

Pre-Breakdown Phenomena in Technical Air with and without C5-Fluoroketone for a Rod-Plane Gap

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Abstract

Technical air with a few %vol C5-fluoroketone (C5-FK) is one of several alternatives to the potent greenhouse gas SF₆ in medium voltage (MV) gas insulated switchgear. MV products using this gas mixture are already commercially available, but there is still a lack of knowledge about this gas mixture especially regarding pre-breakdown phenomena. In this study, positive and negative streamers are studied in technical air with 7.5 %vol C5-FK at 1.0, 1.3, and 1.5 bar (absolute pressure). Similar tests were done in technical air (80% N₂, 20% O₂) for comparison with the C5-FK results. The streamers emerged from a grounded needle electrode placed 53 mm below a planar electrode. The electrode setup was stressed by a non-standard lightning impulse voltage with voltage peaks varying from 52 to 129 kV. A photomultiplier tube (PMT) was used to register the streamers, and an iCCD camera was used to image the streamers. The pre-breakdown phenomena in C5-FK+air were found to be shorter, less than 1/5 of the length, and to branch less than in pure technical air. The streamer branches in both gas mixtures became wider and less clear when the pressure was decreased. Leader-like channels were observed for C5-FK+air at 1.5 bar (both polarities) and at 1.3 bar (negative streamers).

1. Introduction

SF₆ is a potent greenhouse gas commonly used in gas insulated switchgear (GIS) for both medium and high voltage. It is used because of its good arc quenching and insulation properties, but due to the high global warming potential (about 23 000 times that of CO₂) the industry is looking for an alternative [1]. One of several SF₆-alternatives, which is also commercially available, is technical air with a few %vol C5-fluoroketone (C5-FK).

A good understanding of the electrical breakdown and pre-breakdown (e.g. streamer) mechanisms in the gas mixtures used in GIS are important for more reliable operation and further development of the equipment. Streamers consist of ionizing fronts moving at a high speed [2]. The electric field is enhanced at the streamer tip. This leads to acceleration of electrons and collisions between electrons and the nearby gas molecules [2]. The streamers can form complex structures, like tree-shapes, with branching of the streamer channels. In order for streamers to occur, a start electron has to be present,

making this a stochastic phenomenon, and the electric field has to be strong enough to support the increasing electron density [2]. Leaders, i.e. hot, conductive plasma channels, are known to occur as a pre-breakdown phenomena in air gaps of several meters [3]. This is considered a large-scale event, but leader-like channels in short rod-plane gaps have also been reported [4].

Whilst there are still knowledge gaps to be filled, pre-breakdown phenomena in both SF₆ and air have already been studied for decades, see for instance [5–10]. Positive streamers in air are known to be more critical, they usually occur at lower voltages and are larger/branch more, than negative streamers [2, 5]. Streamers in air are also known to be wider and more blurry, with lower inception and breakdown voltage, when the pressure is decreased [2, 6]. There is, however, hardly anything published about the pre-breakdown phenomena in C5-FK+air. The aim of this work is to characterize the pre-breakdown phenomena in an inhomogeneous field in C5-FK+air. This will be done by studying the key differences between streamers in technical air with and without 7.5%vol C5-fluoroketone (C5-FK) in a rod-plane gap stressed by a fast voltage impulse. The length, branching and general shape of the streamers will be the main focus. The gas pressure and the voltage polarity was varied in order to see how this affected the results.

2. Methods

All the experiments were performed on a rod-plane geometry with a 53 mm gap inside a cylindrical stainless steel 400 L (approximately 0.8 m diameter) pressure vessel. A 1 mm diameter needle, with 0.2 mm curvature radius of the needle-tip, was protruding 3 mm out of the tip of the rod-electrode on the ground-side, creating an inhomogeneous field, see Fig. 1. The 1.2 MV Marx impulse generator created lightning impulses with a 0.5 μs rise time. The shape of the voltage when measured using a North Star PVM-100 voltage probe at the HV-electrode was, however, somewhat different, see Fig. 2. One stage of the impulse generator was used for the experiments in technical air, whilst two stages were used for C5-FK+air since this mixture required higher voltages for pre-breakdown phenomena to occur. This resulted in slightly different voltage curves for the two gas mixtures, see Fig. 2. The voltage magnitudes were chosen in order to maximize the amount of observable pre-breakdown phenomena. It was therefore set below the breakdown

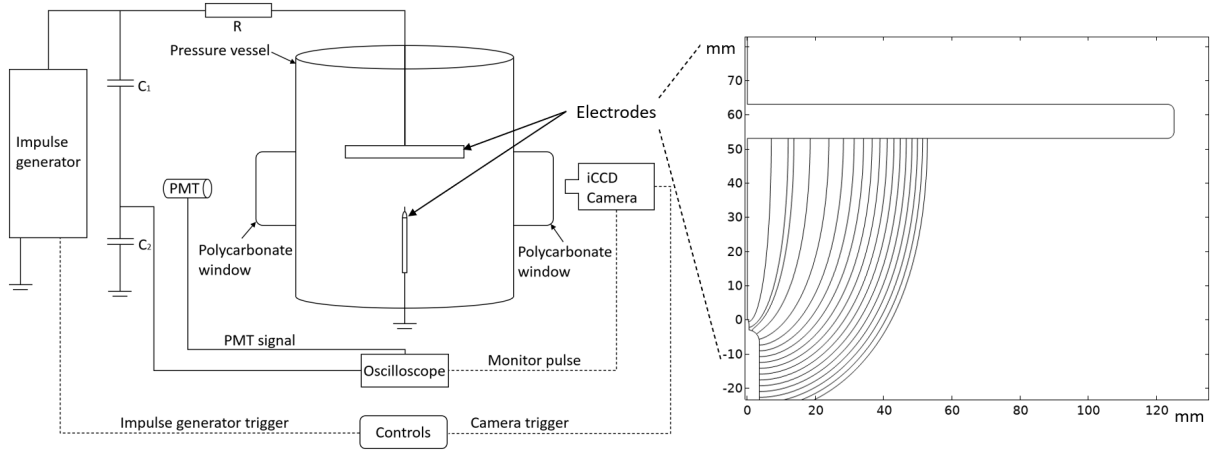


Fig. 1 – The lab set-up used to perform the measurements. A correctly scaled representation of the electrodes, with lines representing the electric field (simulated in COMSOL), is also included.

voltage and far above the streamer inception voltage. This was done for each configuration resulting in several different voltages being used, all within the medium voltage range, see Table 1. The pressure vessel was put under vacuum before filling with the gas mixtures. The gases were filled through a valve at the bottom of the tank. C5-FK was filled first, in order to ensure the gases mixing.

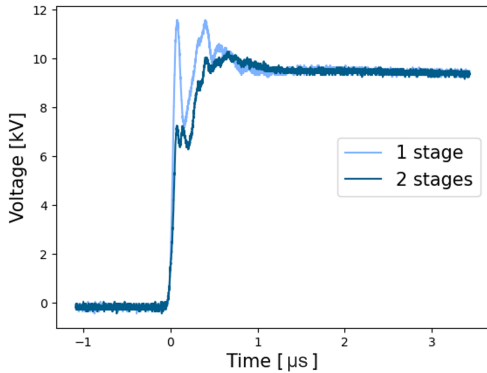


Fig. 2 – The shape of the applied voltage over the gap. 1 stage of the impulse generator was used for the experiments in technical air, 2 stages were used for the experiments in C5-FK+air. The impulse generator was charged to 10 kV for the two impulses in this figure.

Table 1 – The voltage peak (absolute value) over the gap for each configuration. *pos* indicates positive streamer, *neg* indicates negative streamer. C5-FK+air is technical air with 7.5%vol C5-fluoroketone (C5-FK).

	1.0 bar	1.3 bar	1.5 bar
C5-FK+air (pos)	103 kV	113 kV	113 kV
C5-FK+air (neg)	82 kV	113 kV	129 kV
Techn. air (pos)	52 kV	52 kV	52 kV
Techn. air (neg)	81 kV	81 kV	92 kV

There were two polycarbonate windows on the pressure

vessel. These were situated on either side of the the vessel, and enabled the use of both a high-speed video camera with a dual image intensifier (Lambert HiCAM 500) and a photomultiplier tube (PMT), see Fig. 1. The intensifier gain (501-951 V) was varied between 700 and 750 V. The PMT used was a Philips 56AVP with a spectral range of 380-680 nm. The spectral ranges of the camera and the camera lens (Nikkor 180 mm f/2.8) were 200-800 nm and 400-1000 nm, respectively. These ranges were further limited by the vessel-windows, so only visible light could be detected.

One test series consisting of 15 shots, with 3 minutes waiting time between shots, were performed for both polarities at 1.0, 1.3, and 1.5 bar (absolute pressure). This was done both for technical air with 7.5%vol C5-fluoroketone (C5-FK), i.e. C5-FK+air, and for pure technical air (80% N₂, 20% O₂). The camera intensifier was on for 500 μs, in order to make sure that all of the streamer activity was captured. This turned out to be longer than necessary since all of the activity occurred on the rising edge of the voltage. An image manipulation software (GIMP) was used to study the pictures taken by the camera. The approximate length of the streamer in each picture was measured by drawing a straight line from the needle-tip to the longest branch’s end, see Fig. 3, similarly to [7]. The general shape of the streamers was made clearer by inverting the pictures and adjusting the contrast.

3. Results

3.1. Length of the streamers

The average lengths of the streamers in all 12 measurement series are shown in Fig. 4. The standard deviation is also included in the plot. The width of the streamer-structure contributes to the measured length, as shown in Fig. 3, which is why some streamers appear to be longer than the gap.

The main difference in streamer length is between the

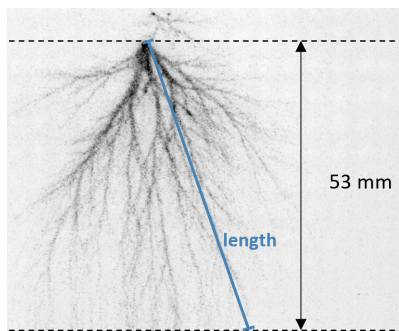


Fig. 3 – The streamer length was measured by drawing a straight line from the needle-tip (streamer starting-point) to the end of the longest branch, as illustrated with the blue line. The height of the needle-tip and the position of the flat electrode are marked with dashed lines. Some shorter streamers are emerging from the rod-electrode above the needle.

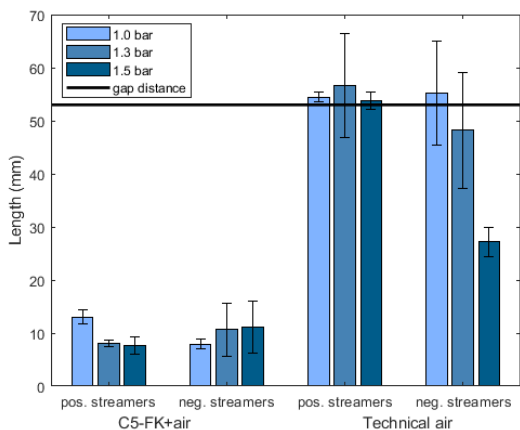


Fig. 4 – The average length of the streamers in mm for C5-FK+air (technical air with 7.5%vol C5-fluoroketone (C5-FK)) and technical air, for both polarities. Each average value is based on a series of 15 measurements. The standard deviation is also indicated in the figure. The voltage peaks for each configuration are listed in Table 1.

two gas mixtures, and not between the different polarities and gas pressures, as seen from Fig. 4. On average, the streamers in C5-FK+air bridged less than 20% of the gap, compared to the streamers in technical air that almost always bridged the gap, apart from the negative streamers at 1.5 bar. The configurations where the streamer lengths varied the most are technical air at 1.0 bar for negative streamers, and at 1.3 bar for both polarities, as can be seen from the standard deviation plotted in Fig. 4. This is due to varying width of the streamer structures for all three cases, as well as varying streamer shapes for the negative streamers at 1.3 bar, as will be discussed shortly.

3.2. Branching and shape of the streamers

All of the streamers were oriented along the field lines, for all 12 measurement series. Apart from this common trait, the shape of the streamers differed between the configurations, as described and discussed below.

3.2.1. Streamers at 1.5 bar (7.95 bar-cm)

The streamers in technical air at 1.5 bar created a tree-like pattern for both polarities. The positive streamers, see Fig. 5A, consisted of many branches emerging from the light-bead at the needle-tip, and dividing into thinner branches (and potentially merging, but this is difficult to say for certain without a 3D-image, as shown in [8]) before some of the channels reached the flat electrode. This is similar to how positive streamers in air usually look [5, 6, 8]. Some streamers emerged from a specific point on the rod-shaped electrode above the needle, as seen from the figure. This is most likely due to a notch or some other type of damage from wear and tear since all of these streamers emerged from the exact same point on the electrode, and not from anywhere else. The negative streamers in technical air at 1.5 bar also created a tree-like structure, but less complex than the positive streamers, see Fig. 5B. These streamers were shorter, approximately half the length of the positive streamers, and had less branching. In addition, the streamer channels were more blurry and vague than for the positive streamers. This matches the results found in [5].

All of the positive streamers in C5-FK+air at 1.5 bar consisted of leader-like channels emerging from the needle-tip, with several thin and vague streamers emerging from the tip of the leader-like channel, see Fig. 5C. Two leader-like channels were observed in almost 1/3 of the tests. In the remaining 2/3, only one channel was visible. Some of the leader-like channels had a bending-point where it slightly changed direction, indicating stepped propagation. Streamers seemed to emerge from these bending-points. Two thirds of the negative streamers in C5-FK+air at 1.5 bar looked like the positive streamers described above, see Fig. 5D. The three main differences are: 1) Some short streamers emerged from the electrode above the needle for almost all of the negative streamers, 2) Only one leader-like channel emerged from the needle, and 3) One of the leader-like channels had a distinct streamer channel emerging from its tip, see the streamer furthest to the right in Fig. 5D. The remaining third of the negative streamers consisted of a bright spot right below the needle tip, with a more diffuse cloud-shape emerging from this bright spot in the direction of the plane electrode, as seen from the figure. One of these mini-clouds had a distinct streamer channel emerging from it, see streamer number three from the right in Fig. 5D.

3.2.2. Streamers at 1.3 bar (6.89 bar-cm)

The positive streamers in technical air at 1.3 bar were very similar to the streamers at 1.5 bar, see Fig. 5A, but branched potentially even more than the streamers at 1.5 bar. The shape of the negative streamers in technical air at 1.3 bar varied between the following three main forms (as seen from Fig. 5B): 1) A tree-shape similar to the negative streamers at 1.5 bar (occurred only once in the measuring series), 2) Cloud shaped streamers (approximately a third of the samples), and 3) Cloud shapes with distinct streamer channels. The cloud

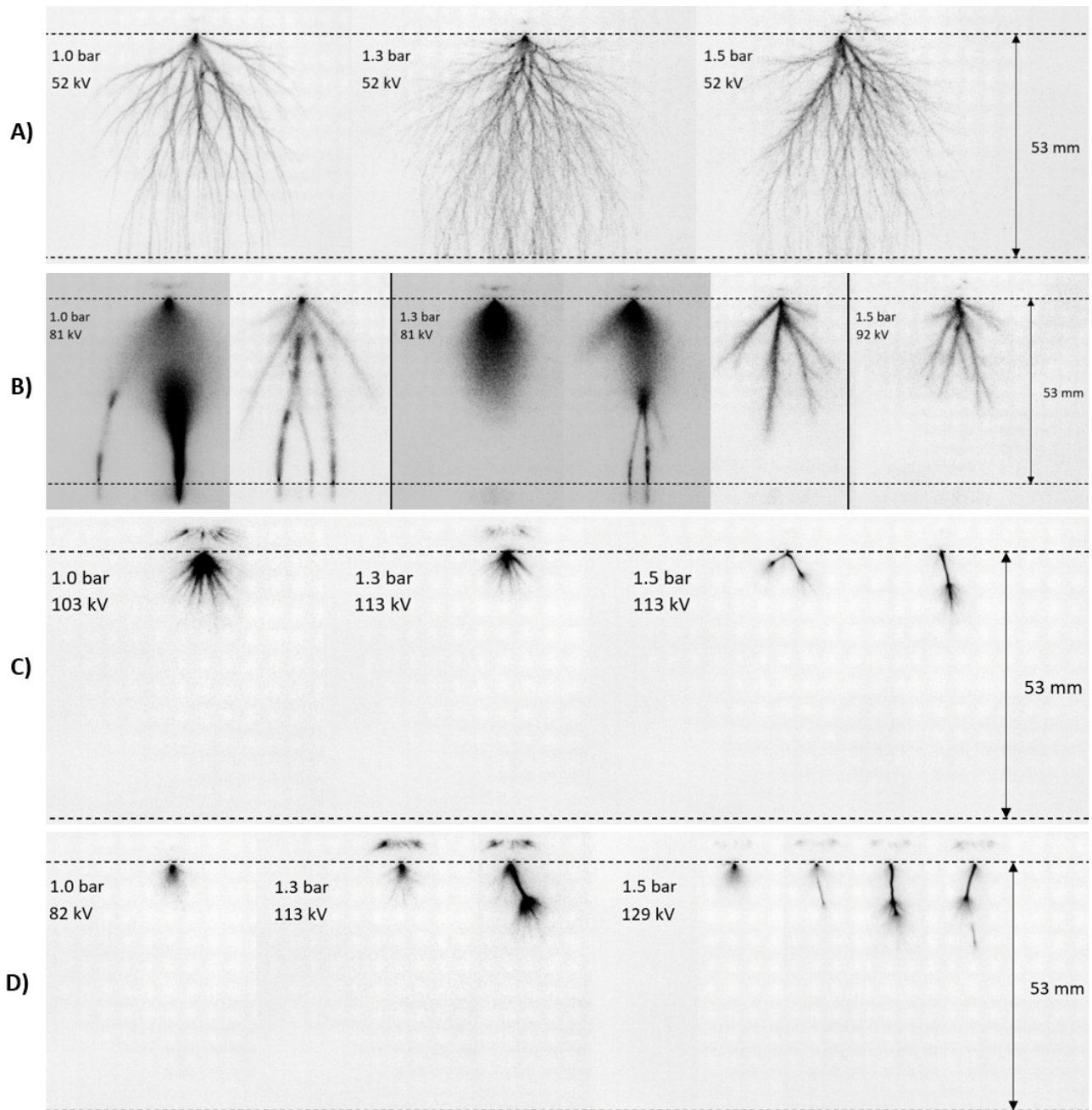


Fig. 5 – A) Positive streamers in technical air. B) Negative streamers in technical air. C) Positive streamers in C5-FK+air (technical air with 7.5%vol C5-fluoroketone (C5-FK)). D) Negative streamers in C5-FK+air. The height of the needle-tip and the position of the flat electrode are marked with dashed lines. Some streamers are emerging from the rod-electrode above the needle in some of the images. In some of the images the streamers appear to continue into the plane, which is impossible. This illusion is likely caused by reflections in the metal and the attempt to capture a 3D event in a 2D-image. The shape of the applied voltage is plotted in Fig. 2. The peak voltages (absolute value) are included in the figure. The images have been inverted and the contrast has been altered slightly to make it easier to study the images.

shaped streamers started as a bright droplet-shaped area out from the needle-tip, and became more diffuse as it expanded (mostly downward towards the plane). These streamers varied slightly in length, the longest reached approximately halfway towards the flat electrode. The cloud shapes with distinct streamer channels started as cloud streamers from the needle-tip, but had streamer channels going out of the cloud. Most of these channels were directed almost straight downward, and bridged the gap between the two electrodes. Several of the streamer channels had streamer beads, i.e. very bright spots at seemingly random places in the streamer channels. This bead-phenomena tended to occur where the channel met the flat electrode and where the channel and cloud met, and sometimes at various places along the channel as well.

The positive streamers in C5-FK+air at 1.3 bar created a star-like shape, see figure Fig. 5C. These streamers consisted of several short channels emerging from a bright sphere-shaped spot just below the needle tip. None of these branches were seen to divide into new branches. These streamers look very similar to the positive streamers observed in SF₆ at 2.5 bar-cm for a strongly non-uniform field in [9]. Some short streamers also emerged from the electrode above the needle, as seen from the figure. The negative streamers in C5-FK+air at 1.3 bar consisted of 1/3 leader-like channels and 2/3 small cloud shapes. The leader-like channels were similar to the negative streamers at 1.5 bar, except that these streamers were wider/more blurry, see Fig. 5D. The streamers emerging from the electrode above the needle were also more prominent at this pressure. The remaining third were bright spots emerging from the needle-tip, similar to those observed at 1.5 bar, see Fig. 5D. Some of the clouds emerging from these bright dots seemed to divide into vague streamer channels, not unlike a vague version of the star-shape observed for the positive streamers.

3.2.3. Streamers at 1.0 bar (5.3 bar-cm)

The positive streamers in technical air at 1.0 bar were very similar to the streamers at 1.3 and 1.5 bar, see Fig. 5A. The main differences are that there were fewer of the thin sub-branches seen at the higher pressures and that fewer of the branches seemed to reach the plane. Additionally, a cloud-like area close to the needle-tip were observed at 1.0 bar and not at the higher pressures, see Fig. 5A. About 2/3 of the negative streamers in technical air at 1.0 bar were similar to the cloud shaped streamers with distinct streamer channels observed at 1.3 bar, see Fig. 5B. The main difference between the two was in the streamer channel(s) between the flat electrode and the cloud. For 1.0 bar this consisted of one main channel, which was very bright and very wide, which seemed to go in a straight vertical line between the cloud and the plane. Smaller channels, similar to the ones observed at 1.3 bar, accompanied this large channel in most of the measurements. The last third of the negative streamers in technical air at 1.0 bar had a more tree-like

structure, see Fig. 5B. The branches were vaguer and less bright than those at the higher pressures, and seemed to have fewer sub-branches. In most of the instances this tree-structure ended up bridging the gap between the electrodes, and these streamers tended to have several streamer beads along the way.

The positive streamers in C5-FK+air at 1.0 bar created a star-like shape similar to the pattern observed at 1.3 bar, see Fig. 5C. The main differences are that the bright sphere-shaped streamer emerging from the needle-tip was larger at 1.0 bar than at 1.3 bar, and that the streamers from the electrode above the needle were longer, brighter and seemed to be slightly thicker at 1.0 bar compared to at 1.3 bar. All of the negative streamers in C5-FK+air at 1.0 bar consisted of small bright dots right below the needle-tip with small diffuse cloud shapes emerging from these dots, see Fig. 5D. These were similar to those observed at 1.3 bar in that some of the clouds seemed to divide into vague streamer channels. Additionally, some short and vague streamers emerged from the electrode above the needle for almost half of the streamers.

4. Discussion

The length and shape of the observed pre-breakdown phenomena in C5-FK+air and technical air were highly different. Additionally, a much larger voltage amplitude was required in order to observe interesting pre-breakdown phenomena in C5-FK+air compared to technical air, see Table 1. This indicates that a much stronger electric field is required for streamers to occur in C5-FK+air compared to air. The streamers in C5-FK+air were also found to be significantly shorter than the streamers in technical air. This indicates that either the increased gas density or C5-FK+air (as an electronegative gas), or a combination of both, prevents streamer propagation since the other factors, i.e. geometry, pressure and polarity, were similar for both gas mixtures.

The shape of the streamers in C5-FK+air, especially the star shaped streamers at 1.3 bar, had a strong resemblance to the streamers observed in SF₆ for a strongly non-uniform field arrangement at 2.5 bar-cm in [9]. The leader-like channels observed in C5-FK+air for the higher pressures, is reminiscent of the leader-like channels observed in SF₆ in [10]. This is very different from the complex tree shaped positive streamers, with countless of branches, and the more diffuse tree and cloud shaped negative streamers observed in pure technical air.

The trend, for both gas mixtures and both polarities, was for the streamers to become wider, and for the streamer channels to bundle together in more cloud-like shapes rather than splitting into clearly defined channels, if decreasing the pressure. This matches the results found in [6]. The most drastic pressure-dependent changes occurred for both polarities in C5-FK+air and for negative streamers in technical air. Why the pressure-dependence for the positive streamers in pure technical air was less pronounced is unclear, since these are known

to be pressure dependent. Maybe it had been more pronounced if higher voltages had been used for the higher pressures, since the inception and breakdown voltage are known to be higher if increasing the pressure [2]. The negative streamers in pure technical air had drastically different shapes at 1.0 and 1.3 bar compared to at 1.5 bar. This is similar to how sprite discharges in the atmosphere becomes less diffuse and branch more as the pressure increases [2].

The inception voltage and shape of streamers in air are known to be highly polarity dependent, where the positive streamers branch more, are less diffuse and start at lower voltages, as these results reaffirms. Positive polarity is, in other words, known to be the critical polarity for pre-breakdown phenomena in ambient air. The optical representation of the streamers in C5-FK+air does not seem as polarity dependent. This might be due to the voltage range at which pre-breakdown phenomena occurred without leading to an actual breakdown were significantly shorter for C5-FK+air than technical air for this electrode configuration. Had this voltage range been larger, as it is for technical air, more/longer streamers might have been observable in C5-FK+air, which might illuminate the degree of the polarity dependence. Despite this, some differences in the results depending on polarity were observed. The main trend was for the negative streamers in C5-FK+air to be slightly more diffuse/wider, and sometimes a bit longer, than the positive streamers.

5. Conclusion

The streamers observed in C5-FK+air (technical air with 7.5%vol C5-fluoroketone) were significantly shorter, less than 20% of the length, branched much less (if at all), and required a stronger field in order to occur compared to the streamers in pure technical air. Leader-like channels were observed for C5-FK+air for both polarities at 1.5 bar and for negative streamers at 1.3 bar. The optical result of pre-breakdown phenomena in C5-FK+air did not seem strongly dependent on the voltage polarity, but did become more diffuse when the pressure was decreased. The pre-breakdown phenomena in pure technical air depended similarly on the pressure-change. As expected, the pre-breakdown phenomena in pure technical air was highly dependent on the voltage polarity.

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