Plasma characteristics and electrical breakdown between metal and water electrodes

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Formation of plasma between a metallic pin and water electrode is investigated. A streamer to spark transition occurs when the pin is anode. The influence of the water surface deformation due to the ionic wind on the spark formation is discussed. High speed photography indicates that the streamers just before sparking are always branched near the water surface. Optical and electrical characteristics of a stable filamentary glow-like discharge regime, ignited after electrical breakdown with currents between 20 and 120 mA are studied.

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1. Introduction

In recent years, there has been considerable interest in discharges in and around liquids for environmental applications [1]. Plasmas in and above liquids are useful for this kind of applications due to the intense generation of UV radiation, shockwaves and active radicals [2]. Atmospheric pressure air discharges between a metal and liquid electrode were also investigated as a possible tool to generate dc-excited large volume plasmas at atmospheric pressure [3].

Discharges between metal and water electrodes have been studied in the past by different groups but due to the highly complex dynamical nature of the plasma-liquid interface, the plasma-liquid interaction is still not understood. Most investigations in the field deal with time-averaged optical characteristics of a burning plasma [4,5].

After a description of the experimental setup, the corona-regime and breakdown properties will be discussed. Breakdown is followed by a high current filamentary glow-like plasma regime. Some optical and electrical characteristics of this regime will be discussed in the last section of this paper.

2. Experimental setup

A sketch of the experimental setup is presented in figure 1. A stainless steel electrode with a hemi-spherical tip of radius 0.5 mm is placed above a reservoir filled with distilled water in an atmospheric pressure air environment. The depth of the reservoir is 4.4 cm. The distance between the metal electrode and the water is adjustable with a micrometer screw. Different ballast resistors (R) are used: i.e. 100 kΩ for corona discharges and 25 kΩ in the case of the filamentary glow-like regime. The breakdown process is studied with short exposure time photographs obtained by triggering a Hamamatsu CCD camera (C8484) through the gate unit C7970 with a signal proportional to the discharge current. A Tektronix P2100 voltage probe is connected across a resistor to measure high frequency current oscillations up to 60 MHz. Time and space averaged emission spectra are obtained by a S2000 Ocean optics spectrometer.

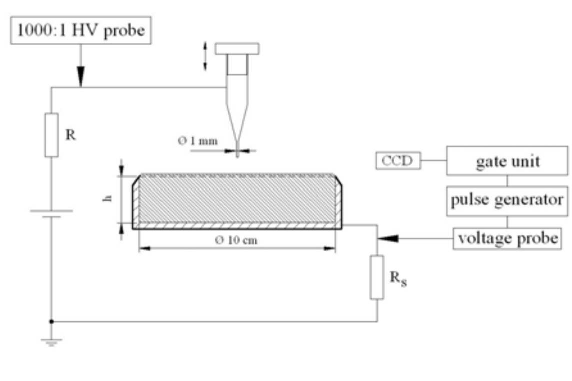

Fig. 1. Sketch of the experimental setup (not to scale)

3. Experimental results

3.1. Corona regime and breakdown

The applied voltage is quasi-statically increased. Below the voltage for corona onset one can observe for small inter-electrode distances (i.e. 1-3mm) a liquid elevation due to the Coulomb force [6]. Once corona occurs, a depression is formed underneath the metal pin electrode. This depression is caused by the ionic wind accompanying the corona discharge. In the case of higher current even a swirl-like behavior is observed.

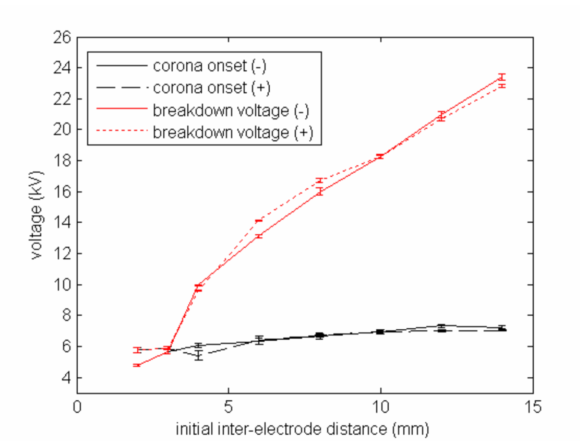

Fig. 2. Corona onset voltages and breakdown voltages as a function of the initial inter-electrode distance for positive and negative polarity of the pin.

Corona onset voltages and breakdown voltages of the setup are presented in figure 2 for positive and negative polarity of the pin as a function of the initial inter-electrode distance. The data are averages of different experiments. Similar to a pin-plate metal electrode geometry the corona onset is in good approximation polarity independent [7]. A significant increase of the breakdown voltage between an initial inter-electrode distance of 3 and 4 mm is observed and coincides with the formation of a pulseless glow-like corona before breakdown at inter-electrode distances of 4 mm or larger for both polarities of the pin electrode. This stable pulseless glow-like corona has a significantly higher current and causes a larger depletion of the water surface than in the case of an inter-electrode distance of 3 mm which causes a sudden increase of the actual inter-electrode distance at breakdown.

In the case of an inter-electrode distance of 3 mm and negative polarity of the metal pin two different breakdown voltages are sometimes observed. One as presented in figure 2 when no stable glow-like corona regime is formed and the breakdown voltage is near the corona onset and one with the formation of this regime. In the later case the breakdown is 2 kV higher due to the larger depression of the water surface. This bifurcation is caused by water surface waves generated during the pulsed corona near corona onset. These surfaces waves can already trigger breakdown at smaller voltages for small inter-electrode distances (3 mm and smaller). This is substantiated by the fact that the bifurcation does not occur in the case of positive coronas when the onset streamer is directly followed by a pulseless glow-like regime.

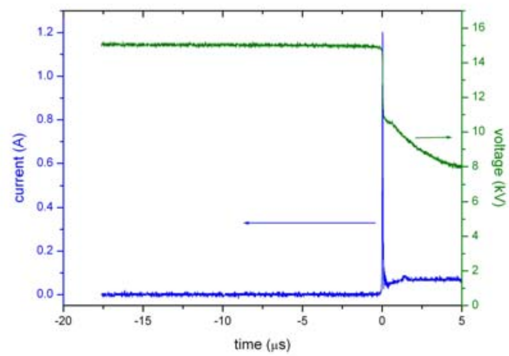

Fig. 3. Current and voltage waveform during breakdown. The initial inter-electrode spacing is 7 mm. The water electrode is the anode.

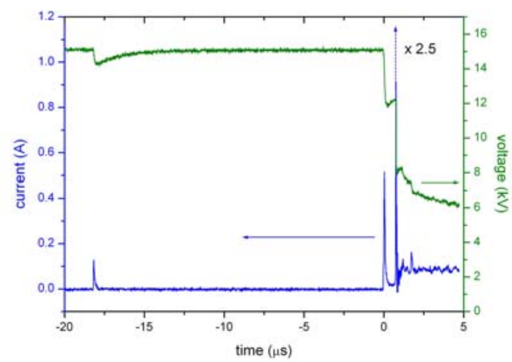

Fig. 4: Current and voltage waveform during breakdown. The initial inter-electrode spacing is 7 mm. The water electrode is cathode. The amplitude of the highest current peak is 2.5 A.

When the water electrode is anode, spark formation occurs during a pulseless glow corona regime. The current and voltage waveform of this process are shown in figure 3. Notice that the current of the pulseless glow corona is in the range of 200-300 μA which is a smaller scale than used in figure 3. It is to be expected from the current waveform that similar to our previous work [6] a glow to spark transition occurs. In the case when the water electrode is cathode, a breakdown streamer regime (not always stable) develops into spark. The breakdown process consists always of two distinct current peaks (Fig. 4) which is significantly different in comparison with Fig. 3. As can be seen in figure 5 (a) the first current peak corresponds to a breakdown streamer which is branched near the water surface.

CCD images of the transient spark triggered by the current pulse are shown in figure 5 (b) and (c) for both polarities and exhibit different behavior. Due to the depression of the water surface which is indicated by the white arrow in the images, the spark is bended towards the edge of the depression especially for negative polarity. Fig. 5 (b) and (c) are the images with the largest lateral extent of the spark taken from a series of experiments. In figure 5(c) low intensity traces from the branched breakdown streamer is visible.

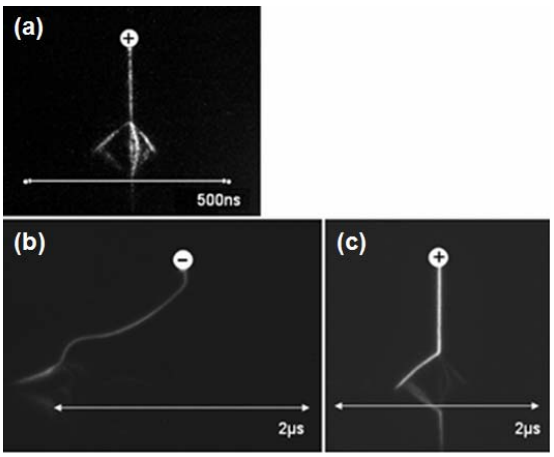

Fig. 5. CCD images of the breakdown events with indicated shutter opening times. The initial inter-electrode distance is 7 mm. The white arrows are an estimate of the depression width of the water surface. The pin with a diameter of 1 mm is drawn on each image with an indication of the polarity. The gain of the CCD is increased for image (a). The trigger of the images correspond with t=0 in the corresponding figures 3 and 4.

This case is similar to the result of Nikiforov and Leys [8], although the branching of the streamers in this study occurs much closer to the pin instead of near the water surface. The main difference is that during the experiment presented in this paper a stable streamer regime occurs before sparking which is not the case in [8] due to the 10 times larger radius of the metal electrode. It is interesting to notice that the distance of the branching point of the streamers is of the same order as the distance where the spark is broadened when a glow to spark transition occurs in the system discussed in our previous work [6]. In the latter work this was explained by space charge effects due to the glow discharge. However, in the case of the streamer one should consider the possibility of image force effects due to the large difference of dielectric constant of air and water.

The relative independence of the breakdown voltage on polarity, in contrast to the breakdown voltage in a metal pin-plate geometry [9] indicates that water surface deformations have a significant influence in the electrical breakdown formation.

3.2. High current filamentary glow discharge

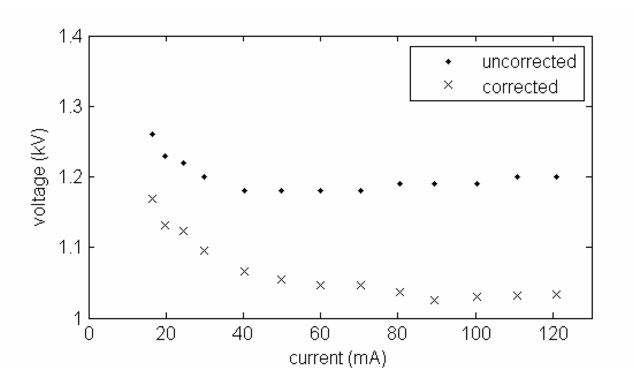

Fig. 6. Current-voltage characteristic of filamentary glow discharge for an inter-electrode distance of 5 mm. The uncorrected and corrected voltages across the plasma (for the voltage drop across the liquid) are shown.

The filamentary glow-like regime, generated after breakdown, is studied with the water electrode as cathode. Characteristics of the discharge are taken when the voltage and current are stable. I.e. the voltage drop across the plasma at constant current initially drops to a plateau as a function of time. The current-voltage characteristic for inter-electrode distances of 5 mm is relatively independent of the voltage in the current range 50-120 mA (figure 6). A correction is made for the voltage drop in the liquid by calculating the resistance of the water electrode between the cathode spot (which changes in diameter with current) and the metal electrode at the bottom of the liquid cathode. The corrected voltage has a precision of 10 percent or better. Although near the water surface a filamentary structure can be observed, corresponding with the observation of several discrete contact points by Laroussi [10], the current voltage characteristic for higher currents exhibits a glow like behaviour. The diameter of the cathode spot on the water surface increases with increasing current. In the case of currents above 40 mA the inner purple-like core of the plasma is surrounded by a white halo.

The voltage increase is in good approximation linear as a function of the inter-electrode distance. Extrapolation of the linear fit to a zero inter-electrode distance with correction of the voltage drop across the water electrode gives an estimate of a cathode fall of 530 V with an error of 10 percent. A large cathode fall of several hundred volts is a typical feature of water electrodes [11] and is due to the typically 2 to 3 orders smaller secondary electron emission coefficient of water than of metals [12].

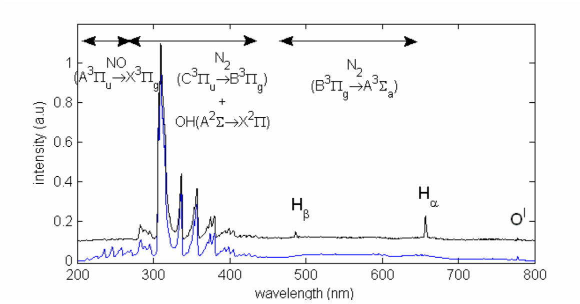

Fig. 7. Optical emission. Lower curve is space averaged emission spectrum. Upper curve (shifted over 0.1) is emission spectrum near water surface.

In fig. 7, a time averaged emission spectrum of the filamentary glow like discharge burning at 50mA is shown. The spectrum is dominated by the OH($A^2\Sigma$ – $X^2\Pi$) -transition and the second positive system of nitrogen ($C^3\Pi_u$ –$B^3\Pi_g$ -transition) in the region of 295-460 nm. Higher resolution spectra show also show a peak corresponding with N_2^+ 391.4 nm ($B^2\Sigma_u$ –$X^2\Sigma_g$ -transition) especially at the lower currents. The elevation in the region 500-700 nm is due to emission from the first positive system of nitrogen. Especially for higher currents a contribution of NH at 336 nm (A^3 Π –$X^3\Sigma$ -transition) superimposed on the N_2 (0-0) transition of the second positive system is observed.

Because the rotational population distribution obeys the Boltzmann law, rotational temperatures of OH emission can be obtained by the Boltzmann plot method. The rotational temperature is in the range of 3300-4300 K at currents between 30 and 140 mA, increasing as a function of the current. This is in the same range as obtained by Mezei et al. [4] who used a water stream from a capillary as cathode.

4. Conclusion

Plasma formation between a metallic and a water electrode is investigated. The influence of the pre-breakdown regime (corona discharge and water surface deformation) on the spark formation is discussed. It is shown that in the case of an anode pin a streamer-to-spark transition occurs. When the pin is cathode a glow to spark transition is observed. The voltage of the filamentary glow-like discharge is relatively independent on the current above 50 mA. The rotational temperature of OH increases with current and is in the range 3300-4300 K. Apart from OH, also N_2, N_2^+, NH, H, O and NO are observed in the emission spectra.

Acknowledgement

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