Propagation of a negative streamer over a bubble floating on a water surface

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Abstract. The main goal of this work is to clarify in detail the interaction of negative corona and negative streamers with a bubble floating on a water surface. The corona and streamers were initiated with the metallic pin stressed by a step-wise high voltage of a negative polarity. It was shown that at low applied voltage and short distance between pin and bubble a negative corona foregoes an appearance of the streamers. This corona produces the ionic wind which directed towards the top of a bubble and influences both the geometry of a bubble and its lifetime. In the case of high amplitude of the applied voltage and long distance between tip and bubble the negative streamer sliding on the bubble surface happens. A difference in the interaction of positive and negative streamers with a water bubble is discussed.

1. Introduction
The non-thermal plasma (NTP) at atmospheric pressure generates plentifully various reactive plasma species like atoms, radicals, excited atoms and molecules, ions, etc [1,2]. This is a reason why NTP has been widely used for initiation or acceleration of the needed bio-chemical processes in a liquid. At present different plasma-liquid systems are developed for activation of many types of liquids including the waste or tap water. Some approaches are based on the use of streamer discharges in ambient air which generate the streamers (thin current filaments) propagating above/over a liquid. Exactly the streamers are enriched with the reactive species. In this case, one may point two key parameters determining the efficiency of plasma activation. One of them is the rate of transfer of reactive species from streamers into the liquid (the higher this rate, the higher efficiency). Another one is the size of a liquid area which tightly contacts with streamers (the larger size of contacting area, the higher efficiency of plasma activation). The best way to satisfy these requirements simultaneously is to form many bubbles (foam) on a water surface and to generate the streamers sliding over the bubble surface. The efficiency of such approach has been demonstrated in paper [3] by the example of positive streamers generated by the pin electrode located above the bubbles. Besides the higher activation efficiency, such approach has an essential advantage from the electrical engineering point of view - because the bubble wall is extremely thin, the formation of streamers on a bubble surface does not require high-voltage pulses with very short (of ns range) rise-time that is necessary in the case of formation of long streamers sliding on a flat surface of a deep water.

In this work, the interaction of negative streamers with a bubble floating on a water surface is studied. The streamers were initiated by the metallic pin stressed by a step-wise high voltage of a negative polarity. There is a fundamental difference in behavior of a discharge in the case of a positive and negative polarity of the pin. In the latter case, a negative corona foregoes an appearance of streamers. This corona exhibits the current pulses (Trichel pulses) and the ionic wind which both
influence the self-consisted behavior of the discharge-bubble system. The main goal of this work is to clarify in detail the mentioned above features of the interaction between negative streamers and the bubbles floating on a water.

2. Experimental setup
The scheme of the setup used in our experiments is shown in figure 1. The sharpened metallic pin of a stainless steel wire of 1 mm in diameter served as a high-voltage electrode initiating the discharge on the floating bubble artificially formed on the liquid surface. The applied voltage amplitude was varied up to -15 kV. The grounded aluminum electrode was covered with a thin layer (about 2–3 mm) of a tap water with the electrical conductivity of $7.5 \times 10^{-4}$ S/cm. Plasma forming gas was ambient air at atmospheric pressure. An isolated bubble floating on flat water was formed by a slow injection of a small amount of air through a narrow nozzle in the center of the aluminum plate. To do that a syringe was used. The diameter of a bubble basis ranged from 10 to 17 mm. A distance between the point electrode and the top of a bubble was varied in the range of 2–10 mm.

3. Experimental results and discussion
At small distance $h$ between the tip of HV electrode and bubble surface ($h = 1$ mm) and under low applied voltage $U$ that is not enough to initiate a negative corona ($U = -2$ kV), we observed the attraction of the top of a bubble to the high-voltage electrode (see figure 2a and 2b). The rising of the bubble top on 0.23 mm in height happens slowly - approximately in 0.5 s. This effect is attributed with a positive charge on the top of a bubble induced by a negative potential on the high-voltage needle. Note that after a while, the attraction of water leads to accumulation of the water droplet on the HV electrode (see figure 2c).

If increase the distance $h$ up to 2.3 mm and applied voltage $U$ up to or above of -4 kV, several new things happen. First, attraction of the bubble to the HV needle is practically absent, possibly due to diminishing the induced charge on the bubble surface. Second, a negative corona appears which exhibits pulsing regime (Trichel pulses). Typical example of the current waveform for Trichel pulses is presented in figure 3. In contrast to normal pin-to-plane corona with a metallic flat electrode, the amplitude of Trichel pulses in corona between the pin and a bubble is strongly irregular. We attribute
this feature of Trichel pulses to non-stationary and inhomogeneous deformation of the bubble surface by the ionic wind generated by negative corona. The jet of ionic wind is directed from the needle towards the top of a bubble, crumples the bubble wall and makes a relatively deep dint.

Figure 3. The fragment of the current waveform showing the behavior of Trichel pulses in the negative corona between HV needle and a bubble.

Third, after a while (approximately in 15 ± 1ms) the negative corona is succeeded by the plasma regime when many low-current streamers shunt the gap between HV needle and bubble. This regime eliminates the ionic wind and the bubble restores its initial shape. Plasma regime is unstable and quickly disappears. After that (approximately in 0.4 ± 0.2 s) the negative corona appears again and the ionic wind afresh crumples the bubble wall and makes relatively deep dint. Such alternating can happen several times. However, every time the jet of ionic wind drives water from the bubble top down to his basis, thins the bubble wall at this place and eventually breaks the bubble. The sequence of events described above is presented in figure 4.

Figure 4. Set of the succeeded images showing the alternating of corona and streamer regimes. The exposure time of each shot is 16.7ms; the applied voltage amplitude is -4kV; the diameter of a bubble basis is 12 mm. Image #9 corresponds to the broken bubble.

As a rule, at the applied voltage lower than 10 kV the negative streamers cover the only small area around the top of the bubble and do not reach its base. However, at higher voltage, the streamers are
able to reach the base (see figures 5a and 5b). There is a difference in the spatial structure of the positive and negative streamers propagating from the needle to the bubble. The positive needle induces a single streamer which does not branch and slides on the bubble in a form of alone current filament and reaches the bubble base (see figure 5c). The negative needle induces also a single streamer but this streamer splits itself into several secondary streamers at some distance in front of the bubble. Note the space between primary and secondary streamers and bubble is filled with glow discharge (see figures 5a and 5b). One may conclude therefore that negative polarity of the needle provides the larger area activated by non-thermal plasma at the same operating conditions. The impossibility of a negative streamer to strike perpendicularly to the bubble surface can be explained by the mechanism of his propagation. This mechanism assumes that electrons quickly drifting from the streamer head provide the ionization in front of the head and promote the forward movement of the streamer. It means that in the case of close approach of a streamer to a bubble some amount of electrons can be quickly accumulated on the bubble surface and negatively charge it. Due to that, the streamer will be repelled from the surface and deviate his trajectory from the normal direction.

A probability for the streamer to form the splitting at the turning point depends on the time spent at this point. Because the time diminishes with the applied voltage amplitude (the higher amplitude, the shorter the time), the probability of the splitting strongly diminishes as well (see figures 5a and 5b). Note the breaking of a bubble at low applied voltage happens after several strikes of low-current streamers but high-current streamer breaks the bubble by a single strike. A reason is that the high-current streamer releases higher energy on the bubble, the amount of which is enough to evaporate locally the bubble wall.

![Figure 5](image)

**Figure 5.** The images of negative (a, b) and positive (c) streamers interacting with a bubble at higher applied voltage. a) $U = -14$ kV; b) $U = -17$ kV; U = +14 kV. The diameter of a bubble basis is 13 mm.

4. Conclusion

It was shown that at low applied voltage and short distance between HV needle and bubble, a negative corona foregoes an appearance of the streamers. This corona produces the ionic wind which directed towards the top of a bubble and influences both the geometry of a bubble and its life-time. In the case of high amplitude of the applied voltage and long distance between tip and bubble the negative streamer sliding on the bubble surface happens. A difference in the interaction of positive and negative streamers with a water bubble is shown and discussed.

5. References

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