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Gas bubbles chain in water and development of pulse electric discharge

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The development of an electric discharge in a liquid in the presence of a distributed gas phase can proceed differently than in a single-phase medium due to faster ionization processes in the gas. It was studied broadly in the numerical experiments by N. Yu. Babaeva and G. V. Naidis. They studied ionization within periodically distributed bubbles – two-dimensional arrays and one-dimensional chains. It was found the increase of electric field at the poles leads to increasing number of bubbles involved in the discharge development and it leads to expansion of the ionization region. However, numerical observation of a single discharge channel emerged from such ionized bubbles is currently impossible due to the multi-scale nature of the processes involved in the calculations. This work proposes a new method for generating ordered chains of gas bubbles in water. It is based on pulsed water electrolysis. Finally, effect of bubbles chain on the development of an electric discharge is examined.

Keywords: electrolysis, bubbles, chains, water, electric discharge.

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Introduction

The presence of a gas (vapor) phase in a liquid plays a major role in the initiation and development of an electric discharge in a liquid. Although direct ionization in the liquid state is theoretically possible at high field strengths and short rise times [1], the experimental realization of such conditions and the registration of ionization in the liquid state still remain a very difficult task [2]. A model concept of streamer propagation in liquid hydrocarbons was proposed in the works of G. V. Naidis [3, 4]. Much more often, the initiation of a discharge is preceded by the stage of formation in the liquid of a region of reduced density, in which ionization processes develop. Depending on the conditions, the formation of such a region is mainly caused by electrohydrodynamic flow [5–8], boiling [9], decompression (a sharp decrease in pressure) [10], or ultrasonic action [11].

The electrohydrodynamic flow arising in a liquid under the action of an electric field can lead to a disruption of continuity and the formation of a vapor-gas bubble in the region of strong field inhomogeneity [5, 6], which is realized, for example, near the tip of a high-voltage electrode [7]. Such a process occurs on nanosecond time scales.

The formation of a vapor-gas region through boiling is characteristic of lower voltages and long fronts of its rise [9]. The region of reduced density is formed where the greatest current flows, after which ionization occurs and a plasma channel appears, which grows into the liquid through evaporation and ionization.

Quite often, small and large bubbles may already be present in the liquid before the voltage is applied. This class of problems – with pre-existing bubbles – has received separate development. The most significant contribution to computational and theoretical studies was made

in the works of N. Yu. Babaeva and G. V. Naidis et al. [12–15], in which cases of both single bubbles and cases of their ordered one-dimensional chains and two-dimensional grids were studied. The development of a streamer inside a bubble is shown, as well as its influence on the initiation of discharges in neighboring bubbles (a kind of "chain reaction" effect). Experimental verification of the results obtained for ordered arrays of bubbles is currently complicated by the absence of a method for producing them. Breakdown of single or paired bubbles is being actively studied [16–19], however, the formulation differs somewhat from the computational one – as a rule, the bubbles are in contact with the electrode and with each other in order to fix them in space. Separately, it is worth mentioning an experiment in which a single bubble was held motionless in the bulk of a liquid using focused ultrasonic radiation [20].

In the present work, a method for producing chains of bubbles using pulsed electrolysis is proposed and studied. By varying the parameters of the electrolysis process, a high stability of the bubble diameter and the spatial repetition period can be achieved. For the most successful regime, shadow kinograms of the development of the electric breakdown of the gap in water with distributed vapor-gas bubbles were recorded.

Experimental Setup

To study the electric breakdown in water in the presence of gas bubbles, an experimental setup was used, schematically shown in Figure 1. The setup consists of a system for creating bubbles in the region between the electrodes, a system for supplying high voltage between the electrodes, a system for optical diagnostics, and measurement of the electrical parameters of the process.

The experiments were carried out in a dielectric container with a volume of 0.2 l, filled with water, with transparent walls (material – plexiglass). To ensure the electric breakdown of water in the region between the electrodes, a high-voltage electrode *E1* of spherical shape (diameter 3 mm) and a grounded electrode *E2* in the form of a disk with a diameter of 20 mm and a height of 5 mm are used. The grounded

electrode has a central through hole with a diameter of 2 mm, intended for the passage of bubbles into the region of electric breakdown. High positive voltage (+*HV*) from a capacitor bank *C* with a total capacitance of 1 μF, charged through a ballast resistor *R_b*, was supplied to electrode *E1* using a semiconductor switch *S* of the "half-bridge" type.

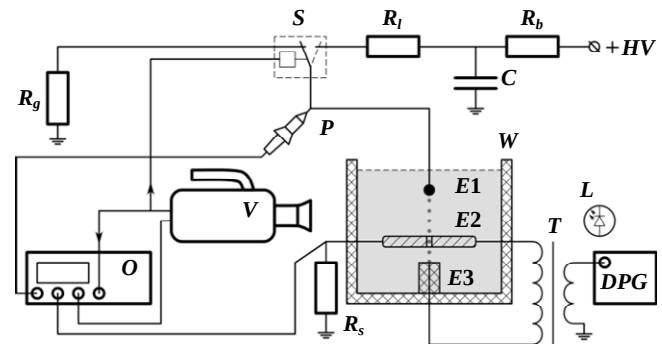


Fig. 1. Experimental setup diagram

To create bubbles in the region between electrodes *E1* and *E2*, an additional (low-voltage) electrode *E3* is used, located under the grounded electrode *E2*. When voltage pulses were applied between the low-voltage electrode *E2* and the grounded electrode *E2*, electrolysis of water occurred with the formation of gas bubbles. The diameter of electrode *E3* is 0.15 mm, the electrode itself is sealed in a dielectric sheath, which ensures an extremely low value of the contact area of the electrode with the liquid and a high local current density at this location. Ultimately, this leads to the localized appearance of gas bubbles near the cut of electrode *E3*. After the bubble detaches from the surface due to the action of buoyancy forces, it moves vertically upward through the hole in the grounded electrode. The opening of switch *S* was carried out by a signal from video camera *V*, used for visualizing the breakdown process. The discharge current was limited using load resistor *R_l*. Resistor *R_g* was used to limit the current through the switch in the "to ground" switching mode.

The mutual arrangement of the electrodes ensures the absence of electric breakdown between electrodes *E1* and *E3*; however, when a high potential is applied to electrode *E1*, the voltage at *E3* can still increase to a value of several hundred volts, which can damage the low-voltage part of the setup intended for electrolysis.

In order to avoid this, this part of the circuit is galvanically isolated from the volume of liquid using a pulse transformer T . The primary winding of transformer T is excited using a programmable digital generator (DPG), which has the capability of regulating the amplitude of the generated pulses. The generator operated in the mode of generating high-frequency pulses with a duty cycle close to 0.5, with a number of n pulses and with gaps of m pulses. Before applying high voltage, the numbers n , m , and the pulse amplitude were experimentally selected in the working container in order to achieve the required frequency of bubble creation and their size. The polarity of electrode $E3$ was positive.

To visualize the process and to determine the path of the electric arc, the shadow method was used, implemented using LED L , high-speed video camera V with a microscope as the objective, providing a spatial resolution of $10\text{ }\mu\text{m}/\text{pixel}$. The light emitted by the LED was collimated by a converging lens into the region between electrodes $E1$ and $E2$, then entered the microscope of the video camera. Registration of the shadow image of the process began after pressing the button of the video camera, and its recording rate was 140.000 fps, with an exposure of $0.3\text{ }\mu\text{s}$. The moment of pressing the button was determined by the operator when in the region between electrodes $E1$ and $E2$ there was a sufficient number of bubbles of suitable size.

To register the electrical parameters of the process, a four-channel digital storage oscilloscope O (2 GHz, 10 GSamples/s), a high-voltage probe P connected to the high-voltage electrode P , and a resistive shunt R_s with a resistance of $25\text{ }\Omega$ were used. The trigger signal for video recording of the video camera was simultaneously fed to the oscilloscope and to switch S , which ensured the start of their operation. To another channel of the oscilloscope, signals of the beginning of the video camera exposure were additionally fed in order to correlate the visible picture of the discharge with the electrical parameters of the circuit at that time. To the remaining two channels of the oscilloscope, signals from probe P and the voltage across shunt R_s were fed to measure the voltage at the high-voltage electrode $E1$ and the current in the circuit, respectively.

Findings and Discussion

At the first stage of the study, a search for an electrolysis regime that would ensure stable formation and detachment of bubbles was made. Figure 2 presents a photograph of a chain of bubbles with a diameter of about $50\text{ }\mu\text{m}$; the number of bubbles in the visible region is 11. The spatial period of succession is about $300\text{ }\mu\text{m}$.

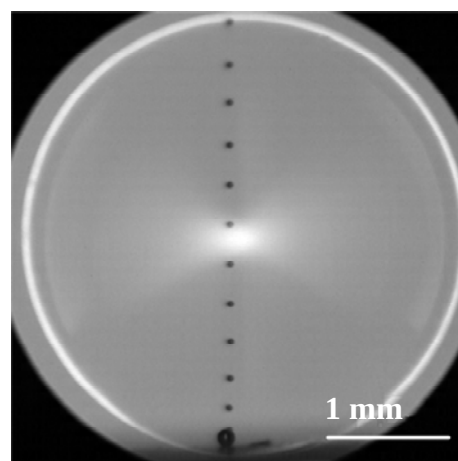


Fig. 2. An example of a chain of bubbles generated by means of electrolysis in a pulse-periodic regime

This regime can be considered the best since it combines a relatively large diameter and the absence of additional parasitic centers of bubble formation. The main difficulty in achieving the working regime consists in satisfying two oppositely directed requirements: on the one hand, to generate bubbles with a size of fractions of a millimeter and their chains, an increase in current is necessary; on the other hand, an increase in current leads to the spontaneous appearance of additional centers of bubble generation on the surface of electrode $E3$, which give rise to additional chains of bubbles of smaller diameter (about $10\text{ }\mu\text{m}$). At the same time, the continuous flow of current, even of a small amplitude, leads to chaotic generation and detachment of bubbles. In order to overcome the described difficulties, a pulse-periodic regime of voltage at electrode $E3$ is introduced in the work. The proposed voltage waveform – n pulses with a duration of about 500 ns and a period of about $1\text{ }\mu\text{s}$, followed by m skip pulses (voltage equal to zero) – solves the posed problem. The high frequency (about 1 MHz) together with a duty cycle of about 50% apparently ensure a pulsed

regime of gas formation in which each new portion of it manages to merge with the growing bubble. An increase in the duty cycle reduces the intensity of gas formation, which leads to longer periods of bubble detachment and larger distances between neighboring bubbles in the forming chain. A decrease in the duty cycle, on the contrary, leads to the appearance of additional centers of gas formation and the formation of undesirable side chains. In the proposed method, the detachment of bubbles after their growth is determined by the presence of m skip pulses in the voltage signal. The key here, apparently, is the influence of flows arising under the action of the electric field near the surface of electrode E_3 . This flow is clearly visible to the eye when observing small bubbles remaining near the electrode after a completed preceding experiment. The application of a new series of pulses leads to the formation of a bubble on the surface of the electrode, while the liquid around it rushes toward the electrode, thereby washing the bubble off the surface and ensuring its detachment. This circumstance is positive and important, since in the absence of a driving force, the detachment of a bubble from the surface and overcoming the forces of surface tension at the expense of buoyancy forces occurs at significantly larger diameters (on the order of 1 mm). The total time of the pulses ($n + m$) coincides in order of magnitude with the period of bubble detachment from the surface, which allows us to assume the main role of the mechanism described above in the detachment of bubbles from the electrode.

It should be noted that, despite the discovered parameters for controlling the process of bubble formation, it has so far not been possible to achieve chains of bubbles with a diameter on the order of 1 mm. The rapid growth of large bubbles with increasing voltage is accompanied by the appearance of secondary centers of gas formation and side chains of small bubbles. Slow growth of large bubbles is possible, however, the long growth time leads to very large distances between bubbles, at which they no longer constitute a chain and cannot serve the purposes of studying their mutual influence in the development of electric breakdown.

Despite the fairly high stability of the generation of the chain of bubbles, the parallel growth of one larger bubble is often observed (see Fig. 2, on the surface of the electrode), which grows over the course of 5–10 seconds and then detaches. No methods of combating this effect have yet been found, and this limits from above the distance at which the high-voltage electrode can be placed, since after detachment the large bubble floats up at a higher velocity and disrupts the structure of the chain obtained before its detachment. In the current implementation, this distance turned out to be less than the height of placement of the high-voltage electrode, chosen from considerations of the safety of the low-voltage (electrolysis) part of the electrical circuit. For this reason, the chain of bubbles along which the electric discharge develops (Fig. 3) turns out to be deformed.

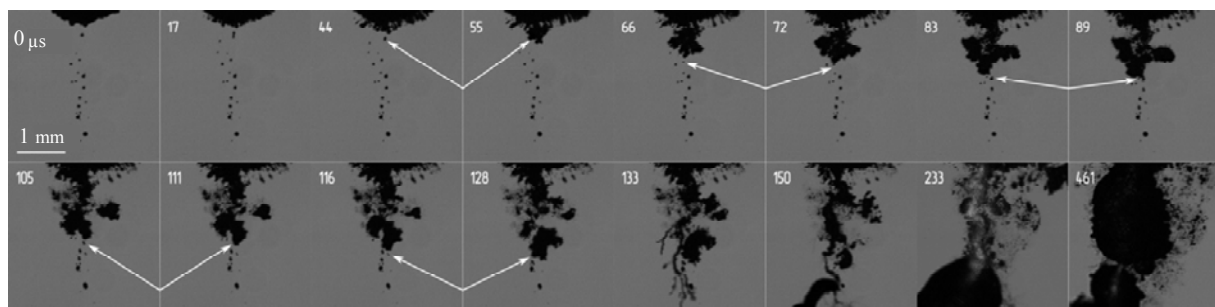


Fig. 3. Kinograms of the development of an electric discharge in water guided by a chain of bubbles

Figure 3 presents a kinogram of the development of a pulsed electric discharge in water with a conductivity of $45 \mu\text{S}/\text{cm}$ in the presence of a fragment of a chain of bubbles. The

magnitude of the applied voltage is 10 kV. At the upper boundary of the figure, a small part of the rounded anode is visible; the main part of the visible region is occupied by the chain of

bubbles; the cathode is outside the image, below the lower boundary. The corresponding oscillograms of voltage and current across the discharge gap are presented in Figure 4. Immediately after the application of voltage, the deformation of the electrolysis bubbles adhering to the surface of the high-voltage electrode *E1* during flotation begins. Their size along the field increases, while across the field it decreases. Then, inside one of them, the initiation of a discharge channel occurs ($44\text{ }\mu\text{s}$), which begins to grow downward in the direction of the grounded electrode *E2*. Comparing successive frames of the kinogram (44 and $55\text{ }\mu\text{s}$, 66 and $72\text{ }\mu\text{s}$, etc.), it is possible with a high degree of confidence to speak of the involvement of the bubbles in the chain (marked by arrows) in the process of advancement of the discharge channel. By the time $133\text{ }\mu\text{s}$, the channel turns out to be sufficiently close to the region of the inhomogeneous field associated with the presence of the edge of the central hole in electrode *E2*, and the relatively slow growth is replaced by a short-term and rapid elongation of the channel. On the oscillograms, this is accompanied by a short-term surge of current up to 0.5 A and a drop in voltage to 4 kV . The final closure of the gap occurs by $233\text{ }\mu\text{s}$, and the discharge transitions to the arc stage with a current of about 1.5 A , after which the high-voltage switch opens upon expiration of the pulse duration time of $500\text{ }\mu\text{s}$.

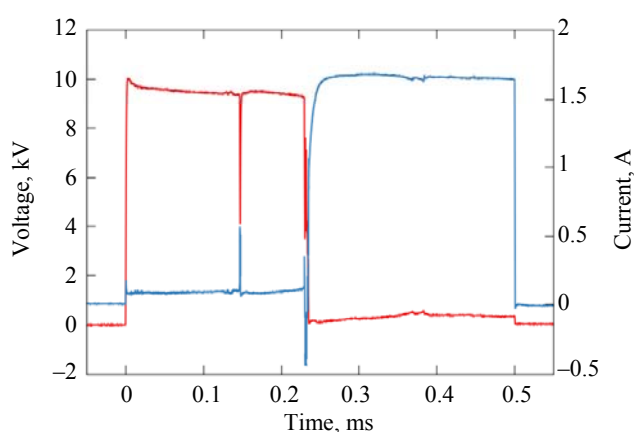


Fig. 4. Oscillograms of voltage and current across the discharge gap corresponding to the breakdown in Fig. 3

Conclusions

The proposed method for producing chains of single bubbles of submillimeter diameter by means of pulse-periodic electrolysis in water has shown its suitability and promise in studying the development of electric discharges in two-phase media. The advantages include the good reproducibility of the bubble diameter in the chain and the distance between neighboring bubbles, the possibility of influencing these quantities through the electrical parameters of the electrolysis process and establishing their required ratio.

The disadvantages include the complexity of tuning and the strong influence of the discharge on the electrolysis process at low water conductivity (about $5\text{ }\mu\text{S/cm}$) – after each application of high voltage, the electrolysis process stops for some time (minutes), which is explained by a deficit of ions after the flow of the discharge current. Increasing the diameter of the bubbles is difficult while preserving their repetition period in the chain, since the intensification of the gas formation process leads to the appearance of several growth centers. Each of them may begin to generate its own chain of small bubbles instead of generating one large bubble. A consequence of the instability of the process at a higher productivity is the periodic appearance and detachment of larger bubbles, whose motion disrupts the structure of the chain. For this reason, the initiation of the discharge process at large distances from the point of generation in a well-structured chain remains difficult.

In the most successful current formulation, the discharge was initiated along a chain of bubbles with a diameter of $50\text{--}100\text{ }\mu\text{m}$ and a repetition period of about $200\text{ }\mu\text{s}$. The propagation of the head part of the discharge channel along the distribution of bubbles in the interelectrode gap was recorded.

Further studies will be directed toward eliminating the above-listed disadvantages and visualizing the ionization processes inside the bubbles.

REFERENCES

1. Ushakov V. Ya., Klimkin V. F., Korobeinikov S. M., and Lopatin V. V. Breakdown of Liquids at pulse Voltage. NTL, Tomsk, 2005 [in Russian].
2. Starikovskiy A., Yang Y., Cho Y. I., and Fridman A., Plasma Sources Sci. Technol. **20** (2), 024003 (2011).
3. Liu Q. and Wang Z. D., IEEE Trans. Dielectr. Electr. Insul. **22** (6), 3228–3236 (2015).
4. Naidis G. V., J. Phys. D: Appl. Phys. **49** (23), 235208 (2016).
5. Tereshonok D. V., Babaeva N. Yu., Naidis G. V., and Smirnov B. M., J. Phys. D: Appl. Phys. **49** (50), 505501 (2016).
6. Tereshonok D. V., Babaeva N. Yu., Naidis G. V., Panov V. A., Smirnov B. M., and Son E. E., Plasma Sources Sci. Technol. **27** (4), 045005 (2018).
7. Marinov I., Guaitella O., Rousseau A., and Starikovskaia S. M., Plasma Sources Sci. Technol. **22** (4), 042001 (2013).
8. Shneider M. N. and Pekker M., Phys. Rev. E **87** (4), 043004 (2013).
9. Panov V. A., Vasilyak L. M., Vetchinin S. P., Pecherkin V. Ya., and Son E. E., J. Phys. D: Appl. Phys. **49** (38), 385202 (2016).
10. Panov V. A., Vasilyak L. M., Vetchinin S. P., Pecherkin V. Ya., and Son E. E., Plasma Sources Sci. Technol. **28** (8), 085019 (2019).
11. Panov V. A., Pecherkin V. Ya., Vasilyak L. M., Kulikov Yu. M., Saveliev A. S., and Filatkin A. A., Applied Physics, No. 6, 29–34 (2022) [in Russian].
12. Babaeva N. Yu. and Kushner M. J., Plasma Sources Sci. Technol. **18** (3), 035010 (2009).
13. Babaeva N. Yu., Tereshonok D. V., and Naidis G. V., J. Phys. D: Appl. Phys. **48** (35), 355201 (2015).
14. Babaeva N. Yu., Berry R. S., Naidis G. V., Smirnov B. M., Son E. E., and Tereshonok D. V., High Temp. **54** (5), 745–766 (2016).
15. Babaeva N. Yu., Naidis G. V., Tereshonok D. V., and Smirnov B. M., J. Phys. D: Appl. Phys. **50** (36), 364001 (2017).
16. Korobeinikov S. M., Melekhov A. V., and Besov A. S., High Temp. **40** (5), 652–659 (2002).
17. Sommers B. S., Foster J. E., Babaeva N. Yu., and Kushner M. J., J. Phys. D: Appl. Phys. **44** (8), 082001 (2011).
18. Hamdan A. and Cha M. S., IEEE Trans. Plasma Sci. **44** (12), 2988–2994 (2016).
19. Wang K., Bhuiyan S. I., Baky M. A. H., Kraus J., Campbell C., Tang X., Jemison H., and Staack D., Plasma Sources Sci. Technol. **30** (5), 055013 (2021).
20. Sommers B. S. and Foster J. E., Plasma Sources Sci. Technol. **23** (1), 015020 (2014).

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