Overvoltage effect on electrical discharge type in medium-conductivity water in inhomogeneous pulsed electric field

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Abstract. The transition between thermal and streamer discharges has been observed experimentally in water solution with conductivity 100 $\mu$S/cm applying positive voltage pulses to pin-to-rod electrodes. The transition happens at five-fold pulse amplitude. Considering streamer propagation as an ionization wave helped to establish relation between the parameters governing transition from one to another discharge mechanism.

1. Introduction
Great attention has been paid to a problem of electrical discharge development in liquids for the last decade. First stated as an engineering problem, electrical discharge development in liquids has turned into a self-sustained field of research for the last decade with the purpose of discharge physics elaboration.

Significant low-voltage liquid conductivity, Joule heating, phase change, and bubbles formation on electrodes surface and in bulk liquid affecting electric field distribution result in much more complicated and diverse discharge processes compared to gas discharge. Hydrodynamic flows in liquid and gas-vapor regions influence a discharge channel velocity. Therefore the initial pre-breakdown behavior is determined generally by liquid low-voltage conductivity.

In high-conductivity liquids the discharge development strongly depends on the rate of energy deposition by conductive currents and formation of a gas-vapor volume near the pin-electrode. Its further ionization leads to temperature rise in the electrode vicinity, subsequent overheating instability development followed by plasma formation near the electrode and slow plasma channel propagation towards the second electrode [1]. All these processes including plasma channel propagation are quite slow while being strongly dependent on energy deposition rate and formation of gas-vapor volume.

Streamer being the other variation of discharge scenario is common for low-conductivity liquids. Streamer theory was developed first for gases. The main idea is field enhancement at a streamer tip which is possible in case of high-conductivity plasma channel behind a streamer tip and low-conductivity area in front of the tip at the same time. In case of growing initial liquid conductivity electric field diffusion and current spreading at the streamer tip result in
broadening streamer front, lowering electric field, and sharply decaying of ionization frequency. Main streamer propagation condition, described above, is natural for gases but is hardly met for non-dielectric liquids with finite conductivity. Low initial liquid conductivity and high amplitude of a voltage pulse are required to keep streamer velocity above the diffusion rate of the potential wave.

The class of fast streamer-like discharges in liquids exhibits large variety of different plasma channel types and its conditions [2–5]. Study of interphase boundary formation under pulsed voltage is very challenging experimental [6] and theoretical [7–9] task, as well as behavior of pre-existing interphase boundary and its effect on field distribution [10–16]. Many recent papers on mathematical simulation address the issues of streamer propagation by direct liquid ionization [17, 18], conditions of streamers formation inside pre-existing bubbles immersed in liquid [19], an influence of neighbor bubbles on each other and their breakdown conditions [20] as well as effect of solid particles clusters inside bubbles on streamer branching [21]. Special attention has been paid to hydrodynamic flows in liquid under pulsed voltage [8], cavity formation and its further evolution in the presence of electric field [8].

Fully-developed hydrodynamics along with plasma formation make a problem of discharge initiation and development in highly conductive liquids with significant initial conductivity quite sophisticated for mathematical simulation. The trick is both type of discharge could develop at such conditions. Previously we have studied slow thermal discharge in high-conductivity water solution [22] and effect of additional microbubbles on discharge development [23, 24].

Physics of streamer-to-thermal discharge transition is not well studied yet and both types were not previously observed together at the same initial liquid conductivity.

In presented paper we show that both fast (streamer or leader) and slow (thermal) types of discharge can take place in water solution at 100 µS/cm conductivity.

2. Experimental setup
The experimental setup was identical to that in [1], but the photo camera was replaced by Photron SA-Z to gain better time resolution. Positive polarity voltage pulse with 0.4 µs rise time and 5 ms of FWHM was used in all experiments. High-speed imaging with constant back illumination was synchronized to current and voltage traces recording to make pre-breakdown processes visible and distinguishable. The experiments were carried out in a mixture of tap and distilled water with total conductivity 100 µS/cm. Shape and relative position of the electrodes are shown in figure 1. Inter-electrode gap distance \( d_g \) was fixed to 10 mm. Curvature radius \( r_t \) of the anode tip was about 100 µm.

3. Results and discussion
Pulse amplitude was varied in a range 5–30 kV during the experiments. At lower voltage the discharge follows thermal mechanism, as shown in figure 2(a, b). Low growth rate of initial gas-vapor volume and following plasma channel, large time lag before first plasma appearance are common for this discharge type. Initial gas-vapor volume reaches its critical size (~ 1 mm) in about 1–1.5 ms after voltage pulse rise, then ionization occurs and further plasma channel grows with the rate up to 20 m/s in the voltage range studied. At this stage most of the light is emitted from the anode region most likely by anode spot [1]. Shape of the plasma volume is close to spherical and disturbed with Rayleigh–Taylor instability-like structures, see figure 2(b), which can develop at interphase boundary during boiling [25]. Final gap bridging passes through plasma channel developed in one of these disturbed structures with presumably the highest electric field.

The discharge parameters change drastically at higher voltage, as shown in figure 2(c, d). Time to breakdown becomes two orders less than for thermal type. Formation of bright (yet unbridged) tree-like discharge channel is preceded by short formation stage of small optical
inhomogeneity at the anode tip where initial streamers propagate. Its critical size is one order less than for large initial opaque volume preceding thermal discharge. Streamers observed in small high electric field region unable to propagate further at average field of 30 kV/cm. Similar small bush-like streamers have been observed previously in distilled water [26] and studied quite well. Size of initial bush-like streamers volume reaches 500 µm, further propagation speed
reaches several km/s. In our case the top average speed was below 7.5 km/s. Then streamers rapidly transform into leader channel. It has up to five main branches at the tip (on captured images among all experiments), which possess their own side branches. Final breakdown passes through one of these main branches and transits into arc discharge. The other branches shrink and finally break up in a number of small bubbles.

Streamer in dielectric liquids like in dense gases propagates as a result of strong field enhancement in its head by its own space charge. The maximum field $E_m$ is gained just at the head front with radius $r_s$. Initial radius of the remaining channel part behind the head is roughly equal to $r_s$.

The problem of streamer propagation is quite complex, especially for liquids where reasonable coincidence with experimental results can be achieved almost only by mathematical simulations [17, 18]. Nevertheless, simplified analytic approach adopted from dense gas theory [27] can give some basic relations between discharge parameters and underlying physics. Considering streamer as an ionization wave its velocity could be evaluated from ionization kinetic at the streamer head as

$$v_s = \gamma_i(E_m)r_s\left[\ln\left(\frac{n_s}{n_0}\right)\right]^{-1},$$  

If $v_s$ is way higher than electron drift velocity: $\gamma_i(E_m)$ to be frequency of molecular ionization by electron impact, $n_0$ to be initial electron density in the medium, $n_s$ to be electron density in the streamer channel behind the head.

Usually $n_0 \sim 10^4$–$10^5$ cm$^{-3}$ and $\ln(n_s/n_0) \sim 10$ is enough for streamer development. Therefore, actual streamer velocity is governed by electric field at the head front through the strong dependence of $\gamma_i$ on $E_m$. In turn, electric field at leading streamer front reaches specific $E_m$ determined by quasi-stepwise dependence $\gamma_i(E)$ [27]. Ionization frequency, small at first, increases dramatically with $E$ and attain the saturation at a very high level. Then the head radius self-adjusts to settled electric field $E_m$.

Capability of streamer propagation in conductive liquid is limited. Streamer development through impact ionization in strong electric field is feasible only if liquid conductivity is lower than some specific value. At higher conductivity diffusion of potential and current from the streamer head supersedes ionization wave. As electric field inside diffusion wave is insufficient for ionization increasing initial conductivity results in smaller and diffused electric field in front of streamer head and lower ionization wave velocity. In this case the problem of streamer propagation is equivalent to ionization wave propagation in conductive medium if streamer and its conductive channel are treated as a part of long-distance transmission line [27, 28].

Diffusion rate of potential $U = 2r_sE$ at the streamer head can be expressed as $\chi/r_s$, where $\chi = 1/(RC)$ to be potential diffusion coefficient, $1/R = \pi r_s^2 \sigma$, $C = 2\pi \varepsilon \varepsilon_0 \ln(L/r_s)$ to be resistance and capacitance per unit length of streamer channel, $\sigma$ to be conductivity, $\varepsilon$ to be medium permittivity, $L$ to be streamer length. Streamer with high electric field at the head is capable of propagating in conductive liquid if its velocity exceeds rate of potential diffusion:

$$\frac{\sigma}{\varepsilon \varepsilon_0} \ln\left(\frac{L}{r_s}\right) < \frac{v_s}{r_s}. $$  

Expression becomes clearer noting that space charge of streamer head inducing high electric field for ionization accumulates in a time $r_s/v_s$ and relaxes during Maxwellian time $\tau = \varepsilon \varepsilon_0 / \sigma_0$.

Since $\gamma_i(E)$ acts like stepwise function in the field range typical for streamers the transition from thermal to streamer discharge in inhomogeneous electric field should be stepwise as well while increasing gap voltage in conductive liquid. Ionization mechanism of streamers propagation in water can take place at average electric field in the gap greater than 100 kV/cm. Streamer velocity and its channel radius were evaluated experimentally using pulse laser back illumination [29]. In this case considering equation (2) at $v_s \sim 10$–$100$ km/s, $r_s \sim 10$–$20$ µm and
ln(L/r_s) ~ 10, we obtain conductivity range \( \sigma \sim 10^{-4} \text{–} 10^{-3} \text{ S/cm}. \) Tap water also falls in this range. There is a lack of experimental results on streamers propagation in conductive liquids due to fast streamer-to-leader transition \([30, 31]\). In our experiment we have observed both thermal discharge from anode at lower voltage (5–15 kV) and streamer initiation with further streamer-to-leader transition at higher voltage (25–30 kV) in water solution with conductivity 100 \( \mu \text{S/cm} \) at all other conditions being equal. Streamers start from the anode tip at electric field \( E \approx 500 \text{ kV/cm} \) then rapidly transit into leader channel bridging the gap.

4. Conclusion

The transition between thermal and streamer discharges has been observed experimentally in water solution with conductivity 100 \( \mu \text{S/cm} \) applying positive voltage pulses to pin-to-rod electrodes. The transition happens at five-fold pulse amplitude. Considering streamer propagation as an ionization wave helped one to establish relation between the parameters governing transition from one to another discharge mechanism.

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