BRANCHING OF STREAMER TYPE CORONA DISCHARGE

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ABSTRACT

The behaviour of positive streamers in air is studied in a rather homogeneous field created by a short plane-protrusion gap in air. Branching is observed to be quite limited, the velocity of the streamers increases with travel distance and “late” streamers are observed. The interaction of streamer heads can be interpreted as electrostatic repulsion, while “late” streamers seem to be attracted by the streamer channels, indicating a net negative charge of the channels.

INTRODUCTION

Pulsed corona discharges are used to create radicals in atmospheric plasmas for water and gas cleaning [1]. They form filamentary channels, so-called streamers, that can split into many branches. This process probably has a large influence on the efficiency of radical production, nevertheless detailed studies are very limited. After earlier stochastic branching models [2, 3] on a more phenomenological level, branching even in simple deterministic models has recently been predicted [4, 5] to be generic at least for negative streamers in high fields.

Streamer propagation is also studied in experiments, because of their applications. Better quipment is now available to produce and measure discharges on a nanosecond timescale. Point-plane [6-11] as well as protrusion-plane gaps [10-12] have been studied. Different media have been investigated: Ar [6, 10, 11], air [7-10], Ar/O_2 [6] and N_2/O_2 [12]. The high time resolution that can now be obtained with CCD cameras [7, 9] makes it possible to determine streamer velocities with resolution in space [8].

This paper gives information on the propagation of streamers in air in a plane-protrusion gap. Only time-integrated pictures have been obtained up to now [10]. Here time-resolved pictures will be shown and it appears that the difference with streamers in a point-plane gap is quite large.

EXPERIMENTAL SET-UP

The corona discharge is created by discharging a capacitor using a fast switch. In this work, the switch consists of a stack of high voltage MOSFET transistors (Behlke HTS-301). It has a voltage rise time of 20 ns and a maximum voltage of 30 kV. In [10] the differences with the conventional spark gap are discussed. The electrical parameters of the corona pulse are determined using a high voltage divider (Tektronix P6015) and a current transformer (Pearson 2677). Their signals are digitized using a 1 Gs/s digital oscilloscope (Tektronix TDS380).

The electrode configuration used for most of the measurements presented here is given in fig. 1a. The protrusion is fixed in the anode plate to ensure good electrical contact. The gap distance is always 20 mm and the pressure always 1 bar (ambient air). Fig. 1b shows the point-plane gap that is used for comparison.

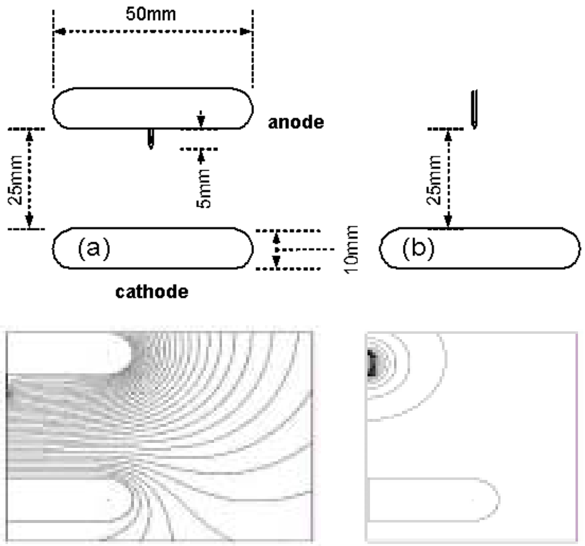

Fig. 1: Plane-protrusion (a) and point-plane (b) electrode configuration to produce corona discharge, below each gap an indication is given of the equipotential lines.

The same needle with a tip radius of 15 μm is used for both; its shape appears to remain unchanged under the relatively low number of discharge pulses used. Equipotential lines of both gaps are calculated in polar coordinates using a boundary element method; an impression is given in fig. 1.

Photos of the discharges are taken with an intensified CCD camera (Andor Technology ICCD-452). Due to the fibre coupling of the intensifier, this camera combines a high spatial resolution (20 μm) with a high sensitivity (photon counting) and a very short optical gate (minimum 0.8 ns). An image of the discharge is made with a UV photographic lens (Nikon 105 mm f/4.5). The complete gap is always imaged on the CCD with a 2:1 magnification. The pictures in this paper are printed in black and white with maximum contrast to preserve the shape of the streamers as much as possible and to ensure a good reproduction. Therefore, information on differences in intensities of different parts of the discharge is lost. The false colour pictures in [7], [9] and [10] do show more detail in this respect.

RESULTS

With gap 1b, many measurements have been done at 12.5 kV because at this voltage the streamers just reach the cathode [9, 10]. The same average field would result from a voltage of 10 kV in gap 1a, but at this voltage, the discharge does not start. At 12.5 kV corona is observed very occasionally, so to obtain time resolved pictures in a reasonable period of experimenting a voltage of 15 kV is used. Even then, most high voltage pulses do not give any result on the CCD pictures. On average about 20 pulses are required to obtain one photo. On a few photos in every 20 pulses, another discharge phenomenon is observed: a very small spot at the anode tip with an intensity higher than that of the streamer channels. The size of the spot is 1-2 pixels, i.e. several tens of micrometers or smaller.

The photos presented in figs. 2-4 show the discharge in five stages of its development. Each stage is a period of 50 ns with increasing time delay. Very short opening times as used in the point-plane gap [9] could not be used here. The intensity of the streamers is lower and nothing is observed using optical gates of a few nanoseconds. This effect is also reflected in the energy of the pulse, which could not be measured because the current was below the noise level of the measuring system. Fig. 2a-d shows streamers, as they appear when the camera is triggered at the start of the voltage pulse. Their length is just over 1 mm, and in case 2a branching is observed. Figs. 2e-i are taken 50 ns later. The streamers now travel a distance of up to 4 mm again in a period of 50 ns. Two or three branches are observed.

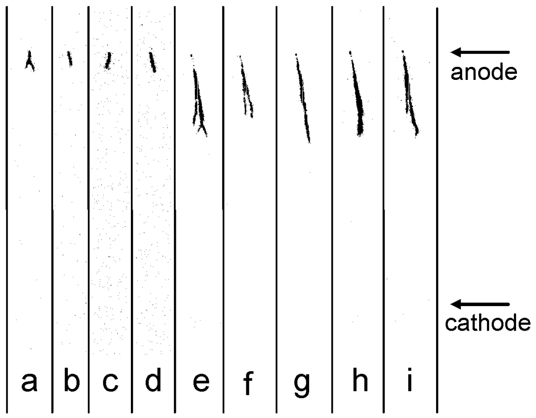

Fig. 2: Streamers observed in the first (a-d) and second (e-i) period of 50 ns after the start of the voltage pulse.

The third period of 50 ns is demonstrated in fig. 3a-d. These photos are made under the same condition so their different appearance is an indication of the variation that occurs from shot to shot. The path length that the streamers travel in this period ranges from 2 to 8 mm. The highest velocities are obtained in the lower part of the gap.

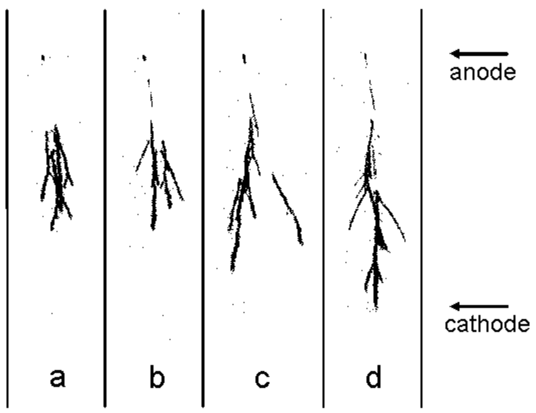

Fig. 3: Streamers observed in the third period of 50 ns after the start of the voltage pulse.

In fig. 4a-b the fourth period is indicated in which the first streamers reach the cathode. An interesting feature is observed most clearly in fig. 4b: the streamers that reach the cathode are straight below the tip but on the sides of this photos there are streamers which are still in the middle of the gap. Their velocity is 2-3 times lower than observed in fig. 3. Therefore, their delay with respect to the streamers in the middle is about 100 ns. In the fifth period only a few streamers are seen that reach the cathode and a few spots on the cathode where probably streamers have just died out.

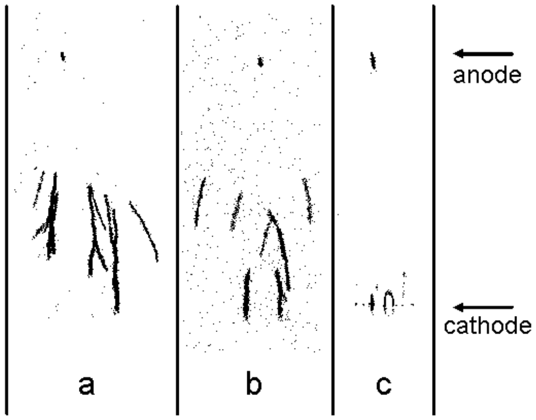

Fig. 4: Streamers observed in the fourth (a, b) and fifth (c) period of 50 ns after the start of the voltage pulse.

From the length of the streamer path on each photo is measured and the exposure time the average velocity of the streamer in this period can be determined. This has been done for all streamers of figs. 2-4. The result is given in fig. 5. The position on the x-axis is at the average over the streamer path. The accuracy of an individual velocity determination is ~10%, so the shot to shot variation is much larger. The points labelled with "+" belong to the "late" streamers of figs. 4a-b. The points labelled with "v" are from streamers that are in contact with the cathode or the anode. For comparison, the velocity data for gap 1b at 12.5 kV [8] are included as circles; the length on the x-axis is rescaled to have the cathode in the same position.

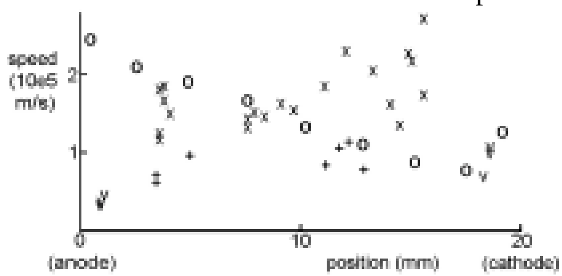

Fig. 5: Streamer propagation velocities determined from the length of the streamer paths, x*: plane-protrusion gap, +: "late" streamers, v: streamers at electrode,* o*: point-plane gap.*

Pictures with longer exposure time have also been taken. Fig. 6a is an example obtained with 200 ns optical gate. Several streamers are seen that reach the cathode. Fig. 6b and 6c have optical gates of 5000 ns but the difference with 500 ns is not noticeable. Fig. 6b shows again streamers that bend outwards in the middle of the gap and they bend back to the other streamers in the vicinity of the cathode. These are probably the "late" streamers as also observed in fig. 4b. Fig. 6c shows another example with long illumination time. The same effect is observed on the right side of this photo, although not as pronounced as in fig. 6b. Again this shows that large shot to shot variations occur.

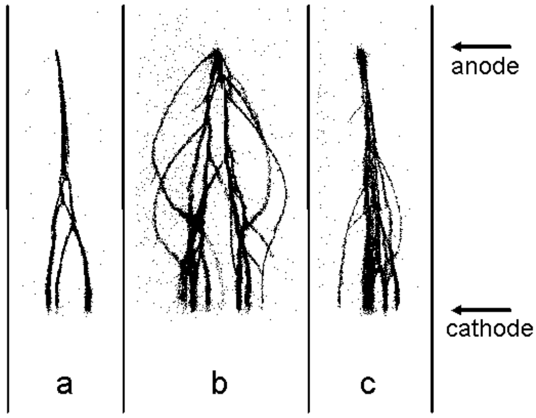

Fig. 6: Time integrated pictures of plane-protrusion corona discharges, (a): 200 ns, (b-c): 5000 ns. Gap distance 20 mm, voltage 15 kV.

For completeness, fig. 7 shows a corona discharge in the point-plane gap of fig. 1b. Here 17.5 kV is used at a 25 mm gap so approximately the same average field strength is applied. The illumination time is also 5000 ns and the same treatment of the photo is used to obtain the maximum contrast. The energy content of this pulse is estimated at 0.2 mJ. These pulses are invisible for the human eye even after a long period in a dark environment. Pulses of 25 kV having 2 mJ energy can just be seen by humans.

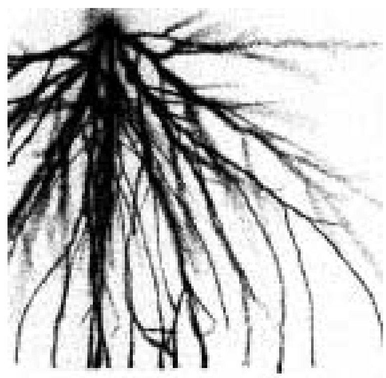

Fig. 7: Time integrated photo (5000 ns) of a point-plane corona, gap distance 25 mm, voltage 17.5 kV.

DISCUSSION AND CONCLUSIONS

The positive corona in a protrusion-plane gap in air behaves quite different from the point-plane case. The main reason is the very different shape and magnitude of the applied electric field (see fig. 1). The protrusion-plane gap has been chosen to make the field almost homogeneous in the entire gap except within ~2 mm from the point of the protrusion. The field strength in the gap is close to the average applied field, ~7 kV/cm, at the tip it is ~1 MV/cm. In the point-plane gap the field strength in most of the gap is ~0.4 kV/cm and at the tip it is ~3 MV/cm. Microroughnesses probably increase the field strength at the tip further. Field emission, which starts at ~5 MV/cm, cannot contribute since the tip is an anode. The inception behaviour of the two gaps is quite different probably due to the different fields at the tip. In the point-plane gap streamers always start but in the protrusion-plane case there is a low probability. In the protrusion-plane gap, only a tiny spot at the anode surface is sometimes seen.

The different starting condition appears to influence the velocity of the streamer. Close to the anode, the streamers travel faster in the point-plane case, i.e. when they start in the higher field strength. When these streamers move into regions with lower field strength they slow down. The streamers in the protrusion-plane gap, on the contrary, increase their speed while they move through a region of ~7 kV/cm. On average the velocities in both gaps are quite similar, 0.15 mm/ns. But, on the point-plane gap 12.5 kV is used across 25 mm and in the protrusion-plane gap 15 kV across 20 mm, i.e. a considerably higher average. In the point-plane gap, an almost constant velocity of 1 mm/ns is found at 25 kV pulses [8]. Therefore, it is expected that at the same average applied field strength the streamers in the point-plane gap are considerably faster than in the protrusion-plane gap.

Two interesting new phenomena can be seen in the protrusion-plane gap. First, streamers on the outside of the discharge arrive later in time than the ones in the center. The most clear example is fig. 4b where the so-called “late” streamers are ~100 ns behind the most advanced streamers. Second, in fig. 6b it is observed that the “late” streamers bend back to the first streamers instead of moving straight to the cathode. The “late” streamers are not clearly observed in the point-plane-gap since the pictures show too many discharge paths as in fig. 7. In such photos, one can distinguish more and less intense streamers and the less intense ones could be “late”.

The observations in the protrusion-plan gap can be interpreted as electrostatic interactions of the travelling streamers: the streamer heads are positively charged so they repel each other. If one streamer head gets a little bit ahead of the other, it propagates in a higher field straight towards the cathode. Due to electric repulsion and screening, the streamer heads staying behind propagate sidewards and slower and become “late” streamers. The bending of “late” streamer heads towards streamer channels can be explained by assuming that the channels carry a net negative charge that attracts the positive streamer heads.

Up to date, there are no simulations or theoretical estimates available for the observations presented here. A polarization of the streamer body can be seen in [6], but it applies to negative streamers in much higher fields. More work on experiments as well as theory is clearly needed.

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