Diameters of positive streamers in pure N_2/O_2 mixtures

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Positive streamers in air and other oxygen-nitrogen mixtures propagate against the electron drift direction. It is generally believed that this is due to photo-ionization. We have studied the morphology and streamer width of positive streamers in pure nitrogen and in different mixtures of pure nitrogen and oxygen. We have found that even in high purity nitrogen (<1 ppm contamination), we still see streamer propagation with roughly the properties as in all nitrogen-oxygen mixtures. We have confirmed the results of Briels et al. who have shown that for a specific gas mixture, the value of $n \cdot d_{min}$ (with n the gas density and d_{min} the diameter of the smallest streamer) is roughly constant as a function of n. This constant reduced diameter depends on the gas mixture; the diameter decreases when the oxygen fraction is decreased.

1. Introduction

Streamers are fast propagating, ionization fronts that can appear when a high voltage is applied over a gap [1]. These fronts leave a conducting trail or channel that can develop into a spark when the voltage is maintained long enough. Therefore streamers occur naturally as an early stage of sparks and lightning. Streamers can also occur separately, e.g. in the case of sprites (large scale discharges above thunderclouds).

Only a propagating streamer head emits light and we can therefore use a camera to image the path of these heads. Because the emitted light is often weak we need an intensified CCD (ICCD) to do this. The intensifier also enables us to take images with very short (nanosecond) exposure times. These images only show a small section of the streamer propagation and can therefore be used to measure the velocity of the streamers [2].

In this paper we will concentrate on the width of positive streamer channels. Briels et al. [3] have shown that the reduced diameter $n \cdot d_{min}$ is constant as function of n for a specific gas mixture. Here n is the number density of the gas (in m^{-3}) and d_{min} is the diameter of the thinnest streamer channel (minimal streamer). At constant temperature (e.g. in a laboratory environment), we can exchange the density for the pressure p.

This minimal streamer occurs when a relatively low voltage is used, just high enough for the streamers to initiate and propagate. At higher voltages the streamer channels become thicker. Also at a low voltage, streamers start with larger diameters near the electrode and reach minimal diameter only after some distance. Therefore only streamer channels far away from the tip that no longer branch are included in the measurement. The choice for these thinnest channels has been mainly made because, from experimental data as well as from theoretical considerations, it has been found that there is a lower limit in streamer diameter, but no upper limit of the streamer diameter with growing voltage has been found yet.

In this paper we will repeat some measurements by Briels et al. [3], but with a better defined purity of the gasses used. We also extend the measured range to nitrogen of 1 ppm (parts per million) purity. Measurements on similar gasses have also been performed by Yi and Williams [4].

According to our theoretic understanding of streamer propagation, a positive streamer can only propagate when there is a steady supply of free electrons in front of the streamer head. One major source of these free electrons in air is photo-ionization; direct ionization of oxygen molecules by UV-radiation from nitrogen molecules. Investigating the effects of lowering the oxygen concentration in nitrogen/oxygen mixtures can help us understand the importance of photo-ionization.

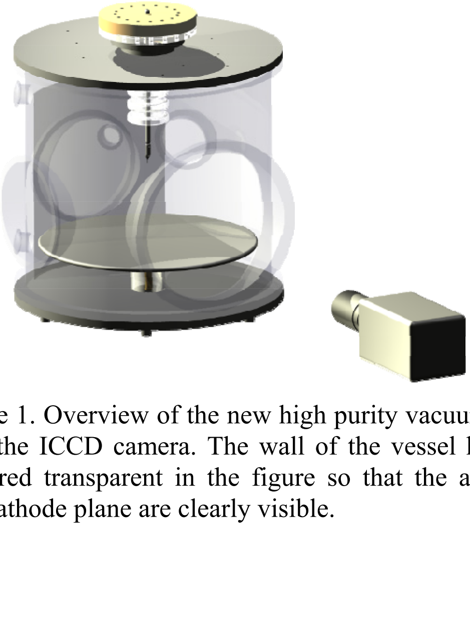

Figure 1. Overview of the new high purity vacuum vessel with the ICCD camera. The wall of the vessel has been rendered transparent in the figure so that the anode tip and cathode plane are clearly visible.

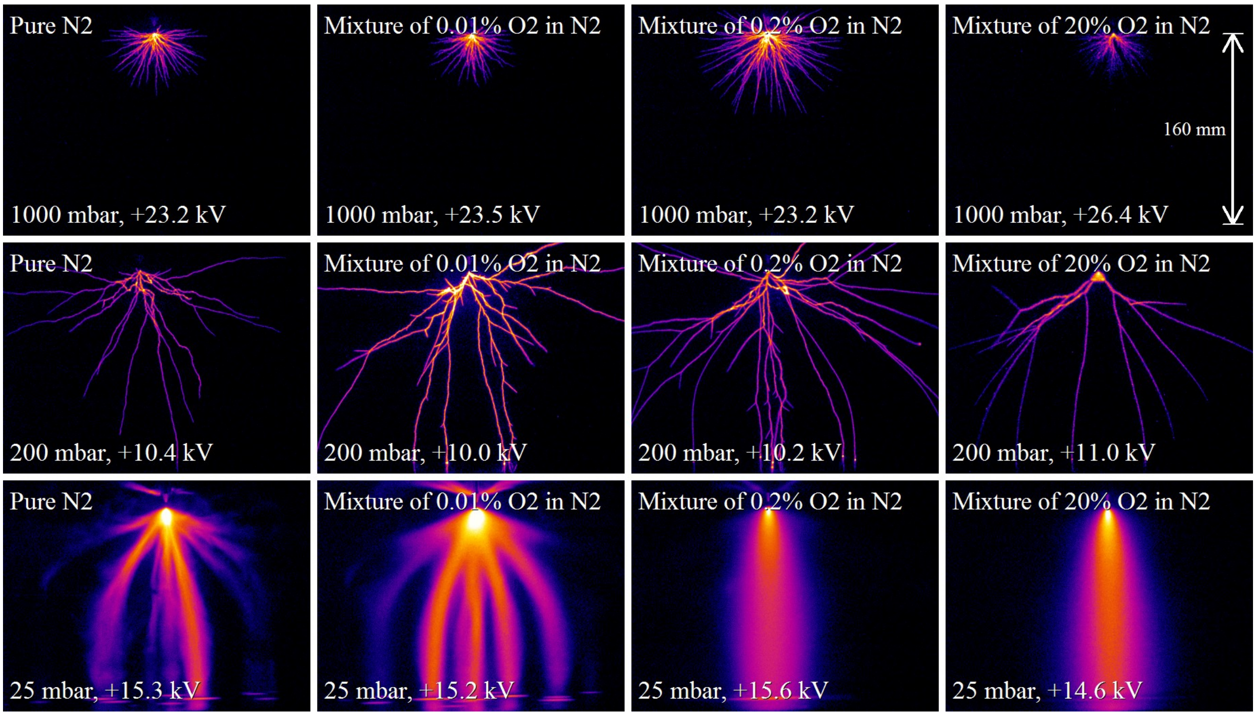

Figure 2. Overview of streamer discharges for all four gas mixtures used (columns), at 1000, 200 and 25 mbar (rows). All measurements have a long exposure time and therefore show the whole discharge. Image colours are scaled for each image separately and therefore give no indication of measured intensity. The white arrow at the top right image indicates the vertical position of the anode point and the cathode plane. The voltages have been chosen so that streamers are just initiated; a lower voltage will not give any streamers.

2. Experimental set-up.

We have built a set-up that is specifically designed to ensure the purity of the gasses inside. For this reason, the set-up can be baked to reduce outgassing, it contains no plastic parts, except for the o-ring seals and it stays closed all of the time. When not in use, the set-up is pumped down to a pressure of about $2{\cdot}10^{-7}$ mbar.

During use, the gas inside the set-up is flushed with such a flow rate that all gas is replaced every 25 minutes. The absolute flow rate is controlled by a mass-flow controller and depends on pressure. The flow rate is sufficiently high that the contamination caused by outgassing is significantly below 1 ppm for all pressures used. We use mixtures of O_2 and N_2 that are pre-mixed by the supplier. According to the specifications, the amount of contamination is below 1 ppm. The mixtures we have used contain nitrogen with 20%, 0.2%, 0.01% and <0.0001% oxygen (volumetric fractions).

The vacuum vessel contains a sharp tungsten tip, placed 16 cm above a grounded plane. A schematic drawing of the vacuum vessel with the camera is given in figure 1.

During a measurement, a voltage pulse is applied to the anode tip. A 1 nF capacitor is charged by a high voltage negative DC source. Now a trigger circuit triggers a spark gap, which acts as a fast switch. The capacitor is discharged and puts a positive voltage pulse on the anode tip. This pulse has a rise-time of about 15 ns and a fall time of about 10 µs.

The streamer discharge is imaged by a Stanford Computer Optics 4QuickE ICCD camera. We use two different lens assemblies: a Nikkor UV 105 mm f/4.5 camera lens directly on the camera and a simple 250 mm focal length, 50 mm diameter achromatic doublet on an optical rail. The latter is used to zoom in on a specific region of the discharge in order to measure small streamer diameters.

From the measured images, the streamer diameter is determined with the following method:

- A suitable straight streamer channel section is selected.
- In this section, several perpendicular cross sections of the streamer are taken.
- These cross sections are averaged so that they form one single cross section.
- The full width at half maximum (FWHM) of the peak (streamer intensity) is determined.

This FWHM is now used as the streamer diameter.

More information about the circuit, discharge vessel and imaging system can be found in [3,5].

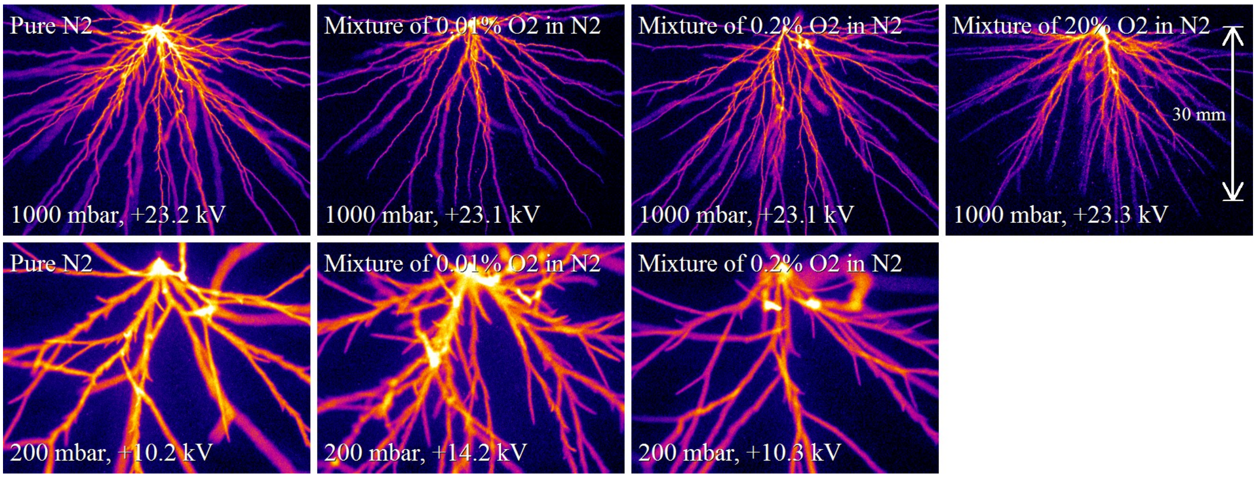

Figure 3. Zoomed images for all four gas mixtures used (columns), at 1000 and 200 mbar (rows) around the anode tip region (see length indication at top right image).

3. Results and discussion

Figure 2 shows an overview of streamers in the four different gas mixtures. The general morphology is very similar for the different mixtures.

One striking feature is the maximum length of the streamers at 1000 mbar; the streamers are longest for the 0.2% O_2 mixture.

A second observation is that the streamer channels become marginally straighter for higher concentrations of oxygen.

Figure 3 shows images from similar discharges as in figure 2 but now zoomed to the region closest to the anode tip by moving the camera closer to the experiment. Unfortunately, no image is available for 200 mbar, 20% O_2.

We can observe that for lower oxygen concentrations, the streamers branch more often. In pure nitrogen at 200 mbar they even form shapes resembling feathers.

3.1. Minimal streamer width

The minimal streamer diameters have been measured on images where the streamer diameter (FWHM) is at least 10 pixels wide. Therefore we used images like the 200 mbar images from figure 3, and even higher magnifications at higher pressures.

Results from the measurement of the minimal streamer diameter are given in figure 4. Some observations:

- The reduced diameter is roughly constant for any gas mixture, but it does increase slightly at higher pressures.
- The reduced diameter increases as a function of oxygen concentration although there is no significant difference between pure nitrogen and nitrogen with 0.01% oxygen.

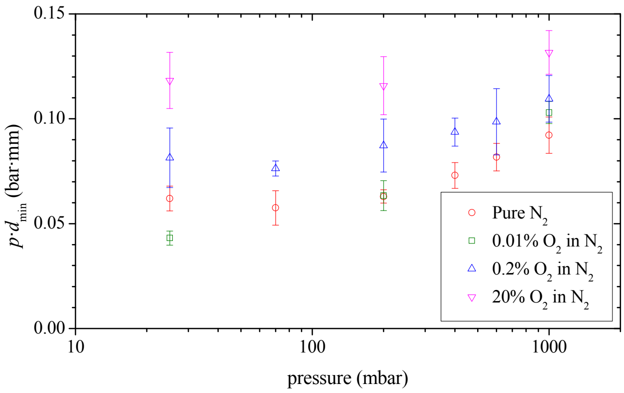

Figure 4. caling of the reduced diameter ($p*d_{min}$) with pressure (p) for the four different nitrogen oxygen mixtures. Every point represents 4 to 10 streamer channels. The error bars give the sample standard deviation.

The increase of reduced diameter as function of pressure could be a measurement artefact: it is possible that the width of the streamers at high pressures is still overestimated because of bad focusing (shallow depth of field) and other imaging artefacts [6].

When we compare the values from figure 4 with the results of Briels et al. [3] we see that they are a bit lower in all cases. Briels et al. give an average value of $p \cdot d_{min}$ of 0.12 bar · mm for 'pure' nitrogen[1]

[1] Note that the pure nitrogen in the work of Briels et al. was probably less pure than in the present work. The new set-up is much better suited for work on high purity gasses than the old one used by Briels et al. It is estimated that the 'pure' nitrogen of Briels et al. has a contamination level of less than 0.1%, while we here achieve less than 0.0001%.

and 0.20 bar · mm for air. There can be several reasons for the differences:

- Influences of other gas component like water vapour and carbon dioxide that are more prevalent in the set-up of Briels than in the new high purity set-up.
- Small differences in voltage pulse rise time and amplitude that could lead to larger than minimal streamers in the case of Briels.
- Overestimation of streamer widths by Briels because of the optical problems explained above.

4. Conclusions

From the overview images, zoomed images and minimal streamer diameter measurements, we can conclude that, although there are differences, the streamers are very similar over the whole investigated range of oxygen fractions (nearly six orders of magnitude). This is remarkable because it means that either the photo-ionization mechanism is not as important in streamer propagation as previously thought, or, that this mechanism can still provide enough free electrons, even at very low oxygen concentrations.

When we assume that the direct photo-ionization mechanism is not the major source of free electrons there are a few options left for these sources:

- Other photo-ionization mechanisms than direct photo-ionization of oxygen by nitrogen emission, are responsible for free electrons. For example, this could be step-wise ionization of nitrogen molecules.
- Background ionization of the gas can deliver enough free electrons for streamer propagation. The background ionization can lead to free or bound electrons. The bound electrons can be detached by the enhanced electric field of the streamer head [7].

We have not worked out an explanation for the feather-like structure of the streamer channels in gas mixtures with low oxygen concentrations. An ad hoc explanation is that the small branches that form the feathers are in fact many avalanches moving towards the streamer head. If this is correct, the number of small branches could be a measure for the background ionization density.

Although there are some quantitative differences, the qualitative conclusions of Briels et al. regarding the similarity laws have been confirmed.

5. References

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