3)\times10^4$ atm values [13]. It is necessary to note, that better to use a positive voltage polarity on *PE* for creation a powerful shock waves and dispersing liquid streams in water. The formula for definition of average value of breakdown time, received experimentally is given below [12]:

$$t_{br} = \frac{al}{\left(U - U_{\min}\right)^2} \tag{23}$$

where, a is constant coefficient ($a = 3.6\times10^5$ V^{2}m/m) on electric water conductivity σ = ($\sigma = 2.5\times10^{-4}$ S/cm), l is interelectrode distance (cm). $U_{\min}=18\times10^3\times r\times\ln(4l/r)$ is minimum tension, at which the thermal regime passes in leader one and conditions for formation of leader channels are created, kV, r is radius of curvature of the "pin" electrode (mm).

It is also possible to determine the energy losses and other parameters in spark discharge during breakdown process at the maximum power in plasma channel. Interelectrode distance l, at which the maximum power in discharge channel is reached, can be defined from the following expression:

$$l = 8\times10^{-9} U_{br}^{3/2} \left(\frac{C}{L}\right)^{0.25} \tag{24}$$

where, C is capacity of condenser battery, L is inductance of the discharge circuit.

At short durations, the pulsed high electric fields can get in a microbe cell and stop its further development, inactivating it [14]. The optimum pulse duration connects with inactivated cell's size. It is more than bigger size of cells. Pulses by long front (t_f > 20 ns) get worse or don't at all get inside of cell. Therefore, it is better to effect on microorganisms by pulses with minimum possible fronts and an optimum duration with the great tension amplitude for reach of more inactivating effect.

Fields with high intensity perniciously influence on microorganisms in water. Are happen the micro explosions inside of cell's membrane and death of live cellular organisms, development of electric discharges in membrane channels, transparented for sodium, calcium ions and other elements during effect of high average field intensities. So, the water disinfecting process is observed.

V. CONCLUSIONS

So, presented article to innovative methods of disinfection of drinking water and wastewater by use of high voltage pulses is devoted. The analytical description of various stages of water breakdown and conditions of their realization are shown. Mechanisms of thermal and electric breakdown of water, leading to formation of gas inclusions, as result of, its boiling up and electrolysis process, and finally to ionization processes inside of them with formation and development of streamer and leader channels in the form of crown and spark discharges, are in detail described.

Expressions, by which the main parameters of breakdown processes (breakdown time, current, consumed energy, etc.) and their dependence from parameters of power source, electrode system and interelectrode distance are given. It is revealed, that depending on some conditions, the water breakdown process can be thermal or electric. It is shown, that at initial intensity of electric field (less 36 kV/cm} the thermal processes, accompanied by water heating (up to boiling temperature) in places with the maximum field intensity and formation of gas inclusions nearly "pin" electrode, and electrolysis process are observed.

Development and distribution of gas inclusions in the direction to an opposite electrode at small tension amplitudes independently from its polarity leads to thermal breakdown of water without formation of leader channels. It is revealed, that delay time of thermal breakdown on negative tension polarity on "pin" electrode is less, than on positive one. It probably is connected with a difference in concentration of gas inclusions at cathode and anode, because of, electrochemical processes in water.

Conditions of formation and development of the crown and spark discharges in water are described. The integrated photos of the discharge processes on various tension amplitudes, polarities and interelectrode distances are given. Transition from thermal stage of water breakdown to electric one by increase of tension amplitude and the features of electric breakdown with formation of high-conductivity streamer and leader channels at various tension polarities are shown.

Experimental data on influence of tension polarity on delay time and leader's distribution speed in all interelectrode distance, the empirical formulas for determination of the average breakdown time value and distance, corresponding to high power in discharge channel are given. Is shown an existence of the complex physical processes in water, such as formation of atomic oxygen, ozone, visible and UV-radiations, powerful shock waves during effect of the high pulsed electric fields, which in total bring to a full inactivation of drinking water and wastewater from pathogenic bacteria and viruses.

So, the obtained data allows to successfully applying this technology for creation of pilot-industrial installations to conditioning of drinking water and disinfecting of wastewater.

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BIOGRAPHY

Elchin Jalal Gurbanov was born in Kurdamir, Azerbaijan on 12/02/1963. In 1980, he Graduated from School No. 151, Baku, Azerbaijan. From 1980 to 1986, he studied on Electronic Equipment Faculty of Moscow Power Engineering Institute. In 1986, he started to work in High Voltage Laboratory of Institute of Physics of Azerbaijan National Academy of Sciences, Baku, Azerbijan. In 1995 he defended the Candidate Dissertation named "Interaction of no Equilibrium Electric Discharges with a Surface of Components of Composite Materials" and received a scientific degree of Ph.D. in physics and mathematics sciences. From 2006 to 2010 he studied in Doctorate in High Voltage Department of Moscow Power Engineering Institute (Technical University). Since 2013 he is working in "Science and Technique" Department of "Azersu" Open Joint Stock Company, Baku, Azerbaijan. He has above 60 scientific articles in different journals, 1 author certificate, and 2 patents.