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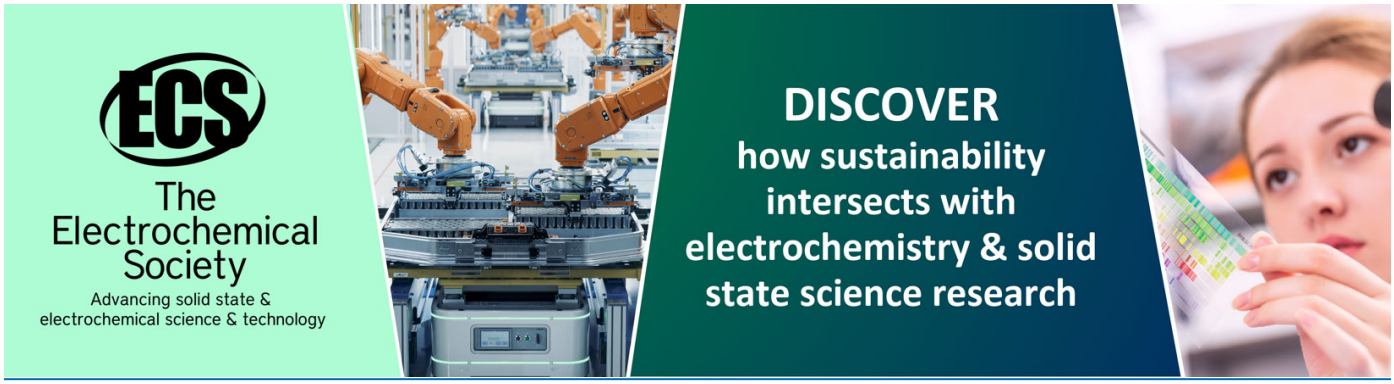

Spark discharge in conductive liquid with microbubbles

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Abstract. Pulse electrical breakdown in 15% water solution of Isopropyl alcohol with air microbubbles from a pointed anode has been studied experimentally. It is shown, that the breakdown is always initiated from the bright region near the anode (anode "spot"). Detailed investigation into dynamic current–voltage characteristics and synchronized images reveals that it is thermal instability in the near anode region that causes spark channel initiation and development. The breakdown voltage, spark channel propagation speed and short-circuit current increase when the microbubbles are presented in the solution. The spark channel propagation speed is about 4–12 m/s and grows along with microbubbles concentration.

1. Introduction

Electrical breakdown in homogeneous liquids with single inclusions of different phase (such as single bubbles [1] or metal micro particles [2]) is well studied. Initiation processes are studied numerically in case of pre-existing bubbles [3] and in light homogeneous liquids [4].

The possibility of effective application of pulsed electric discharges in gas–liquid media, in areas such as, for example, purification and chemical decomposition of harmful substances [5] decontamination and disinfection of aqueous solutions [6] is investigated. In spite of the vast accumulation of experimental and theoretical material a physical model of the discharge channel evolution in liquids is still a gas-approximation that valid for a limited number of light liquids. Slow thermal stage, initiation and development of the spark channel and the influence of microbubbles on the channel development are virtually unexplored. Previously [7] we have studied the electrical discharge in isopropyl solution. Such discharge could be quite an effective and required tool for waste-water purification especially since microelectronic manufactures utilize alcohols for washing (including isopropyl alcohol) at the final stage of printed boards' production. The authors [6] have already made an attempt to develop some sort of plasma-chemical reactor for water purification. However high rate of purification has not been achieved due to luck of solid fundamental assumptions on breakdown development in such bubbled medium. The aim of this work is to study the spark discharge in a homogeneous 15% water solution of isopropyl alcohol without bubbles comparing to this in bubbled solution with gas volume fraction of the microbubbles of 3 and 10%.

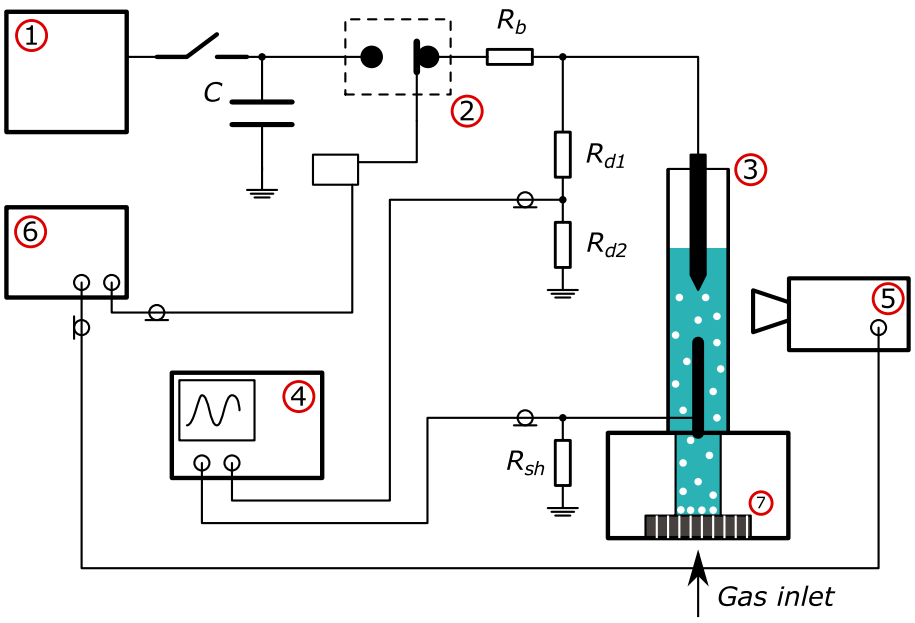

Figure 1. Experimental setup: 1—high-voltage charging power supply; 2—triggered spark gap switch; 3—discharge cell; 4—Tektronix DPO7054C oscilloscope; 5—high-speed camera RedLake MotionPro X3; 6—pulse–delay generator G5-63; 7—porous membrane; R_b—ballast resistor; $(R_{d1} - R_{d2})$—high-voltage divider.

2. Experimental set-up and diagnostics

The experimental setup scheme is shown in figure 1. The experimental setup consists of a high-voltage charging power supply, a pulse generator with impact capacity of 0.8 μF, a triggered spark gap switch, a discharge cell, current–voltage registration system based on a high-voltage divider and a current shunt connected to the Tektronix DPO7054C oscilloscope, and the high-speed camera RedLake MotionPro X3 with exposure in the range from 40 ms down to 1 μs. The HV-divider and the current shunt are assembled from noninductive resistors. All units of the experimental system are synchronized by pulse–delay generator G5-63. Applied high-voltage pulse full width at half magnitude is about 5 ms, the rise time from 10 to 90% level is about 0.8 μs. The maximum magnitude of applied voltage is 40 kV. Discharge current is limited by 10 kΩ resistor so maximum current is 4 A.

The discharge cell consists of quartz tube with the electrodes at the top and the bottom of the tube. The tube inner diameter is 16.6 mm. The pointed anode is made of 3-mm-diameter stainless still rod with 5-mm-height conic tip with 50-μm spherical radius at the very tip. The cathode is made of 2-mm-diameter brass rod with rounding on the working end perimeter. The electrodes are placed in axial alignment. Microbubbles with 150-μm mean diameter are injected into solution through a porous membrane installed under the cathode in the quartz tube support. The tube is filled with 15% solution, the gas volume fraction is regulated by the air pressure on the membrane.

3. Experimental results and discussion

Three sets of experiments have been performed: in the solution without bubbles, in the solution with microbubbles at 3% gas volume fraction, and in the solution with microbubbles at 10% gas volume fraction. Initial specific electrical resistance of the solution without bubbles was 3.5 kΩ cm. The evolution stages of breakdown were investigated. In all three cases the spark

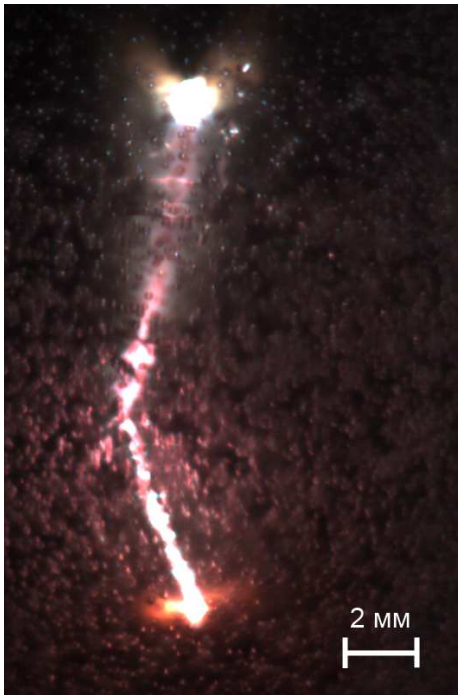

Figure 2. Developed spark channel in 15% isopropyl alcohol solution in tap water with microbubbles (3% gas volume fraction, 150 μm mean diameter). Camera exposure 200 μs, frame rate 1600 fps. Gap voltage and current at the moment of recording are 0.7 kV and 1.5 A respectively. Recorded moment is 5450 μs after voltage was applied. Gap length is 15 mm.

discharge starts with appearance of weakly emitting plasma region near the anode tip, indicating the end of the first stage—highly conductive region formation. On the second stage the spark channel grows in the direction of the cathode and finally shorts the discharge cell circuit. Near anode glowing appears almost 500 μs after the voltage is applied. Such a long time delay is attributed to the thermal instability development in the anode region due to intensive vibrational excitation of molecules when the solution is heated by initial conductive currents in the near anode region [1]. When the microbubbles are presented in the solution the first light emission is observed in ones that are closest to the anode, then the glowing region slips toward the cathode. In such manner the spark channel grows through the bubbles with partial discharges preceding the spark channel tip. Developed spark discharge in the solution with 3% gas volume fraction is shown in figure 2. The side microbubbles are illuminated by the spark channel.

Voltage and current waveforms are obtained for each set of experiments. The typical waveforms are shown in figures 3 and 4.

The breakdown voltage for each media is determined as the minimum applied gap voltage that leads to the short of the discharge cell circuit. The small amount of bubbles (3% gas vololume fraction) results in slightly decreased breakdown voltage (see trace 2 in figure 3), while adding of considerable amount of bubbles (10% gas vololume fraction) results in 35% increase of the breakdown voltage (see trace 3 in figure 3). The voltage just before the short circuit moment is twice as much in case of 10% gas volume fraction as compared to 3% gas volume fraction case. The arc channel with negative resistance characteristic is formed after the spark channel bridged the gap. Bright glowing of the arc channels typically lasts for about 5 ms. On the first stage when the voltage is applied and no emission is registered by the camera, initial current is quite high (about 1.5–1.8 A) due to finite electrical resistance. On the first stage the current

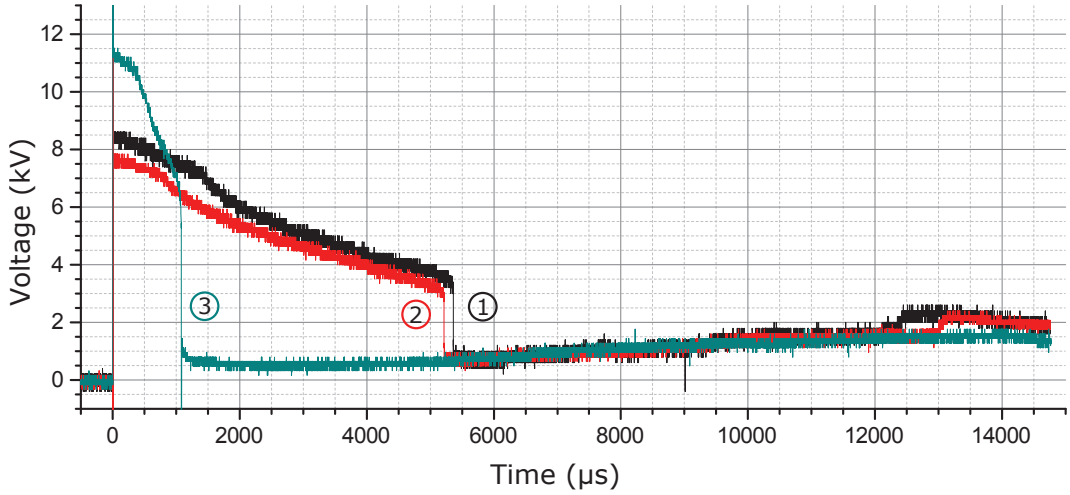

Figure 3. The gap voltage waveforms: 1—without bubbles; 2—with microbubbles at 3% gas volume fraction; 3—with microbubbles at 10% gas volume fraction.

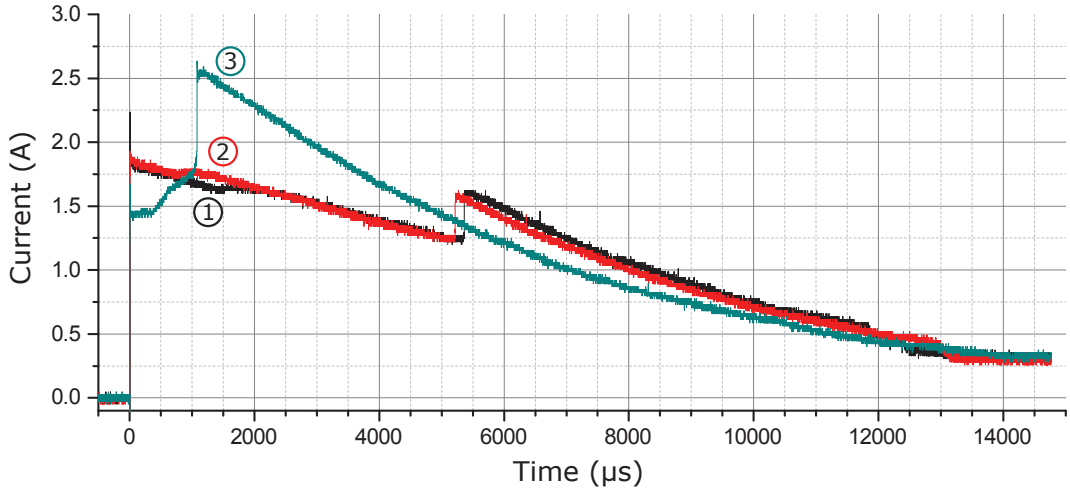

Figure 4. The gap current waveforms: 1—without bubbles; 2—with microbubbles at 3% gas volume fraction; 3—with microbubbles at 10% gas volume fraction.

dependence on voltage (see traces 1 and 2 in figure 5) departs from linearity when the certain amount of energy is deposited in the near anode region and the light emission starts from the bright anode spot. The anode spot origination is related to vertical parts of the current–voltage curves. After that point differential resistance $\mathrm{d}U/\mathrm{d}I$ of the gap becomes negative revealing the thermal instability development and ionization processes in the near anode region similar to these at electrical breakdown of wet sand [8, 9]. The thermal instability leads to current contraction at the anode side and anode spot formation. Once anode spot has formed the ionization current adds to the conductive current so the total registered current decreases by 10%. Frame-by-frame analysis at the higher frame rates (12000 fps) provides the time delay for instability development in the range from 600 μs to 1000 μs for the solution without bubbles.

On the second stage the current increases momentarily due to ionization processes in bubbles just before the thermal instability develops, then the current decreases constantly in the solution without bubbles and in case of 3% gas volume fraction of microbubbles in contrast to 10% gas

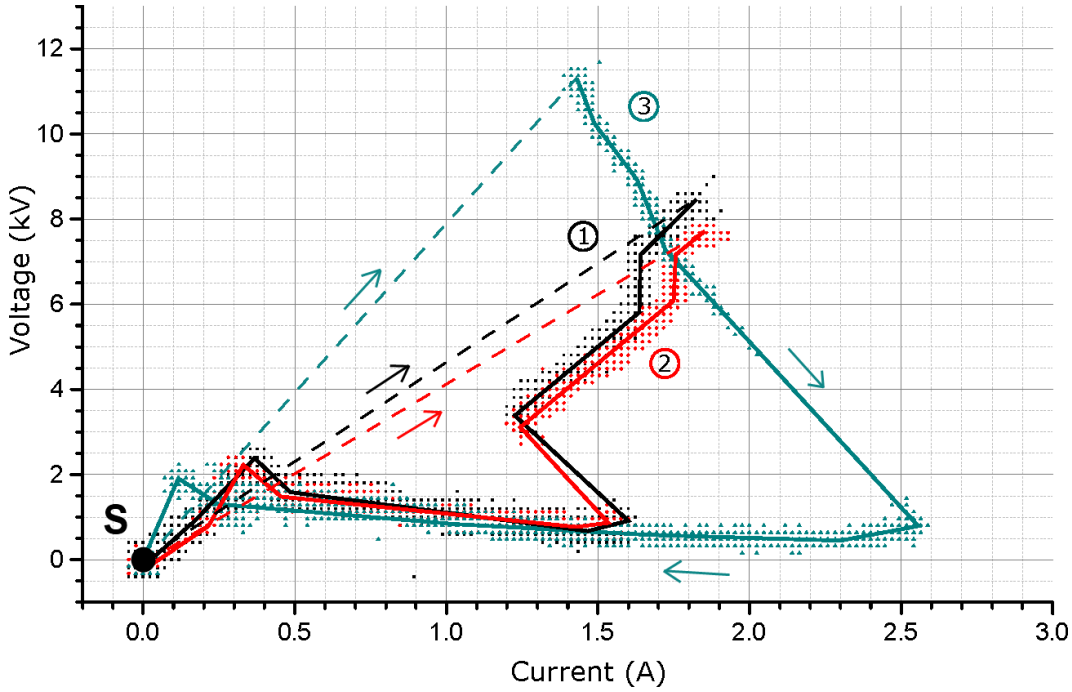

Figure 5. The current–voltage curves: 1—without bubbles; 2—with microbubbles at 3% gas volume fraction; 3—with microbubbles at 10% gas volume fraction. Dots denote measured experimental points, color-matched solid lines are the trend lines for experimental points. Initial parts of current–voltage characteristics are unresolved due to switching ringing and are shown dashed. The arrows show evolution in time. S—start point $t = 0$ s.

vololume fraction solution where the current increases up to the moment of the gap bridging by highly conductive arc channel. After the bridging the current increases stepwise by 30% and the cathode bright spot appears. The cathode spot is larger than the anode one and stays much longer—for about 12 ms. The gap resistance decreases by five and eight times in the solutions with 3% and 10% gas volume fraction of microbubbles respectively. Analysis of the full image recordings reveals hydrodynamic destruction of the arc channel in 5 and 10 ms after gap bridging in the solutions with 3% and 10% gas volume fraction of microbubbles respectively. The time delay between the moment voltage is applied and the moment spark channel bridges the gap is 1.2 ms at 10% gas vololume fraction and is considerably larger at 3% gas vololume fraction, about 5 ms. Significant initial conductivity of the isopropyl alcohol solution governs the electrical breakdown mechanism of development from a pointed anode. It's explained by the high current density on the anode tip where electric field is enhanced. The conductive current heats the liquid and its vapor up to 4000–5000 K, where thermal ionization occurs and thermal instability develops. This process could be simply observed on the current–voltage traces (figure 5) as described in [9], where the differential resistance becomes negative. The certain amount of energy should be deposed by the conductive current in the near anode region for the thermal instability to develop. Electrical field in the vicinity of the anode tip could be calculated as [10]:

$$E_a = \frac{2U}{\varepsilon r_a \ln(4L/r_a)},$$

where $\varepsilon = 80$ is the water dielectric constant, r_a is the spherical radius of the anode tip, L is the gap length. For the solution without bubbles one could take $U = 10$ kV, $r_a = 50$ μm and then obtain the electric field about 10^5 V/cm. The deposed energy density could reach

then the values about 10^5 J/cm^3 at the current density 10^4 A/cm^2 on the anode tip and time delay of instability development about 100 μs. This energy is enough to cause vaporization and heating of the media up to 5000 K. The traveling speed of the spark channel is about 4 m/s at low microbubbles density and proves the thermal mechanism of the development. Pre-ionization inside the microbubbles preceding the spark channel tip significantly increase its traveling speed, by a factor of three.

4. Conclusion

The electrical breakdown of conductive 15% solution of isopropyl alcohol by long high-voltage pulses (up to 20 kV magnitude, 5 ms FWHM, 0.8 μs rise time) has been shown to follow the thermal mechanism of development. The discharge develops from the bright anode spot on the tip. The spark channel propagation speed increases if the microbubbles are added to the solution due to pre-ionization inside the microbubbles preceding the spark channel tip.

Acknowledgments

This work was funded by the Russian Science Foundation (No. 14-50-00124).

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