COMPARISON OF PULSED CORONA DISCHARGE IN WATER AND AIR

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ABSTRACT

Point-plane pulsed coronas are investigated using de-ionized water or air as discharge medium. Similar gap configurations have been used in both cases, i.e. 25 mm point-plane distance and the same voltage pulse of 25 kV amplitude and 30 ns rise time. Measurements of the pulse voltage and current show a much larger energy dissipation in water. Pictures from a CCD camera show branching behaviour in both media, but with quite different appearance. In air streamers spread out from the anode and many branches reach the cathode. The discharge in water is only up to 5 mm long; it shows one main discharge path with branches that remain short. It resembles the stepped leader form of lightning in air. The step length scales with the density of the medium, i.e. ~1 mm for the water discharge and ~1 m for long discharges in air.

1. Introduction

Treatment of gas using pulsed discharges has received a lot of attention the last two decades. Configurations used are barrier, packed bed and corona reactors. Important similarities are a current duration in the nanosecond range and an electron energy in the active part of the discharge in the range of 10 eV. An important difference in these reactors is the relative contribution of volume and surface discharges. An extensive review can be found in [1].

Discharges in water have been investigated to a far lesser extend. In the 1970’s high voltage pulses in water have been studied in relation with dielectric breakdown. Pictures of small gaps (~1 mm) have been made by interferometry and Schlieren photography [2, 3]. Both methods show a brush-like development of the discharge and propagation velocities of $10^2$-10$^3$ m/s are mentioned, i.e. relatively slow. In [4] the development in point-plane gaps is photographed with one ns time resolution. Supersonic propagation velocities are found with values of 10$^4$ and 10$^5$ m/s. Further streamer diameters of a few micrometers are seen. Another important aspect of discharge development in a liquid is the presence and/or formation of bubbles [5].

Since roughly 10 years, the discharge in water is under investigation for oxidation purposes by in-situ creation of OH radicals. Phenol is a substance that has been used by several authors as a test case for breakdown of organic molecules [6-8]. Another possible application is killing of micro-organisms like bacteria [9].

Recently it was claimed that water cleaning could be done more efficiently by creating the corona discharge over the water surface [10]. This raises again the question of the differences in fundamental processes that play a role in the production of radicals in liquid or gas. We present measurements here where both media are investigated in the same conditions of electrode configuration, power supply and measuring equipment in order to make a good comparison.
2. Experimental set-up

Discharging a capacitor of 1 nF with the use of a triggered spark gap creates the pulsed corona studied here. It is created in deionized water or ambient air using a point-plane electrode configuration. The point is made of tungsten with a radius of ~15 μm, the plane made of brass and covered with a dielectric sheet (perspex). The experiments in water are carried out in a cubic reactor with a perspex bottom, 2 sides of glass and 2 sides of quartz, fixed with silicon glue.

The electrode gap is 25 mm in all cases and the power supply that charges the capacitor is set between 20 and 30 kV. The voltage and current of the discharge pulse are measured by probes (Tektronix P6015 and Pearson 2877). Their signals are recorded by a digital oscilloscope with a time resolution of 1 ns (Tektronix TDS380). For details see [10].

Pictures of the discharge are taken using a CCD camera equipped with a gated intensifier. This camera (Andor Technology ICCD-452) has the following specifications:
- 1024 x 1024 pixels
- pixel size 13 μm x 13μm
- sensitivity 180-850 nm
- minimum optical gate time 0.8 ns
- overall spatial resolution 21 μm
- intensifier gain up to 3600

The discharge is imaged onto the camera using the Nikon UV-Nikkor 105mm f/4.5 lens. This lens is chosen because it is made of quartz. This is advantageous because almost all of the optical emission from the pulsed corona in air originates from the Ne Second Positive System [1]. Besides this, the lens has good imaging properties. The magnification is set so that one pixel of the CCD corresponds to 27 μm at the discharge gap so that the camera observes the complete gap. Pictures have been made using an opening time of 100 ns to give an overall impression of the streamer paths. The intensifier is set to 30x (according to the specifications given by the manufacturer).

3. Results and Discussion

Figure 1 shows the voltage and current of the corona in air. The voltage (thin line) shows an oscillation after reaching its maximum and its final level does not completely reach the 25 kV set on the supply (VHV). The current (thick line) has a few short oscillations just after t=0, these originate probably from the spark gap. The larger pulse at t=30 ns is the capacitive current. At t=60 ns the corona current starts, it has a maximum at t=100 ns and decreases with an oscillation. The halfwidth of the largest current pulse is ~40 ns, the energy content of this pulse is ~0.5 mJ.

Fig. 1: Voltage and current of the corona discharge in air, gap 25 mm, VHV=25 kV
Fig. 2: Voltage and current of the corona

*pulse in water, gap 25 mm, V_{in}=20 kV*

The discharge in water behaves rather different. Figure 2 shows the voltage and current at a power supply setting of 20 kV, which is just above inception. As to be expected, the corona current pulse shows considerable jitter, up to several hundred nanoseconds. The pulse at t=0 is again the capacitive current which is now much higher than in the case of air because the dielectric constant of water is high. The capacitive currents differ by a factor ten; this indicates that at nanoseconds risetime the dielectric constant of water is already considerably lower than its DC value of 83. Figure 3 is taken at 25 kV. At this voltage, the jitter in the corona current is so small that it cannot be determined anymore. Another difference with the discharge in air is that the corona current in water has the same value (12 Ampere peak) for 20 and 25 kV applied voltage. The energy of these pulses is 2 and 4 mJ resp., so it is an order of magnitude higher than in air.

Fig. 3: As fig. 2, but with $V_{in}=25 kV$

Fig. 4: CCD picture of a pulsed corona in air (25 mm gap, dielectric cover on cathode, tungsten anode tip, 25 kV with 30 ns rise time).

Fig. 5 CCD picture of corona in water, same conditions as fig.4.
Figure 4 gives an example of a CCD picture obtained in air; fig. 5 is a picture under the same conditions of the discharge in water. The images are inverted digitally, i.e. black is high emission intensity. The picture in air is taken with a gate of 100 ns and the gate opens when the streamers are already halfway the gap. Other examples can be found in [11-12] where also an analysis is made of the streamer diameter. The value found for individual streamers is $160\pm30 \mu m$. It is seen that the discharge spreads out in many channels, branching occurs at the anode but also in the gas volume. A part of the streamers reaches the dielectric cover of the anode where they form a surface discharge. The discharge spreads over a larger diameter than the point-plane distance. The contrast with the discharge in water is large. It develops only over several mm near the anode and most of the branches that are formed stop over shorter distances. Near the cathode, one vaguely emitting spot is observed.

The resolution of the CCD combined with the intensifier is 21 $\mu m$ according to the manufacturer. Since the magnification here is ~2, the smallest structures observed are about 40 $\mu m$. In refs. [2-3] channels with a diameter of a few micrometers are mentioned. Therefore, photographs have been made of the discharge in water using 1:1 image on a large negative (Mamiya 645). Fig. 6 shows such a photograph, which has been made with a 30 kV pulse in a 20 mm gap and a stainless steel anode tip. The photo integrates all emitted light of one corona pulse. The total length of the discharge on the photo is ~1 cm. The finest channels observed at the end of the streamers are about 10 $\mu m$ in diameter. Therefore, the resolution of the photograph is better than the CCD image and it is likely that this minimum diameter is determined by the equipment. The spot on the bottom is not observed on any photo. This shows that the CCD has a much higher dynamic range than the photo as to be expected.

Fig. 6 Photograph of corona discharge in water (gap 20 mm, voltage 30 kV)

Fig. 7 Part of a photograph of lightning in air (taken form ref. [14]).
In fig. 6 some intense spots are seen, which show up much more clearly on a color image (see: http://www.phys.tue.nl/EPG/). It was described earlier that such spots turn up only in de-ionized water [13]. Other differences between discharges in tap water or de-ionized water were found to be: the color of the discharge channels, the length of the branches and the number of the branches.

For comparison, fig. 7 shows a part of a photograph of a lightning discharge [14]. The left branch, which is broad and diffuse, is a breakdown to ground. The right branch dies out before making contact and its shape resembles clearly the discharge of fig. 6. A rough estimate of the length of the picture is 100 m. The breakdown mechanism of lightning is usually described as stepped leader. This implies that the discharge propagates stepwise and in air, these steps have a length in the order of a few meters [14]. The total length of the discharge in fig. 6 is \( \sim 1 \) cm, so what can be recognized here as steps has a length of a fraction of a millimeter. The ratio of these steps sizes has an order of magnitude of one thousand, which is the same as the ratio of the density of the media.

Time resolved CCD pictures of the corona in air have been published earlier [11-12]. In water, such pictures have not been made yet. The opening time of the gate for fig. 5 was 1 \( \mu s \). From this time span, it can be derived that the discharge propagation is in the "fast mode". In [2] this is called the formation of the main ionization channel having a propagation speed of \( \sim 10^8 \) m/s. In [13] this velocity was estimated from photomultiplier measurements to be \( 10^8 \) m/s. This fast mode produces streamer channels with diameters down to \( \sim 10^6 \) m with tree-like structure. The second, slow mode that is observed in [2] is streamers that move with \( 10^5 \) m/s and has a so-called brush structure. This propagation is related to a shock front having a pressure in the order of several hundred bar. In this slow mode probably the formation of bubbles occurs. Very similar observations on streamer propagation and structure have been made in organic liquid dielectrics [15].

**Conclusions**

Images of the spontaneous optical emission of pulsed corona in denonized water and air in the same gap configuration show very distinct appearance. In air, many streamers propagate from the anode tip to the cathode plate where they form surface discharges on a dielectric sheet. In water, one main discharge path develops from the anode and many fine branches remain short. The main path only travels a small part of the gap. The energy content at the same voltage is one order of magnitude higher in water compared to air. In previous measurements, the energy content of the discharge pulse in water was even much higher [16]. This was due to a conduction current because the cathode was also inside the water. This clearly shows the effectiveness of the dielectric bottom of the water container.

The discharge in water is, from its appearance, more similar to lightning in air. Lightning develops in air according to the "stepped leader mechanism" with steps of \( \sim 1 \) meter. From the photos in water a step length is derived of \( \sim 1 \) mm. So, one is tempted to say that this mechanism is also applicable to water where the step length scales with the density. From the opening time of the CCD pictures of the discharge in water, it can be said that the development is definitely in the "fast mode". In this mode the streamers develop in thin channels with velocities \( \sim 10^8 \) m/s. The thinnest channels observed have a diameter of \( \sim 10 \) \( \mu \)m, but this size is determined by the equipment.

The discharge in air develops in many branches that spread out over a large area. Several of them reach the cathode and form surface discharges. The smallest diameter of the
streamers is found to be 160±30 μm, i.e. much larger than in water. It cannot be concluded if this dimension scales with the density of the medium. Another question that remains is the process or mechanisms that causes the branching phenomena. Further investigations are necessary to answer these questions. This is of importance to predict the amount and the efficiency of radical production as to be used in various applications [1].

References