Generation of pin-hole discharges in liquids

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Electrical discharges in liquids can be generated in several electrode configurations; one of them is called as pin-hole. The discharge is created inside a small orifice connecting two chambers filled by any conductive solution. Each chamber contains one of the electrodes. Based on the orifice length/diameter ratio, the discharge is called as capillary or diaphragm. The presented contribution gives the preliminary detailed observation of the discharge creation in the dependence on the orifice shape for selected solution conductivities. The non-pulsing DC high voltage was used for the presented study. The bubble theory of the discharge generation was confirmed at the set conditions. However, the streamer like character was ocassionally observed after plasma ignition, too.

Introduction

Electrical discharges in liquids are still a big challenge to investigate compared to discharges in gases. Especially, the problem of underwater discharges has been in an intensive focus of researches for the approximately last three decades, only. Although several applications such as water [1-3] and surface treatment [4, 5] or plasma sterilization [6] have been developed during the underwater research, exact mechanisms of the discharge creation and related processes still desire a detail study and description.

Non-thermal plasma of underwater discharges can be generally generated by various electrode configurations and voltage regimes. The most studied configuration is a point-to-plate electrode geometry [7-9] where DC pulsed high voltage up to tens of kV is applied. The coaxial [10] configuration is a modification of the previous one, and it is more suitable for water treatment applications in a flowing regime. The pin-hole systems where the discharge is created inside a small orifice connecting two chambers filled by any conductive solution (each chamber contains one of the electrodes) were intensively studied, too [11-13]. Besides the DC pulsed high voltage, also AC, high frequency, microwave or DC non-pulsed voltage regimes can be used for the generation of this kind of the under liquid discharge.

Generally, there are two groups of theories describing the discharge ignition in liquids, electron and thermal (also called as bubble) theory [14]. The electron theory is based on the fact that water molecules are ionized and dissociated by the applied very high electric field, and plasma creation is more or less analogical to the Townsend’s theory of electron avalanches in gases. According to the thermal theory, liquid is heated by passing current which leads to its evaporation and bubble (or more exactly micro bubble) formation. Subsequently, the discharge is ignited in the vapour phase due to the potential gradient over the bubble size.

Experimental set up

A specially constructed batch discharge reactor (total volume of 250 ml) was used in the study of the pin-hole discharge formation (Fig. 1). The main polycarbonate chamber was divided by a polyacetal (POM) changeable insulating wall with a ceramic diaphragm into two spaces with one stainless steel electrode in each part. A Shapal ceramic discs of 0.3–1.5 mm thickness were mounted in the centre of the insulating wall. The pin-hole (diameter of 0.3 mm) was drilled in the disc center. Thus, the length/diameter ratio was in a wide range from 1 to 5 which allowed studies of the breakdown either in the diaphragm (l/d=1) or capillary (l/d=5) configuration. A DC high voltage source providing constant power supply up to 500 W was used. Water solution containing NaCl as a supported electrolyte was applied with the initial conductivity of 570 $\mu S \cdot cm^{-1}$.

Breakdown moment of the pin-hole discharge as well as its further behaviour was studied from time resolved electrical characteristics recorded by a four channel digital oscilloscope Tektronix TDS 2024B.

Besides voltage applied between electrodes (measured by a HV probe Tektronix P6015A) and current (measured at balast resistor of 5 Ω), sound (detected by a piezzo microphone mounted under the reactor) and light emitted by the discharge (determined by PMT connected by optical fiber to the vicinity of the orifice) were recorded, too.

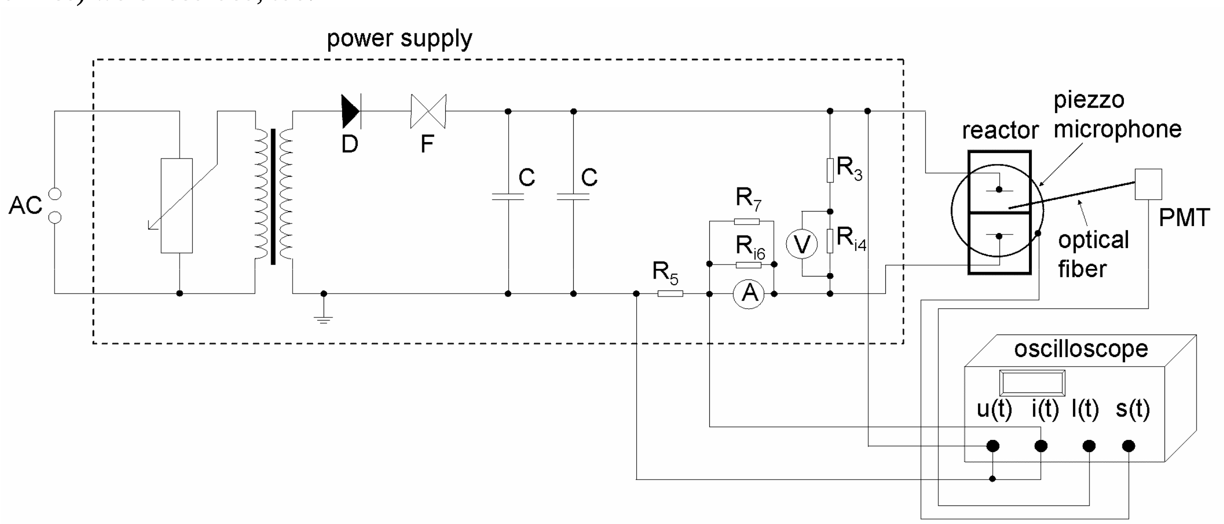

Fig. 1: Full scheme of the experimental setup used for the presented observations; D – HVR-1x7 SB 3714, F – safety-fuse 0.5 A, C – 0.85 µF microwave capacitor 25M854S095T, 2500 VA, R3 – 100 MΩ, R_{i4} – 3.114 kΩ, R_5 – 5.13 Ω, R_{i6} – 105.5 Ω, R_7 – 0.13 Ω.

Results

In order to estimate the exact discharge breakdown, current-voltage characteristics based on the mean values were employed. The obtained data (see Fig. 2) reveal not only the breakdown moment, but the current-voltage curve can be divided into four parts representing partial processes related to the discharge ignition. If low voltage is applied, current only slightly increases with the voltage enhancement. The time resolved current records show smooth curves. This evaluation indicates that only electrolysis takes place in the reactor. At higher voltage (in Fig. 2, over 300 V), the first breakpoint on the curve is observable. Based on the simultaneous time resolved characteristics [15] as well as ICCD images (see below), we have assumed that this part of the curve corresponds to the bubble formation. Bubbles of evaporated liquid appear in the pin-hole vicinity due to the strong Joule heating caused by high local current density. At these conditions, some noise records are also recognized irregularly (see Fig. 3). However, significant current oscillations are well visible. There is still no evidence of the light emission.

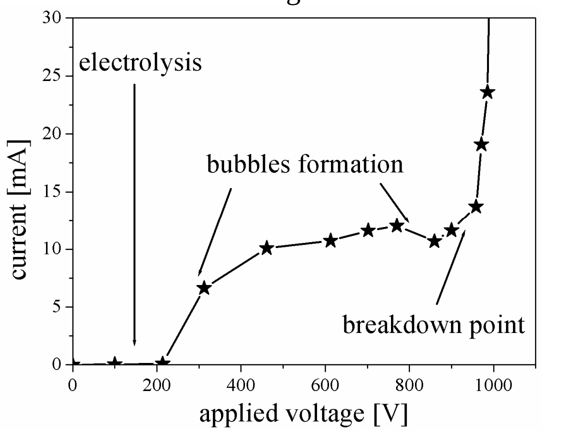

Fig. 2. Current-voltage characteristics of the pin-hole discharge with 0.4 mm barrier thickness.

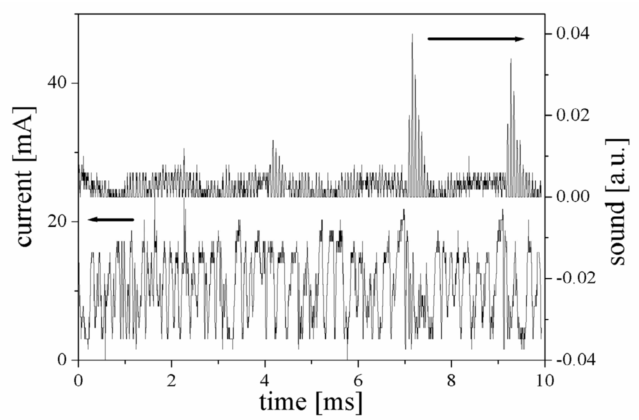

Fig. 3. Current and sound records during the bubbles formation (barrier thickness of 0.4 mm, applied voltage of 620 V).

The second breakpoint on the curve appears around 860 V. This moment represents the ocassional discharge breakdown in the pin-hole which has been confirmed both by time resolved current-voltage characteristics and light emission records [15, 16]. The noise generation starts to be more intense at this point, too. Exceeding the voltage over 950 V, the stable discharge operation is observed together with the rapid current increase. Emitted light starts to be much more intensive and noise is nearly uninterrupted. Even shock waves can be observed. The detailed description including the voltage, current, noise, and light time resolved records will be given in the full text.

Obtained current-voltage characteristics are dependent on the solution conductivity as well as on the pin-hole parameters. Figs. 4 and 5 show two selected dependences.

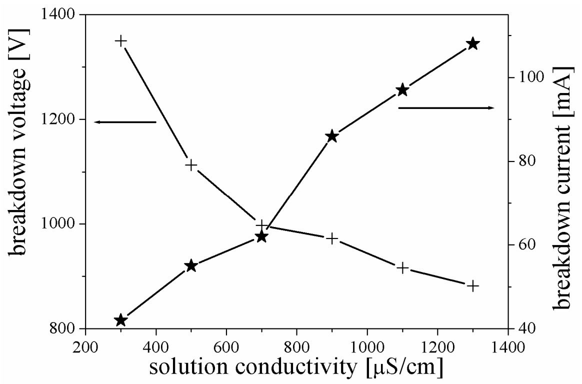

Fig. 4. Breakdown voltage and breakdown current as a function of the solution conductivity (pin-hole with diameter of 0.2 mm and thickness of 0.25 mm) [17].

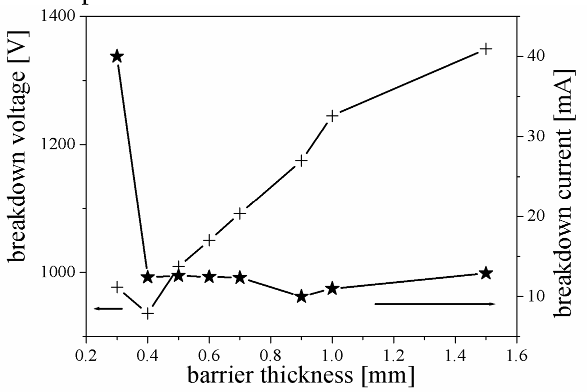

Fig. 5. Breakdown voltage and breakdown current as a function of the barrier thickness (solution conductivity of 460 μS/cm).

Fig. 4 (reproduced form [17]) clearly shows that the breakdown voltage decreases nearly linearly with the increase of the solution conductivity. On the other hand, the breadown current linearly increases. This effect was related to lower resistance of liquid in the case of higher conductive medium and vice versa. The breakdown voltage increases linearly with the barrier thickness while the breakdown current is independent on this parameter as it is demonstrated by Fig. 5. The value obtained for the thinnest barrier seems to be erroneous, but it is fully reproducable, and the same effect is observed for all conductivities. We suppose that this effect is caused by a fast destruction of the bubbles in the pin-hole because current is also much higher during the part of bubbles formation than in the other cases [18]. Detailed description of both problems will be given in the full text, too.

The last interesting effect is observed during the regular discharge operation. Although the discharge is located inside the bubbles and it is operating in the glow mode, the streamer like structures propagating from the bubble into the surrounding liquid are ocasionally observed. An example of the streamers evidence is given by Fig. 6. Another independent experiments given in bubbles of exact volume placed at HV tip were carried out in water solutions of low conductivity. The pulsed voltage was applied and the iCCD camera was used for the discharge observations. The reach streamer like structures can be seen in this case at it is shown in Fig. 7. Exact conditions required for the streamers evidence are unknown up to now.

Fig 6. Photo of the discharge forming streamer like structures propagating outside the bubble (barrier thickness of 1.5 mm, applied voltage 1.6 kV, discharge current 300 mA, exposure time of 1 ms). Capillary is marked by white lines.

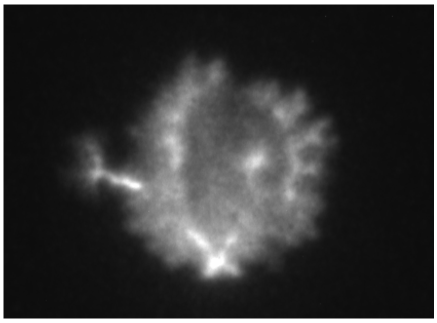

Fig. 7. Photo of the discharge forming streamer like structures propagating outside the bubble (nitrogen bubble volume 12 μl, solution conductivity of 12.2 μS/cm, applied voltage of 28 kV, recorded 60 μs after HV application by exposure time of 5 μs). HV tip is at the bottom. Plasma volume is about 10x bigger with respect to Fig. 6.

Conclusion

The presented contribution gives the preliminary detailed observation of the pin-hole under liquid discharge creation in the dependence on the orifice shape for the selected solution conductivities. The experimental results demonstrated that the micro bubbles were generated initially if the DC non-pulsing voltage was applied. Their formation was also associated with the generation of noise due to the bubble cavitation. The real breakdown voltage confirmed by the light emission was decreasing with the increase of the solution conductivity. The strong sound generation (shock waves) was observed during the stable discharge operation. The length/diameter ratio dependence shows the increase of the breakdown applied voltage with the increase of the barriere length but the breakdown current is more or less independent on the pin-hole length except very thin barriers. These results confirmed validity of the bubble theory of the pin-hole discharge creation. However, the high speed camera images showed the streamers propagation outside the bubble, too.

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