Transitional regimes of pulsed electrical discharge in medium-conductivity water

V A Panov, L M Vasilyak, V Ya Pecherkin, S P Vetchinin and E E Son
Joint Institute for High Temperatures of the Russian Academy of Sciences, Izhorskaya 13 Bldg 2, Moscow 125412, Russia
E-mail: panovvladislav@gmail.com

Abstract. New regimes of pulsed electrical discharge development have been observed during experiments in water with conductivity 90 µS/cm. Two new transitional regimes between common thermal and streamer–leader discharge mechanisms were observed in the voltage range (2.8–3)U_{br}, where breakdown voltage is U_{br} = 9 kV. The first transitional regime initiates on anode as fast discharge: leader-like structure with strong self-glowing shoots into the gap by 2 mm in first 10 µs at half voltage drop and transforms then into regular thermal mechanism finishing the gap breakdown in about 1 ms. The second transitional regime initiates on anode as a thin, 0.3 mm length single streamer-like channel in first 10-µs which disappears rapidly at half voltage drop and the plasma channel develops only after long time period (about 2 ms) from cathode at the speed of 30–50 m/s.

1. Introduction
At present, much attention is paid to the investigation of breakdown mechanisms of liquids. In the absence of a unified theory, two basic approaches explaining the origin of a conducting discharge channel in a liquid are developed: direct ionization in a liquid as well as preliminary formation of regions with reduced density (vapor–gas regions) and subsequent ionization in them.

To date, there is no strict classification of the abovementioned mechanisms by their discharge channel propagation speed. The velocity of the discharge channels, the propagation of which is interpreted on the basis of direct ionization in a liquid, is very high—about 100 km/s or more [1, 2], while the primary streamers velocity can be an order of magnitude smaller than for the secondary ones. Such velocities are common, in general, under the action of pulses with a very steep front, which duration is comparable with the Maxwellian relaxation time of the accumulated volumetric charge. Under the action of more prolonged voltage pulses along with increasing conductivity of the liquid, pre-breakdown currents and phase transitions in the liquid begin to play a significant role, observed phenomena are more diverse, the propagation velocity of the channel decreases while remaining at the level of tens of km/s.

It was shown previously [3] that an increase in fluid conductivity to values about 100 µS/cm leads to a sharp transition from the fast streamer–leader breakdown with the speed of several km/s to the slow thermal discharge with average speed of 10 m/s [4] at the overvoltage U/U_{br} of more than 3, where U_{br} is breakdown voltage and U is applied voltage.
Figure 1. Experimental setup scheme: 1—high voltage pulse generator HVG; 2—5.5 kΩ ballast resistance $R_b$; 3—voltage divider; 4—passive voltage probe Tektronix P6015A; 5—discharge cell; 6—2 Ω current shunt $R_{sh}$; 7—digital delay and pulse generator Berkeley Nucleonics Corp Model 575; 8—oscilloscope LeCroy HDO4054; 9—high-speed complementary metal–oxide–semiconductor camera Phantom v2012.

The present work is devoted to the transitional regimes of the pulsed electric discharge development in water with conductivity of 90 $\mu$S/cm, combining the elements of both thermal and streamer–leader mechanisms of the discharge development.

2. Experimental setup
The experimental setup scheme is shown in figure 1.

The discharge cell and the pin-to-rod electrode system are the same as in our previous work [4]. The interelectrode distance is 10 mm. In the experiments, shadow images of the discharge gap, recorded by a high-speed camera Phantom v2012, synchronized with oscillograms of current and voltage, recorded by the oscilloscope LeCroy HDO4054, were registered. The current in the discharge circuit is limited by the ballast resistance to a value of not more than 6 A. Water conductivity was measured by a conductivity meter WTW Vario Cond. Polarity of the incident pulse is positive, the pulse full width at half magnitude is 3 ms, pulse amplitude is up to 35 kV, rise rate is 40 kV/$\mu$s.

3. Results and discussion
The voltage range $(1–3)U_{br}$, where the breakdown voltage is $U_{br} = 9$ kV [3], is investigated. Up to $2.8U_{br}$, the discharge develops according to the thermal mechanism described in [4] for water with conductivity of 330 $\mu$S/cm. Reduced value of the conductivity leads to an increase in average velocity of the discharge channel propagation from the anode to the cathode, about 20 m/s, as well as to an increase in the ignition delay of the discharge during the thermal
Figure 2. Shadow images for three different mechanisms of pulsed discharge development in water with conductivity of 90 \( \mu \)S/cm. Anode conic tip is at the top, cathode tip is at the very bottom of the images (shown partially in (a) and (b) and is right below the bottom edge of the (c) images). (a) Discharge channel right before the short-circuiting by the thermal mechanism, \( t = 3.95 \) ms, \( t_{\exp} = 8.4 \) \( \mu \)s. (b) First type transitional regime, streamer–leader initiation at the anode tip (\( b_1, t = 5.4 \) \( \mu \)s), transforming into thermal mechanism (\( b_2, t = 1.1 \) \( \mu \)s) accompanied by onset of the counter-moving channel from the cathode, \( t_{\exp} = 350 \) ns. (c) Second type transitional regime, disappearing short initiation at the anode (\( c_1, t = 11.6 \) \( \mu \)s), onset of cathode channel after 1.5 ms delay (\( c_2, t = 2.1 \) ms), \( t_{\exp} = 350 \) ns, \( t \) is time after voltage onset, \( t_{\exp} \) is time of image exposure.

phase of the first 0.5–2 ms, and finally the same values of the total breakdown time of 2–4 ms, as at conductivity of 330 \( \mu \)S/cm. The channel structure, common for thermal breakdown, is generally preserved [figure 2(a)], both components are seen: quasispherical part near the anode and channel part at the front.

At voltages higher than 3\( U_{br} \), a transition to the streamer–leader mechanism of the discharge development from the anode was observed [3]. The total breakdown time is about 40 \( \mu \)s.

In the voltage range (2.8–3)\( U_{br} \), two transitional regimes of the discharge development are observed, combining elements of both thermal [4] and streamer–leader [3, 5] mechanisms of the discharge development.

Following the transition mechanism of the first type, the discharge initiates at the anode tip by the fourth microsecond after the voltage is applied. In submicrosecond time a tree-like plasma channel with consistent self-glowing penetrates into the gap by 2.5 mm [figure 2(b1)]. Appearance of the plasma channel is common to breakdown of dielectric liquids [5]. Onset of the channel is accompanied by a sharp drop in the impedance of the discharge gap. The current thus increases sharply, and the voltage drops along with the strength of electric field in the channel, which is now insufficient for intensive ionization at the channel tip. After that, the channel propagation velocity drops to values of about 10–20 m/s, and the channel itself expands radially [figure 2(b2)], as occurs under the thermal mechanism. Expansion by this mechanism eventually leads to a gap closure by 1 ms. Shortly before the gap closure a counter-channel starts from the cathode, but its length does not exceed 1–1.5 mm [figure 2(b2), at the bottom]. Comparing it to the anode channel, one can assume its lower conductivity, since its appearance
Figure 3. Voltage (1) and current (2) waves of the discharge following transitional mechanism of the first type. Horizontal axis has a log-scale to the base 10 on a segment [0.001, 0.01] and a linear scale on a segment [0.01, 1.5].

results in a less significant increase in current [figure 3, additional small current rise on the time period from 1.04 to 1.07 ms, just before the complete breakdown at 1.07 ms], together with a lower intensity of its own glowing [see bright anode channel on the figure 2(b1) and dark cathode channels at the bottom of the figure 2(b2)].

The transitional mechanism of the second type is more complex. The discharge is initiated at the anode by the tenth microsecond. In submicrosecond time, a short thin dark channel penetrates into the bulk liquid in a direction perpendicular to the surface of the anode, and then decays and disappears within the next several tens of microseconds [figure 2(c1)]. After this, the vapor–gas region begins to grow near the cathode, from which a discharge channel starts after 2 ms, which structure is close to the bushy one [figure 2(c2)]. The propagation speed of the cathode channel is a little higher than the speed of the thermal channel: 30–50 m/s versus 10–20 m/s. Initiation of the cathode channel is most likely due to the emission of electrons from the cathode into existing vapor–gas bubbles on the cathode surface.

4. Conclusion

The transitional mechanisms comprising elements of both thermal and streamer–leader breakdown mechanisms at constant electrical conductivity all other conditions being equal are revealed in the narrow overvoltage range of 2.8–3.

Transitional mechanism of the first type is characterized by developed fast streamer–leader initiation with channel speed up to several km/s followed by thermal stage with channel speed about 10–20 m/s.

The second type mechanism is characterized by weak streamer–leader initiation followed by long time lag and onset of anode-directed channel with the speed about 50 m/s.
Acknowledgments
The work is supported by the Russian Science Foundation (grant No. 14-50-00124).

References
[1] An W, Baumung K and Bluhm H 2007 J. Appl. Phys. 101 053302
[2] Starikovskiy A, Yang Y, Cho Y I and Fridman A 2011 Plasma Sources Sci. Technol. 20 024003
[3] Panov V A, Vasilyak L M, Pecherkin V Ya, Vetchinin S P and Son E E 2018 J. Phys.: Conf. Ser. 946 012160
[4] Panov V A, Vasilyak L M, Vetchinin S P, Pecherkin V Ya and Son E E 2016 J. Phys. D: Appl. Phys. 49 385202
[5] Ushakov V Ya, Klimkin V F and Korobeinikov S M 2007 Impulse Breakdown of Liquids (Berlin: Springer)