Experimental analysis of a pin-to-pin electrical discharge in water: Influence of solution conductivity and applied voltage

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Abstract: A pin-to-pin electrical discharge in water has been investigated using two complementary time-resolved diagnostics: electrical measurements and schlieren fast imaging. Two major parameters of the experimental set-up, the water conductivity and the applied voltage, have been varied in order to highlight main characteristics of the discharge.

Keywords: Plasma-liquid, Time resolved diagnostics, Electrical measurement, Schlieren fast imaging, Parametric study

1. Introduction

Plasma-liquid is a very attractive topic since many promising applications have been considered recently [1]. The potential of plasma-liquid system appears as important as their complexity. In particular, two schools of thought have emerged in order to explain the initiation of discharges in liquid: either the low density region theory or the direct impact ionization model in the liquid state [2]. While several experimental studies have been reported in the literature, physical issues related to discharges in liquid have not been overcome.

This work aims to provide new insights into plasma-liquid physics. The parametric study of the experimental conditions is a first approach to obtain a better understanding of the discharge mechanisms in water. The authors report synchronized measurements on a single discharge using both time-resolved Schlieren optical techniques and electrical measurements. The effect of the conductivity and the applied voltage on the discharge initiation and propagation are presented.

2. Experimental set-up

Platinum electrodes (d=100 µm) are placed in a horizontal pin-to-pin configuration with a gap distance of 2 mm. They are immersed in a solution of distilled water and NaCl (to adjust the conductivity) filling a reactor (≈ 200 mL) which holds two optical windows. The pulse generator consists of a 1 nF capacitor constantly charged by a 30 kV high voltage power supply. Positive high voltages mono-pulses (rise time of 30 ns, duration from 100 µs to 1 ms and amplitude up to 16 kV) are produced using a fast high voltage solid-state switch. Electrical measurements are performed using a high voltage probe and a coaxial current shunt (R = 10 Ω). The source light of the schlieren optical set up is a 300 W Xenon light source and the signal is monitored by a high speed camera (Phantom V1210). Videos have been recorded with an exposure time of 0.91 µs and a widescreen resolution of 128x32 pixels which allows 571 500 frames per second. It is worth noting that the camera allows monitoring both variation of the refractive index and strong light emissions. The scheme of the experimental set-up is depicted in Fig.1 and more details can be found in [3].

Single discharges are carried out in order to maintain as constant as possible the initial conditions of the experiment. Hundreds of experiments have been performed for a same experimental set in order to take into account the reproducibility of the phenomena.

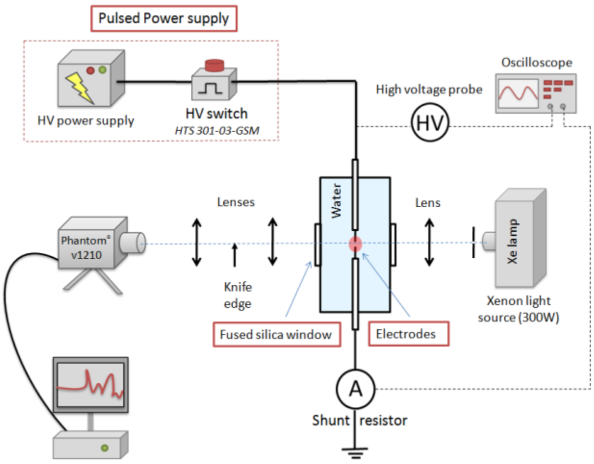

Fig.1 Experimental set-up

3. Description of the discharge features

The authors have already reported the analysis of pre-breakdown and breakdown phenomena for underwater pin-to-pin discharge [3]. Considering the structure of the discharge, the propagation velocity and direction, two main regimes of discharge have been highlighted. Cathode regime involves bush-like structures propagating slowly from the cathode to the anode whereas anode regime involves a filamentary structure emerging faster from the anode (Fig.2). Among the cathode regime 2 different behaviours can be distinguished: partial discharges, called Case(1) and complete discharge (the channels span the electrode gap) called Case(2). Anode regime is also referred as Case(3). In order to better understand the physics underlying these two regimes, it is of great interest to study the influence of major parameters as the solution conductivity and the applied voltage on the discharge characteristics [4].

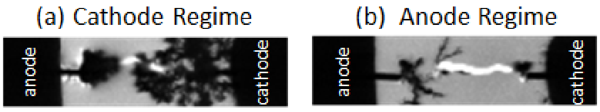

Fig.2 Schlieren images illustrating the breakdown process for (a) the cathode regime – Case(2) (100µS/cm – 12kV) and (b) the anode regime-Case(3) (50 µS/cm – 12kV)

4. Effect of solution conductivity

Experiments have been carried out for different conductivities from 10 to 1500 µS/cm. As reported in [5], the conductivity has strong influence on the electrical signals. The electrical measurements show that the increase of the conductivity causes shortening of the voltage pulse width and the increase of the RLC current. Discrepancies on the waveform of the current appear between low and high conductivity, in particular regarding the presence or not of a transient current during the pre-breakdown phase. This result is consistent with the Schlieren images which have highlighted differences between results obtained at low and high conductivities in terms of gas phase apparition.

A statistical analysis over several hundreds of experiments shows the distribution of the cases according to the conductivity. In the frame of this paper, these results are represented in terms of probability for only significant conductivities (Fig.3). These results confirm that the mechanisms involved in the discharge ignition or propagation strongly depend on the conductivity. From 10 to 200 µS/cm, for a given applied voltage, the increase of the conductivity involves the decrease of Case(1) and Case(3) probabilities but the increase of Case(2) probability. In these conditions, a higher conductivity favours the breakdown phenomena and the cathode regime. When the conductivity is increased from 200 to 500 µS/cm, the opposite phenomena is observed, Case(2) probability decreases when those of Case(1) and Case(3) increase. Then for higher conductivity, *i.e.* 1000 and 1500 µS/cm, the cases distribution are very close, so the increase of the conductivity does not play a significant role.

The analysis of the breakdown phenomena is of great interest in order to understand the initiation and propagation of the discharge. Fig.4 represents the breakdown voltage in relation with the current peak value. The breakdown voltage corresponds to the value of the voltage measured just before the voltage drop due to the breakdown and the current peak corresponds to the maximum intensity of the current waveform resulting from the breakdown. The conductivity has a strong influence on the relation between the breakdown voltage and the current peak on both cathode and anode regimes. No relation between the electrical measurements is observed for low conductivity, since point clouds are either lined up along a horizontal line or scattered. But at higher conductivity the measurements are lined up along a straight line. For Case(2), this effect is observed from 50µS/cm to 1000µS/cm (over this value, no more Case(2) is monitored). Whatever the conductivity, the same slope is observed but the intercept increases slightly with the conductivity (for example me have measured 0.65 kV at 50µS/cm and 1.75 kV at 500µS/cm). For Case(3), measurements deviate from horizontal from 200 µS/cm and the slope increases with the conductivity.

5. Effect of applied voltage

Experiments have been carried out for different applied voltage from 8 to 16 kV.

From this value, the increase of the applied voltage, *i.e.* the injected energy, changes the distribution of the regimes defined previously. A statistical analysis over several hundreds of experiments shows the distribution of the cases according to the applied voltage (Fig.3).

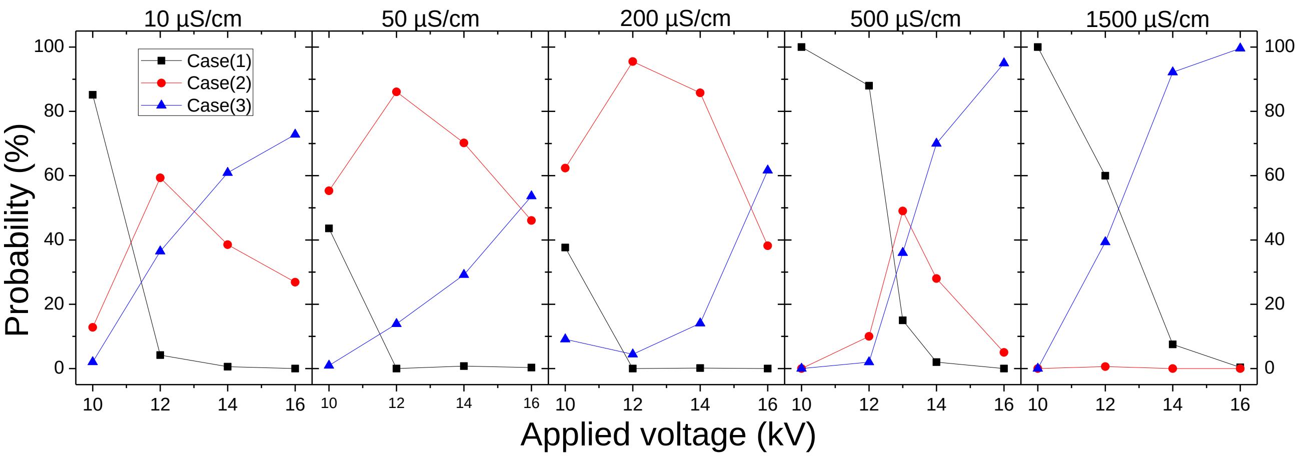

Fig.3 Probability of the discharge cases in relation with the solution conductivity and the applied voltage

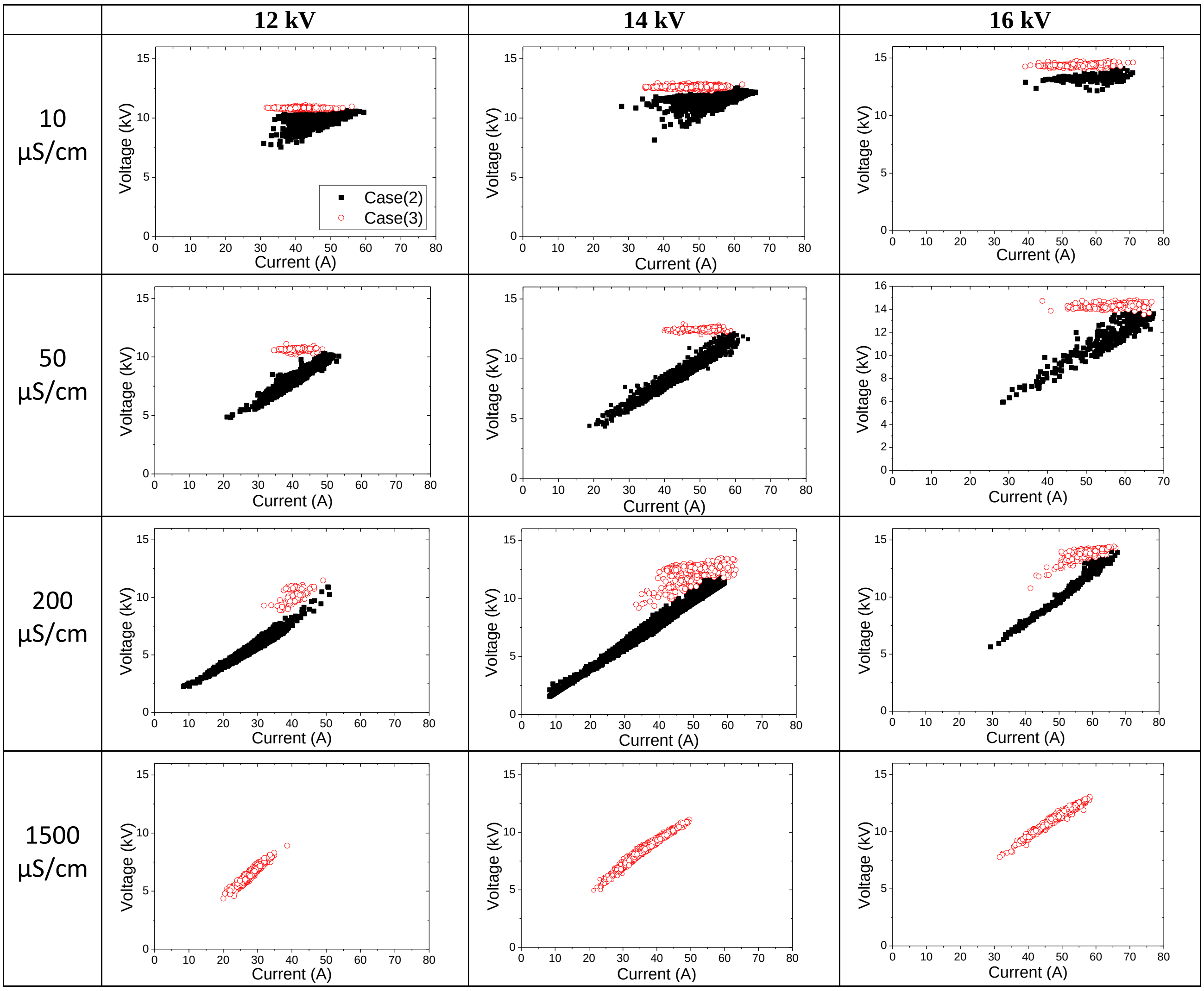

Fig.4 Breakdown voltage according to current peak for 5 conductivities (σ=2, 10, 50, 200,1500 µS/cm) and 3 applied voltages (U=12, 14, 16 k). Black squares refer to cathode regime (Case(2)) and red circles refer to anode regime (Case(3))

These results confirm that the mechanisms involved in the discharge ignition or propagation strongly depend on the applied voltage since the probability of cases change. Whatever the conductivity, the results show that Case(1) probability decreases when the applied voltage increases. As expected, a higher electric field involve a higher breakdown probability. However the influence of the applied voltage on the breakdown regime depends on the solution conductivity. In the range [10-500] µS/cm, the increase of the applied voltage show the following trend: from 8 and 12 kV, simultaneously with the Case(1) probability decrease, Case(2) and Case(3) probabilities increase. Then from about 12-13 kV, Case(2) probability starts decreasing for the benefit of Case(3). The cathode regime is most probable around 12-13 kV whereas the anode regime probability increases quite monotonically. In the range [1000-1500] µS/cm, the increase of the applied voltage involves the decreases of Case(1) probability for the benefit of Case(3) whereas Case(2) probability remains very low. At high conductivity, the anode regime dominates the breakdown process.

Regarding the influence of the applied voltage on the breakdown characteristics (voltage and current peak), Fig.4 shows that we do not notice any significant changes on the relation between the breakdown voltage and the current peak. We only report that the increase of the applied voltage involves a shift of the measurements towards higher breakdown voltage and current peak.

6. Conclusion

The present work confirms that underwater pin-to-pin discharges propagate according two different regimes, the cathode regime (partial discharge or breakdown) and the anode regime, which show different characteristics. The mechanisms that cause these differences are not well understood. This paper presents experimental results obtained by two complementary diagnostics, electrical and refractive index measurements, by varying the solution conductivity and the applied voltage.

On the one hand, the results have shown that the increase of the applied voltage first makes the breakdown more achievable and then favors the apparition of the anode regime. It could be interpreted in terms of injected charge since the increase of the applied voltage results in the increase of the injected charge. The influence of the applied voltage on the breakdown characteristics (U_{bk}, I_{pk}) highlight that channels observed by schlieren technique is a complex medium, certainly not only made of neutral gas but containing excited species which properties are strongly dependent on the electric field.

On the other hand, the variation of the solution conductivity also provides valuable results. We have highlighted strong discrepancies about the discharge characteristics between measurements performed at low conductivity (below 500 µS/cm) and high conductivity (above 500 µS/cm).

The discharge in liquids depends on many different parameters; the conductivity and the applied voltage are ones of the most important since their influence is significant, but also different for the initiation and propagation of the discharge. Estimation of injected charge has shown that the increase of the solution conductivity favors the deposition of the charge during the pre-breakdown whereas the increase of the applied voltage changes mainly the charge deposited during the first breakdown.

These results confirm the complexity of plasma-liquid systems and the necessity to multiply the diagnostics in order to provide a full description of the involved mechanisms.

7. References

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